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**Genetically Inherited Amyotrophic Lateral Sclerosis: A Holistic Overview**
**By Saanvi Bhadouria**


## Abstract

This paper discusses Amyotrophic Lateral Sclerosis(ALS), the affected genes that cause it, symptoms, possible treatments, cost of expenses, laws, and effects on relationships and daily life. With approximately one in four hundred people being affected every year, this neurodegenerative disease can, and most times is, fatal, with various types of ALS having different effects. According to multiple sources(listed below), the neurodegenerative disease is known to cause severe damage in the motor neurons, eventually leading to muscle and skeleton dysfunction, paralysis, and even failures in the respiratory system due to nervous system damage affecting the spinal cord and ribcage as well. The average lifespan of someone with ALS is around two to five years, but with proper treatment, can be extended much past simply that. There is currently no set cure for ALS ever since its discovery in 1869, although treatments to ease the repercussions are being discovered and refined over time, with expenses usually being quite high.


## Introduction

Amyotrophic Lateral Sclerosis, also known as Lou Gehrig's Disease(ALS Association, n.d. *Understanding Lou Gehrig's Disease*), is a chronic neurodegenerative disease that specifically targets one's motor neurons, mainly in the spine up to the brain, eventually leading to extreme muscle fatigue, restricted movement, paralysis, and even death in cases of utmost severity. It is typically inherited through dominant inheritance patterns, but can also be inherited recessively or through X-linked patterns on rare occasion. Around 90%-95% of ALS cases are sporadic, meaning they were random and not inherited, while 5%-10% of ALS cases were familial, which will be the focus of this report(Kiernan, M.C. (2011). Amyotrophic lateral sclerosis. *The Lancet*).

Within the realm of familial ALS rises three different types of ALS, all affecting different neurons and parts of the body at different rates, those being Primary Lateral Sclerosis(PLS), Progressive Muscle Atrophy(PMA), and Pseudobulbar Palsy(PBP). ALs can completely change the course of one's state of living, and can be detrimental to their interactions with those around them.

## Biology Overview - What Is ALS?

Being discovered in 1869 by French neurologist Jean-Martin Charcot(ALS Association, n.d. *Understanding Lou Gehrig's Disease*), ALS has had a long history of study, particularly in comparison to other diseases of its such. Familial ALS typically occurs when mutations are present on wide varieties of genes, but most commonly of those are C9orf72 on chromosome 9, and SOD1 on chromosome 21, on the short arm and long arm of the chromosomes(Kiernan, M.C. (2011). Amyotrophic Lateral Sclerosis. *The Lancet*). Other gene mutations causing the

disease to occur are TARDBP, FUS, and ANG mutations, with one genetic abnormality being able to lead into the others.

The disease has been coined “Lou Gehrig’s Disease” because of how it took the life of one of the most famous baseball stars, Lou Gehrig on the New York Yankees, in 1941. He had been diagnosed with it in 1939, with his life being taken only two years afterward, leaving people in shock about the severity of the disease for quite a while. Based on the type of genes the mutations occur on, ALS has a wide array of symptoms which usually worsen overtime, most prominently being effects on the muscular system(muscle weakness, paralysis, increased fatigue, speech impairment due to muscles that control speech) and effects on the skeletal system(spinal cord damage, paralysis, increased stiffness, difficulty breathing and swallowing, eventual respiratory failure which usually is the most common killer amongst ALS patients) which all lead into the types of ALS present as well(Your ALS Guide. (n.d.). *Types of ALS*). PLS only affects the upper motor neurons and primarily limb damage and restricted movement, as well as restricted speech, having a longer life expectancy than the others. PMA affects mostly lower motor neurons, causing muscle weakness, fatigue, and atrophy, progressing faster than PLS does. PBP starts off by affecting the upper motor neurons and then affects the lower motor neurons, and has the most severe symptoms, causing bone stiffness, immobility, difficulty breathing and swallowing, and eventual respiratory failure, with it also having the shortest lifespan of the three different types of ALS(Your ALS Guide. (n.d.). *Types of ALS*).

**Human Interactions and Day-to-Day Life**

ALS is detrimental to a person, significantly deteriorating their quality of life. On top of an already wide range of health issues, it impacts communication and mobility the worst, as the disease can literally impair one’s speech rendering them unable to talk with others, and also demobilize a person to the point of paralysis. Day-to-day contact with others is difficult for someone with ALS, and something as simple as taking care of yourself can become much more difficult. People with ALS often must be accompanied by friends or caretakers, in order to help them carry out basic tasks.

Due to the fact that ALS can cause respiratory failure in certain instances, some people with ALS may have to live the rest of their life with medical assistance(Muscular Dystrophy Association. (n.d.). *Everyday life with ALS: P-532*). Luckily in the modern age, alternate strategies for mobility and communication for ALS patients exist, including wheelchairs, mobility devices, eye signals, facial expressions, sign language, and text-to-speech technology. It is near impossible to live one’s life normally if diagnosed with ALS, even with the workarounds present, on top of treatment costs and job unavailability.

**ALS Treatments and Costs**

Although there is no known cure for ALS, more progress has been made in the discovery of medicines and treatments for this fatal disease. Two known medicines in particular are Rizoule and Edaravene. Rizoule, both a tablet and a liquid drug, contains the drugs Rilutek,

Exservan, and Tiglutik, which all help in fighting off ALS symptoms for as long as possible. Rizoule is mainly used in lengthening the life expectancy of someone with ALS, so while it does not directly do action against the disease itself, it can prolong a person's life a lot longer than it would be without the drug. Unfortunately, the medicine does cause quite a few side effects, including dizziness, gastrointestinal issues, and liver complications, which aren't enough to get a person hospitalized, but causes one pain and discomfort nonetheless(Mayo Clinic. (n.d.). *Amyotrophic lateral sclerosis: Diagnosis and treatment*). On the other hand, Edaravone, a liquid drug, contains the drug Radicava, is primarily used in slowing down the speed of decline in daily functions of a person, such as declining how badly mobility and speech are affected. It is administered less often than Rizoule(only once per day) which is daily for two weeks each month, either through the mouth or through a vein in one's arm. While it is an effective medicine in fighting off function decline, it in itself has some mild symptoms coming with it, most notably headaches, bruising, and trouble walking(mainly balance issues).

Unfortunately even with the effectiveness of these medicines, the costs of them are quite high, with One 50 mg bottle of Rizoule being around 100$-300$, and one 30 mg bottle of Edaravone being around 500$, which in the long run, are very high costs for annual medications. Along with these existing drugs, other processes and therapies such as physical therapy, MRIs, and nerve or muscle biopsies can help one understand what a person's condition is with ALS, helping them figure out which treatment works the best for them(ALS Therapy Development Institute. (n.d.). *1 in 400: How many people will get ALS?*).

**Laws and Organizations for ALS**

With the issues that ALS brings, and the high cost of medicine and treatment, there do exist federal laws and organizations that help ALS people have equal rights to able-bodied people, cheaper access to healthcare and treatment, and necessary working accommodations for people with the disease. For starters, the Accelerating Access to Critical Therapies for ALS Act recognizes the ALS patients that exist under the US government and is actively working towards funding for the discovery and improvement of treatments for ALS, with more funding and time given towards ALS research by the year(U.S. Congress. (2021). *H.R.3537 – Accelerating Access to Critical Therapies for ALS Act*).

Given how rapidly ALS is increasing in severity by the year, patients have eligibility for Social Security Disability Insurance, issued by the US federal government, in order to compensate for being unable to attend their working class jobs after a certain point, providing them the financial compensation and resources needed for daily life. Along with these, the American with Disabilities Act(ADA) protects ALS patients from workplace discrimination, as well as ensuring the necessary accommodations for ALS patients in the workplace and in public spaces(ALS United North Carolina (n.d.). *ALS Legal Rights: Understanding Your Protections and Benefit*).

**Discussion - Why is this Important?**

With the rise of Amyotrophic Lateral Sclerosis over the years, and the severity increasing overtime, it is important to stay educated on topics regarding this neurodegenerative disease. Given all of the different types it can come in, the fact that it is both sporadic and familial, the intense symptoms, and the various levels of severity, it's important to understand that this disease can affect anyone at any point in time. The physical, mental, financial, and emotional toll it takes on both the patient and their loved ones is much more than the average non-affected person may understand and resonate with.

It is important to support those with ALS in one's community, and work towards finding more efficient treatments and cures for the disease. Particularly for scientists, being able to understand how the disease works, evolves, and functions is especially important for coming up with less expensive and more personal treatments for the disease, and eventually work towards a possible cure for it. Having easy-to-access medicines and technologies to help assist ALS patients with day-to-day tasks would be incredible for patients. This disease is no joke, and it's up to those who are able-bodied to help improve financial, physical, mental, and emotional conditions for these patients and their loved ones to ensure that they do not get left behind.

**Conclusion**

Amyotrophic Lateral Sclerosis is a debilitating neurodegenerative disease that harms the motor neurons particularly near the spine, neck, and brain areas, leaving them with degrading symptoms such as muscle fatigue, bone stiffness, weakness and mobility issues, eventual paralysis, impaired speech, and even issues with breathing and respiratory complications. It is caused by mutations in quite a few genes, but post primarily in the SOD1 and C9orf72 genes, located on chromosomes 9 and 21. There are three different types of ALS, Primary Lateral Sclerosis(PLS), Progressive Muscle Atrophy(PMA), and Pseudobulbar Palsy(PBP), that each affect different motor neurons and lead to functional deterioration overtime including in mobility, speech, and other simple tasks like swallowing and breathing properly. There currently exist two medicines, Rizoule and Edaravone, that are used to treat ALS and prolong the effect of symptoms, however they are quite expensive when stretched out long term, and currently there is no set cure that exists for the disease. Laws such as Accelerating Access to Critical Therapies for ALS Act, the law for Social Security Disability Insurance, and the American with Disabilities Act allow scientists to continue to work towards a cure for ALS, with more and more information being discovered each day, as well as providing financial and workplace compensation and treatment to those with the disease. Currently, there is more and more being discovered about ALS by the day, and with the growing severity of the disease, scientists are dedicated to finding a cure for the dangerous disease, hopefully not just temporarily, but permanently.

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**Learning with Caution:**
**Exploring Responsible ChatGPT Use Among Korean High School Students By Ellie Cho**

**Abstract**

Using a quantitative research design, data were collected through an online survey in the language they feel more comfortable with in English or Korean. It was distributed to students in Seoul. Fourteen questions examined students' frequency of ChatGPT use, experiences with inaccurate or biased information, authenticity concerns, and strategies for responsible usage. Findings revealed how ChatGPT affects students' originality, dependence, and trust in learning, while also identifying practices that promote responsible engagement with AI. The study underscores the importance of the education on AI and ethical awareness among students in the age of generative AI, emphasizing that responsible use can balance technological convenience with authentic learning.

**Keywords** Generative AI, ChatGPT, Korean High School Students, AI in Schools

## Background of the Study

Ever since its release in November of 2022, ChatGPT sparked fear in schools for possible cheating and plagiarism (Chen et al. 16046). The program is able to self-learn, meaning that its knowledge and therefore potential can continue to grow with no limitations as it gains more information from users. (Bochniarz et al.1). However, the endless possibilities of ChatGPT and other generative AI tools have also brought on the increased possibility of using these tools to cheat on assignments or plagiarize other texts.

Teachers have also been shown to use ChatGPT just as much as students. A study showed that ChatGPT use increased between the 23-24 and 24-25 school years for both students (58% increased to 70%) and teachers (51% increased to 70%) (Merod). Meanwhile, another study showed that in 2024, 18% of K-12 teachers were actively using AI tools (Chen et al. 16046). While students mostly use ChatGPT to define concepts, complete parts of or even a whole assignment, and to generate images, teachers use ChatGPT to develop lesson plans, and 4 in 10 special education teachers use ChatGPT for tracking student progress, goal setting, and developing Individualized Education Programs (Lee et al. 3-6, Merod).

## Problem Statements

One of the biggest issues with ChatGPT is that it can provide inaccurate results to users. "AI is only as good as the algorithms it is based on. If the data it draws from is inaccurate or biased, then the information it creates will be inaccurate or biased" (Office of Communications). Additionally, some teachers use AI detectors to check if their students used any AI-generated content in their work. However, even these detectors proved to be inaccurate, as they are AI tools themselves. While 39% of teachers use AI content detection software, 1 in 5 students reported that they or someone they knew had been wrongly accused of using AI (Merod).

Some worry that ChatGPT also may take away the creativity and authenticity students portray in their assignments. Furthermore, teachers who taught at higher grade levels in general were more likely to oppose students using ChatGPT tools, meaning high schoolers face the most opposition to using ChatGPT (Chen et al. 16046). Students who generate work, especially writing, from ChatGPT, end up creating writing pieces that are not in their own writing voice, which diminishes a sense of authenticity. Moreover, continuous use of ChatGPT can lead to overdependence, which prohibits them from being creative and actually taking the time to learn and study. While ChatGPT can be used to generate facts, general ideas, and other objective content, it still lacks an aspect of authenticity and prevents students from actually learning.

**Research Questions**

1. What are the potential negative effects of ChatGPT use on Korean high-school students?
2. What are some ways that ChatGPT could be used responsibly?

**Purpose of the Study**

The purpose of this study is to reveal, not necessarily *highlight* the risks that come with using ChatGPT. This study will show what students think about ChatGPT and what experiences they have had with ChatGPT's possible negative impacts.

**Literature Review**

*Accuracy*

One of the main issues with ChatGPT and similar chatbots is that ChatGPT can produce inaccurate information. A study by Kanjee et al., tested a generative AI model's accuracy in diagnosing medical diseases, and the model was 64% accurate for differential diagnoses and only 39% accurate for top diagnoses. A different study by Johnson et al. shows that out of 180 questions about medical guidelines, 57% of ChatGPT's answers were "nearly all correct" or "correct." Not only does the issue pertain to the information itself, but the fact that "ChatGPT offered false information that sounded convincing" (Al-Gibawi 6). Although AI chatbots seem to have the potential to provide accurate information, there is room for improving accuracy. In addition to accuracy, biased information can also be generated by ChatGPT. ChatGPT generates information based on the information it has taken in from the user. "If chatbots are trained on biased data, they may perpetuate unfair assessment outcomes and contribute to inequality in education" (Al-Gibawi 5).

*Guilt*

Another concern related to ChatGPT usage is how students may be emotionally affected and feel guilt for using ChatGPT. When students recognize that they have used ChatGPT excessively, they may experience a feeling of guilt for relying on it to complete their assignments rather than doing their own work (Jo 10). An article by Chan describes some terms that relate to what students may experience with ChatGPT use:

- Imposter phenomenon describes “feelings of fraudulence and doubt about one’s abilities despite evident success” (21728). This idea most relates to excessive ChatGPT use as students may believe they are not actually capable of the work that had been generated (21730).
- Self-Determination Theory is a theory that stems from the idea that students feel incapable of completing their assignments. They believe that they are incompetent when it comes to their schoolwork, and become completely dependent on AI and are unable to function on their own (21730).

These ideas suggest that excessive AI use and the guilt that follows originates from a lack of self-confidence and self-efficacy rather than simply from mal-intent such as cheating.

**Theoretical Framework**

*Benefits of AI*

AI has so many uses in our lives, and can offer relevant and accurate information in urgent situations since it is generally much quicker than searching for information online. A study by Forman et al. found that 57% of the surveyed high school students used ChatGPT daily for reasons such as “academic support, information retrieval, and entertainment” (99). The majority of these students also found ChatGPT to be helpful in understanding complicated concepts or saving time (Forman et al. 99). Other AI tools, such as citation generators or grammar checkers, can help improve students’ writing assignments. As a high school student, I have had many more positive experiences when using AI platforms such as ChatGPT or Gemini. As a general, I tend to believe that AI is quite helpful with providing general information and helpful tips or guidelines.

*Concerns of AI*

One concern about ChatGPT as a tool in education is related to overdependence. Students who use ChatGPT excessively may become overly dependent on the platform, and they may be incapable of completing tasks or creating writing pieces without its help. A study at Wharton and Penn demonstrated that during an experiment, a group of students who studied with the help of GPT Base scored 48% better than the group who had no AI assistance (Basiouny). However, when their AI platform was taken away, they scored 17% worse than the same group. (Basiouny). From this study, we can observe that these students did not actually learn during their study session but rather depended on AI for answers. Looking at the bigger picture, continuous use of ChatGPT would have caused these students to completely depend on ChatGPT, further hindering their learning.

Another concern pertaining to ChatGPT in education is the use of writing that is ChatGPT-generated. High school teachers are highly likely to forbid students using AI in their writing, especially those who teach Humanities where writing is one of the main components (Chen et al. 16060). In addition, it is also possible for student work to be wrongly flagged as AI.

An experiment in 2023 showed that Turnitin's AI-writing detector was incorrect in determining whether half of the provided essays were real, fabricated, or mixed-source essays, even though Turnitin says that its detector is “98 percent accurate overall” (Fowler). An incorrect flag can be detrimental to students, especially if their grades are affected, and it is necessary that the flaws of AI detectors are also addressed.

**Methodology**

This study employs a mixed-method research design, combining both quantitative and qualitative data. Quantitative data include numerical and statistical information about students’ ChatGPT usage, while qualitative data consist of students’ opinions and explanations regarding AI use. Mixed-methods research involves combining both qualitative and quantitative data collection and analysis to gain a more complete understanding of a research topic than either method alone. This approach allows researchers to use both inductive and deductive reasoning, taking advantage of the strengths of each method. Similarly, mixed methods provide a comprehensive way to study complex problems, enabling researchers to explore patterns, trends, and personal perspectives simultaneously.The design is both descriptive and exploratory, aiming to describe students’ experiences with ChatGPT and explore their thoughts on responsible AI use.

Data will be collected through a survey consisting of two parts. The first part contains quantitative questions, which ask about ChatGPT usage frequency, perceived helpfulness, accuracy of information, and impact on originality in schoolwork. The second part includes qualitative questions that explore responsible AI use and suggestions for improving ChatGPT. This approach allows the study to examine both statistical trends and personal opinions. Demographic Questions include name, age, gender, and residence within Seoul.

Quantitative Questions ask students how often they use ChatGPT, how helpful or harmful they consider it, how often they receive inaccurate information or face false accusations of AI use, and their perceptions of AI’s effect on originality and authenticity in student work. Qualitative Questions ask students what study habits could support responsible AI use and what changes they would suggest to make ChatGPT better and more reliable.

Data were collected using a structured online survey through SurveyMonkey. The survey included questions that measured how often students use ChatGPT, how helpful or harmful they think it is, if they have received incorrect information or been falsely accused of using ChatGPT, and how they feel it affects the originality of their work. Other questions asked about responsible ways of using ChatGPT, suggestions for improving it, and how students make sure their work stays authentic.

The population for this study consists of a small group of twelve Korean high school students ages 15-17 studying in Seoul, Gyeonggi Province, and North Jeolla Province, though geographic location was not a main component or focus of this study. A convenience sampling method will be used. Students who are readily accessible through school networks, friends, or online student groups will be invited to participate in the anonymous survey. Participants will be

recruited by asking classmates and friends at school and posting invitations in online student groups for high school students in Seoul. Participation is voluntary, and students will be informed that they may skip any questions or withdraw from the study at any time without penalty.

**Findings**

*Finding 1: Normalization and Cautions of ChatGPT in Students' Everyday Learning*

One noticeable pattern emerging from the survey responses pertaining to ChatGPT usage is that AI has become a prevalent aspect of student life. The data signals that AI is no longer considered as a novel or difficult technology but rather as a familiar and accessible tool for everyone to learn and communicate. In the survey, over 90% of participants reported using ChatGPT more than five times per week for various reasons primarily for academic purposes. Notably, no participants answered that they had never used AI, showing how AI is used universally among this sample population with varying degrees. Regardless of age, gender, or place of learning–whether in Seoul, the capital city of Korea, technologically highly developed, or in less urbanized regions and smaller cities in the country– all students had used ChatGPT at least once. It can be inferred that many Korean high school students have implemented ChatGPT as a part of their learning and studying process across geographical and socioeconomic contexts.

Furthermore, even in districts that may not be seen as "developed" as other important cities such as the capital, ChatGPT is still regularly used by students. However, half of the participants only used ChatGPT five to ten times a week. From this we can guess that, while students enjoy and find purpose in using ChatGPT, they are careful not to use it too much. Later questions also support the idea that students are aware of the flaws and potential risks of ChatGPT use, and are careful when using it in their studies.

The students' responses also revealed highly positive views toward ChatGPT and using AI. The majority of participants responded that ChatGPT was "not very harmful." Similarly, more than 80% of participants voted that ChatGPT was very helpful. Because ChatGPT is quite widespread across the world, and has become common in most developed societies, students seem to have positive thoughts overall on ChatGPT and AI as a whole.

In conclusion, the survey results point to a dual pattern: ChatGPT is both a very normalized and cautiously used learning tool. Many of the participants were aware of the technological benefits as well as the awareness that comes with the advantages, meaning acknowledging there are some potential drawbacks of using ChatGPT. This finding aligns with the recent trend in research in youth AI engagement with many ethical concerns and implications of using AI especially among young populations. This finding illustrates the need for further discussions of responsible usage of ChatGPT and teaching and learning opportunities supporting these students.

*Finding 2: Growing Concerns and Awareness of ChatGPT*

Despite the overall positive shared by participants in the previous theme, the survey also revealed that Korean high school students are clearly aware of ChatGPT's flaws and limitations. Many participants shared concerns related to accuracy, bias, originality, and authenticity. When asked about the extent to which ChatGPT reduces originality in their schoolwork, more than half (over 50%) agreed that it negatively affects the authenticity of their ideas. This finding indicates that while students recognize the convenience and accessibility of ChatGPT, they also perceive it as a potential threat and risks to their creativity and studies.

The most commonly reported negative experience was encountering incorrect or biased information, with approximately 75–80% of participants indicating that they had faced this issue at least once. Students noted that ChatGPT sometimes produces inaccurate answers or reflects biased assumptions depending on how questions are phrased. These experiences often led to skepticism: about 60% of participants said they had "lost trust" in ChatGPT after receiving unreliable or inconsistent responses.

However, this loss of trust does not mean that it prevented students from using ChatGPT necessarily; instead, many students described becoming more cautious and analytical with some repeated observation of those inaccurate responses. Several respondents explained that they now verify ChatGPT's answers through textbooks, teachers' feedback, or other online sources—demonstrating that distrust has fostered more active and critical engagement rather than complete rejection of the tool or just take and perceive responses as it is.

In addition to accuracy concerns, authenticity and creativity emerged as equally significant issues. About half of the respondents indicated that ChatGPT made it difficult to express their individual writing style or unique perspective, reducing the sense of personal ownership in the writing process. While many students attempted to revise or personalize ChatGPT's suggestions, they acknowledged the challenge of maintaining an authentic voice while relying on AI assistance. This tension between efficiency and originality underscores a growing self-awareness among students of the cognitive and ethical dimensions of AI use in learning.

However, this struggle cannot be understood apart from broader educational and cultural contexts in Korea. The nation's education system remains highly exam-oriented, with strong emphasis on the College Scholastic Ability Test (CSAT or phonetically, soo-hahk neung-ryeok shee-hum, in short, *Suneung*) (Asahina & Park 3). Students spend years preparing for this high-stakes exam, often prioritizing memorization and accuracy over creativity or critical thinking. Korean students often face immense pressure to score highly on the CSAT, and schools lack an "emphasis on critical thinking, creativity, and problem-solving skills, in favor of focusing on exam content" (Ferguson). Within this environment, the introduction of AI tools like ChatGPT may unintentionally reinforce existing tendencies toward formulaic thinking. With AI further fueling these ways of thinking, Korean students in the future may be unable to think creatively or critically, making it even more essential that AI is used in a way that does not diminish a student's individual voice.

While ChatGPT has become a normalized learning tool, these experiences have prompted many students to use it more thoughtfully and reflectively. Ultimately, this theme underscores the need for more education on AI that extends beyond technical instruction to include critical awareness of accuracy, bias, and authorship.

*Finding 3: Students' Responsible Practices and the Call for Transparent AI*

A third pattern identified from the survey centers on students' growing sense of responsibility when using ChatGPT and their expectations for ethical accountability from AI developers. The data indicate that Korean high school students are not passive users of technology; rather, they are reflective learners who consciously monitor their engagement with AI. Nearly 90% of participants reported that they *already practice responsible study habits* when using ChatGPT, such as verifying information, rephrasing AI-generated text, and limiting dependence on automated tools. The same proportion—around 90%—found such strategies "somewhat" or "very helpful," suggesting that awareness of responsible use is both widespread and meaningful among this group. Participants view ChatGPT as a useful too rather than a replacement for genuine thinking. This pattern reinforces findings from previous themes: while students appreciate the efficiency of AI, they are also aware of its potential to undermine originality if relied upon excessively.

Moreover, findings suggest that participants have this idea that the responsibility for ethical AI use cannot rest solely on individuals. Several participants expressed that AI companies must be more transparent about the limitations and possible inaccuracies of their platforms. Although ChatGPT includes a disclaimer stating, *"ChatGPT can make mistakes. Check important info,"* at the bottom of the page, not only are these messages small and unnoticeable at first glance, but also these messages are not enough to encourage students and adults to be responsible when using ChatGPT. For example, as mentioned before, Turnitin's AI writing detector claims that it is 98% accurate even though a brief experiment concluded that it was really only 50% accurate (Ferguson). Even though Turnitin displays their own message alerting users that their flags should be "treated as an indication, not an accusation," it still begs the question of whether teachers will follow through with this comment or not (Ferguson).

Overall, this theme illustrates a twofold awareness among Korean high school students: they not only recognize the importance of responsible study habits but also expect AI companies to uphold similar standards of honesty and transparency. Their insights reveal an evolving ethical consciousness in which responsibility is shared between humans and technology. In conclusion, students' proactive stance toward responsible AI use signals a promising foundation for students' AI use.

**Discussion/Implication**

*Significance of the Study*

As AI becomes more prevalent in our world, especially in education, it is even more important that students and adults understand the consequences that come with using it. This

study shows the importance of using ChatGPT responsibly so that students and teachers are not affected by its negative impacts. Students must be aware of the fact that despite ChatGPT being a quick and easy tool, it can produce inaccurate results and lead them to practice unhealthy study habits. Likewise, adults must also be cautious of their ChatGPT usage, and understand that its negative repercussions can affect both themselves and others around them.

*Limitations*

The limitations that came with this survey were a small sample size, the sample population, and honesty. Because participants were only selected from certain areas or schools, it is difficult to generalize the information for the entire population of Korean High School students. In the future, it would be better to ask people from multiple different schools, areas or familial backgrounds. Furthermore, only asking certain people meant that the sample size was much smaller than a traditional experiment's sample size. A small sample size means that there was not a large variety in answers, making it even more difficult to truly determine the effects of ChatGPT and generative AI on these students. In order to prevent this issue, I could use social media and other networking platforms to reach a wider audience and entice a larger variety of people to participate.

Honesty is another limitation of this survey. The students who participated may feel uncomfortable or embarrassed talking about their AI usage, especially if it resulted in negative consequences. During the survey, they may have purposefully provided alternate or incomplete answers so as to hide the truth. This would lead to inaccurate results in the survey, and an incorrect conclusion. Though it is not easy to determine whether somebody is lying or not, there are ways to make a participant feel more comfortable in sharing about themselves. For example, this survey was conducted anonymously. Surveyors had no methods of connecting the responses to the responders, and this may have allowed students to be more open with their responses.

## Conclusion

This study explored how Korean high school students perceive and use ChatGPT in everyday learning and studying experiences. Findings drawn from the survey responses revealed that while ChatGPT has become a normalized tool in students' academic and personal lives, many recognize its flaws—particularly in accuracy, bias, and originality. Students demonstrated responsible studying habits using AI, such as verifying information, checking and revising information, and limiting overreliance, while also calling for greater transparency from AI companies. These findings suggest that high school students in Korea have a growing understanding and awareness of using ChatGPT given South Korea's highly structured and exam-driven education system, which may lack some areas for creativity. The study underscores the need for more education and guidance in AI that promotes creativity, authenticity, and responsible engagement with the new technologies.

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**A Comprehensive Analysis of Chinese Economic Growth From the Year 1978-2023: Analyzing Political and Economic Reform in China By Vihaan Bathla**


## ABSTRACT

In much of the twentieth century, capitalists and communists were viewed as two opposing ideologies. The collapse of the Soviet Union reinforced the idea that communist states, such as China, would not be able to survive the era of mass-market reform and globalization. Yet, modern China defies this idea (Guthrie 41–45). This paper examines how the Chinese Communist Party (CCP) has integrated capitalist practices into its political systems to ensure the longevity of its country, thereby redefining what it means to be a communist state and creating a hybrid model of both authoritarian rule and a successful economy. This paper argues that the Chinese economic reforms occurring after 1978 were not, in fact, a departure from the practices of communism, but rather an adaptation necessary for preserving one-party control. This paper will examine the emergence of Chinese capitalist reforms as well as the emergence and implications of this hybrid model throughout the world.



**Key Words/Terms**

China, Chinese Communist Party (CCP), economic reform, post-Mao era, hybrid governance, market liberalization, Special Economic Zones (SEZs), poverty reduction, income inequality, authoritarian capitalism, comparative economic policy, globalization.


## Historical Context of Mao's Reforms

China's current economic state has evolved from the conditions of the late Maoist era. Before 1978, China operated under a centrally planned economy, which was mainly composed of collective agriculture as well as state-owned companies (Naughton 54–57). This economy placed great weight on total government control over the production and distribution of domestic products. While these policies were key in uniting the Chinese state at the time, they were economically inefficient. Agricultural production, as well as industrial products, were constrained by outdated technologies and had stagnated (Vogel 112–120).This was met with constant shortages of essential products. This effect was exacerbated by political movements such as the Great Leap Forward (1958–1962) and the Cultural Revolution (1966–1976), which extremely destabilized the economy (Vogel 112–120).

By the late 1970s, governmental bodies realized that strict compliance with Maoist economic policies threatened economic and political stability. Deng Xiaoping, who emerged as the foremost leader after Mao's death, realized that economic growth would only be possible if aspects of market economies could be integrated into the Chinese politburo (Guthrie 41–45). These reforms were made carefully to preserve the ideals of the Chinese Communist Party (CCP) in the context of the political fragmentation, or constant divide, of the Soviet Union.

Due to this, the reforms introduced after 1978 were not reinventive, but rather strategic alterations that set up China for economic growth. These initiatives included the Household

Responsibility System in agriculture, the establishment of Special Economic Zones (SEZs), and the slow alleviation of global trade restrictions (Bramall 167–175). This was done to attract foreign investors as well as bolster productivity. These initiatives were specific implementations of certain capitalist practices that were done to bolster the economy while maintaining significant party oversight.

**Ideological Justification for Economic Reforms**

A central struggle for the Chinese Communist Party (CCP) in implementing impactful reforms after 1978 was maintaining adherence to communist ideology (Naughton 54–57). By many, the implementation of market policy was seen as a blatant betrayal of Marxist-Leninist ideology, undermining both the principles and the authority of the Party. In order to prevent this, the Party portrayed these reforms as maintaining consistency with, rather than betraying, socialism.

Deng Xiaoping created rhetoric that supported this new-found ideology, often saying, "It does not matter if the cat is black or white, as long as it catches mice." Deng's reign highlighted the importance of not strictly adhering to arbitrary doctrine, but rather modifying it to achieve economic success (Deng qtd. in Vogel 302). He called this "socialism with Chinese characteristics." Overall, Deng Xiaoping effectively executed strategic market reforms without alienating the imputed communist ideology.

**Mechanisms of Hybrid Governance**

Newfound flexibility allowed the Chinese government to justify new economic reforms. This narrative continued through the implementation of mechanisms that allowed these reforms to have a larger impact. Furthermore, they created a hybrid system in which the CCP would be able to benefit from market liberalization without ceding power or losing the authority of their authoritarian government.

One of the most significant mechanisms was the retention of key market sectors while allowing them to grow and develop. These sectors included energy, banking, general communications, and transportation, which remained under the ownership of the Party in the form of state-owned enterprises (SOEs) (Naughton 215–230). By controlling these specific sectors, the Party ensured that the general movement of the economy was controlled by them, and any movement would be the result of Party mobilization, thereby only catering to the needs of the Party. Even as private companies, such as Huawei, expanded, they still remained dependent on the CCP for banking and credit, thereby reinforcing the Party's control.

A second way the Party retained control was through the co-optation of private businesses into the Party (Dickson 88–95). Beginning in the 1990s, the CCP adopted policies that encouraged business leaders to join the Party. Best represented by Jiang Zemin's "Three Represents" theory, this expanded Party membership to economic sectors. This was done to subdue capitalist elites and prevent them from controlling the Party. Effectively, private wealth was contingent on loyalty to the Party.

Investments from foreigners were also heavily controlled by the CCP (Bramall 167–175). The establishment of Special Economic Zones (SEZs) acted as spaces for experimenting with capitalist practices. Through the slow expansion of these zones and the requirement for joint ventures with domestic companies, the Chinese Communist Party was able to obtain foreign money and technology while maintaining control over economic development.

Moreover, the Party maintained extensive control over information, labor, and civil society, thereby preventing the formation of independent organizations that could challenge its authority (Shirk 210–212). Instead, the Chinese Communist Party strengthened surveillance, censorship, and civil repression to ensure that market growth and the implementation of market policies would not liberalize or democratize the government.

Through this combination of selective liberalization, governmental control of important resources, and the co-optation of private actors, the Chinese Communist Party was able to institutionalize a system that allowed markets to improve under authoritarian rule. These mechanisms lead to the conclusion that China's resulting hybrid model was not an outcome of reforms over time, but rather the deliberate construction of a politicized economy designed to maintain unilateral Party control.

**Data**

**Economic Growth and Basic Transformation**

Since the reforms began in 1978, China's annual real GDP growth rate has been approximately 9.4% over the period 1978–2018 (World Bank, "China Overview").

- Per capita GDP rose from being the world's lowest in 1978 to approximately 64,644 yuan (Guo et al.).
- In 1978, the primary sector (agriculture) accounted for approximately 27.7% of GDP. By 2018, it had fallen to about 7.0%, while the tertiary sector grew from 24.6% in 1978 to 53.3% in 2018 (OECD 2019).

I. **Poverty Reduction**
   A. Over the past forty years, China has lifted approximately 800 million people out of extreme poverty (using the baseline of $1.90/day), accounting for nearly three-quarters of the global reduction in extreme poverty over that period (World Bank, "Poverty & Equity Data").
   B. At the national poverty line, about 770 million people globally were lifted out of poverty in the same timeframe (UNDP 2020).
   C. The hybrid model has continued to generate strong economic performance. In 2024, China's GDP growth rate was 5.0%. Beijing has set a goal of 5% growth for 2024. To achieve this, the government has created no new policies. The deficit-to-GDP ratio has been raised to 4%. Urban employment is expected to stay below 5.5%, and inflation is set to be controlled at about 2%.

D. In terms of poverty and inequality, China has successfully eliminated absolute poverty in most rural areas. Nonetheless, relative poverty remains a serious concern. Despite these positives, weaknesses in China's hybrid model are beginning to show. The real estate market slump is dragging both domestic and foreign investment, domestic consumption trends downward, and international issues are proving to be serious roadblocks to China's export-led momentum. These risks suggest that while China's hybrid model continues to serve the country, its sustainability is not guaranteed.

## II. Recent Developments in Wealth Inequality

### A. Rural and Age Inequality

Despite the success in eliminating absolute poverty, inequality remains a significant problem in China, particularly across regions and demographics. The poorer income distributions are mainly in rural areas, older age cohorts, and undeveloped regions. The implementation of a hybrid system has not translated into "uniform prosperity." For example, rural households in eastern China have a poverty rate exceeding 59%, while in western provinces, rural relative poverty is roughly 47% compared to 43% in urban areas (UNDP 2021 Report).

1. Among elderly populations (60 years and older), poverty fell from 35.2% in 2011 to about 13.1% in 2020. However, in 2020, rural elderly poverty was nearly four times the urban rate (16.9% vs. 4.3%). These disparities are reflected in household expenditures: in rural areas, 32.3% of income in 2024 was consumed by basic necessities like food (Engel's coefficient) (NBS China 2024).

**Comparing Chinese Economic Reform Success With Other Communist/Post-Communist States:**

The success of China's hybrid communist-capitalist model becomes more apparent when compared to other communist states that underwent economic reform. While some nations tried to rescue socialist ideology with market mechanisms, none achieved the same scale or political stability as China.

### I. The Soviet Union

The difference between China and the Soviet Union exemplifies the importance of a controlled reform. In the 1980s, Mikhail Gorbachev's policies of Perestroika and Glasnost were meant to modernize the Soviet system by introducing elements of market economies. However, these reforms undermined the Communist Party's monopoly on power before a stable market could be established (Kotkin 331–339). Rapid liberalization weakened central authority and accelerated nationalist movements, leading to the dissolution of the Soviet Union in 1991.

A. Chinese leadership, closely observing this, concluded that political control must never be sacrificed for economic reform. Unlike the Soviet Union, China implemented market reforms without losing political control. The CCP maintained strong control over ideology, the military, and the media while slowly experimenting with the economy, such as through the creation of SEZs.

II. **Vietnam's "Doi Moi" Reforms**

In 1986, the Vietnamese Communist Party launched the Doi Moi reform, encouraging private enterprise and foreign investment. Like China, Vietnam described these changes as compatible with socialism, calling its model a "socialist-oriented market economy." These reforms produced economic growth averaging 6–7% since the 1990s and significantly reduced poverty rates (Masina 44–49). However, Vietnam's smaller population, industrial base, and lower level of foreign investment constrained the impact of its model. Furthermore, while Vietnam remains authoritarian, it allows a more decentralized administrative structure compared to China's heavily centralized Communist Party.

III. **Other Comparative Examples**

Other socialist states have struggled to balance capitalist mechanisms and communist ideology. Cuba, for example, introduced market reforms in the 1990s but was hindered by international sanctions (Mesa-Lago 125–130). Its leadership allowed private enterprise in sectors like tourism and small-scale agriculture. North Korea represents the opposite extreme: the state maintains near-total political control and resists market modernization except in very limited areas (Haggard and Noland 92–100).

**Conclusion**

The evolution and growth of China's political and economic system since 1978 demonstrate that the contrast between capitalism and communism is not as stark as twentieth-century conflicts suggest. Through deliberate adaptation over time, the CCP has maintained—and even strengthened—its control while creating a hybrid model that fuses market efficiency with authoritarian governance. This system, often referred to as socialism with Chinese characteristics, has enabled the Party to prosper economically while maintaining unchallenged political authority.

China's economic reforms were not a departure from communist ideology but rather pragmatic changes designed to maintain prosperity and one-party rule. The CCP's ideological flexibility allowed it to reinterpret Marxist-Leninist principles to justify market mechanisms, not as a betrayal, but as instruments that strengthened the Party's power. Institutional mechanisms, such as state control of important sectors, co-optation of private entrepreneurs, and broad political oversight, preserved Party dominance.

The results of this hybrid model have been extraordinary. Over more than four decades,

China's economy has expanded at an average annual rate of 9%, lifted 800 million people out of poverty, and become the world's second-largest economy. However, this success has been accompanied by growing inequality, regional disparities, and further concentration of political power. The CCP's continued legitimacy depends on its ability to manage these contradictions. Comparatively, China's experience diverges sharply from other communist or post-communist states.

The Soviet Union's collapse revealed the risks of premature liberalization, while Vietnam's Doi Moi reforms were a more modest version of China's approach (Kotkin 331–339) (Masina 44–49).Cuba and North Korea demonstrate economic stagnation resulting from resistance to market adaptation (Mesa-Lago 125–130; Haggard and Noland 92–100). China's combination of gradual reform, institutional control, and pragmatic approaches has been responsible for its remarkable economic achievements (Guthrie 201–210).

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**Improper Water Quality Management and its Impacts on Adolescent Vitality in Rural South Carolina Communities By Robert Hucks**


## Abstract

It's easy to assume that unsafe drinking water is a problem of the past, until you see the numbers from rural South Carolina. Ensuring safe drinking water is a foundational public-health requirement, yet rural communities in the United States, including those in South Carolina, persistently face water quality inequities. This study examines how deficient water-quality management practices disproportionately affect adolescents in rural South Carolina communities by comparing contamination levels, regulatory enforcement, and socioeconomic conditions between urban and rural regions. While researching these inequalities, I discovered a vast disparity in water quality violations and governmental enforcement between rural and urban regions of South Carolina. In a country where clean water flows freely from most taps, few realize that entire rural communities still drink from poisoned wells.

The significance of this research lies in its potential to inform policy interventions that address environmental-justice concerns. Identified key pollutants include PFAS (per- and polyfluoroalkyl substances), nitrates and chromium, all of which pose particular developmental risks to adolescents. Importantly, existing research shows that socially vulnerable and rural communities are disproportionately impacted by water-quality failures. These findings were directly applicable to South Carolina as comparisons were made through public data published by the Environmental Working Group and South Carolina Fiscal Affairs Office, establishing that areas classified as rural and lower income maintain greater levels of water quality violations than compared to urban areas across the state. In South Carolina's rural towns, the difference between a healthy childhood and chronic illness can be traced back to a single glass of water.

To address these issues, this paper proposes a three-part strategy: strengthen enforcement of water-quality regulations in rural systems, allocate state and federal funding to upgrade rural water infrastructure, and implement school-based monitoring and educational programs to protect youth. By illuminating the intersection of water-management inequalities, socioeconomic disadvantage, and adolescent health, this research highlights the urgency of equitable water-quality enforcement and targeted methods to safeguard youth vitality in rural South Carolina.


## Introduction

The safety of a nation's water is not determined by its abundance, but by its vigilance, and in America, that vigilance is faltering. Water management practices are the methods by which a population takes to ensure proper water quality within a specific area. Within the United States today, the Environmental Protection Agency (EPA) holds the power to create country-wide regulations for what is considered "safe" water (U.S. Government Accountability Office). "Safe" refers to a body of water's alignment with set country-wide regulations for water

quality, which include factors such as physical contaminants, acidity, dissolved matter, suspended sediment, odor, and taste (Michigan Sea Grant).

Throughout the 21st century, country-wide water quality has faced emerging challenges through the increase in various pollutants resulting from factors such as industrial discharge and city runoff (Greenfield). These factors result in a widespread issue of water quality contamination, with infected water carrying harmful chemicals and diseases that impact the health of individuals consuming such water. Viewing this issue from a countrywide perspective, the most notable example of improper water defense and its effects is Flint, Michigan and its water quality crisis. Flint's intense increase in industrialization directly resulted in the contamination of the Flint River, and upon the city switching to that river as its primary drinking water source, widespread contamination occurred. The example of Flint, Michigan detailed the effects of surface-level water pollution and how, when not properly managed, it can lead to widespread water contamination and consequential health effects on a population. This event could be prevented through proper monitoring of South Carolina's drinking water (Denchak).

Similarly, South Carolina holds direct risk for such contamination effects due to the state's rapid industrialization paired with heavy reliance on groundwater and surface water for drinking. It is more common that primary sources of drinking water for both rural and urban areas are emerging as contaminated. The issue of inadequate water management is intensified through a lack of proper water quality control within rural settings, as water quality governmental regulations are less likely to be upheld in rural areas due to a lack of direct governmental focus (Hendryx). With city areas more commonly holding direct defense against such contaminants to their water supply, many rural areas lack the proper technology, funding, and security to adequately defend their populace against a contaminated water source (Rose).

This is directly reflected in South Carolina's current water quality statistics, reflecting that areas belonging to rural/low income status hold significantly higher levels of drinking water violations when compared to areas of urban/high income ("Explore Drinking Water Violations in South Carolina | AHR). Viewing into South Carolina's standard of water quality as a whole, 1,150 identified waterways are currently classified as "impaired", meaning these areas fall below the federally set standards for water quality contents (Cities Battle Water Pollution | MASC).

The primary issues affecting the rural waterways of South Carolina include harmful forever chemicals, known as polyfluoroalkyl substances (PFAS), and general physical pollutants that impact the water utilized within these rural societies (Fretwell). Polyfluoroalkyl substances are man-made chemicals that living organisms have extreme difficulty breaking down (United States Environmental Protection Agency). Issues begin to present when viewing into the effects of such pollutants on the health and well-being of consumers, as both general pollutants and PFAS are known to show adverse health effects when consumed in excessive quantities.

This information fosters the question of how water inequalities between urban and rural areas of South Carolina impact the populations within these regions. This paper examines how inadequate water quality management disproportionately affects adolescent health in rural South

Carolina, emphasizing disparities between urban and rural regions. Ultimately, water should not be a privilege of place, but a universal right.

**Background (History of S.C drinking water and overall negatives)**

Over 1,150 South Carolina waterways are currently classified as "impaired" under governmental regulations for clean water. These regulations are set by the Federal Clean Water Act, which establishes a basic country-wide standard for clean water classification and administration (Environmental Protection Agency). A primary limitation of the act, however, are the regional disparities in regulation enforcement, as within South Carolina, the state Department of Health and Environmental Control (DHEC) is the primary agent of enforcing the federally set regulations across the entire state, creating difficulties in proper management of clean water across the varying regions.

This development in turn fosters an unequal focus towards areas of higher population for clean water regulation enforcement, promoting higher levels of contaminated water in rural areas ("Explore Drinking Water Violations in South Carolina | AHR). Challenges also emerge due to broader difficulties in statewide management over rural area water containment, as private wells make up a significant portion of rural drinking water supply and cannot be properly managed by statewide forces. Directly reflecting this, the existence of PFAS was found in 155 private wells tested across South Carolina, although assumed by the EPA to be present in significantly more across the state (Fretwell). These tested wells contained more than four parts per trillion, which is the upper limit of the EPA's proposed drinking water limit. Within the testing conducted by the EPA, they deemed that "virtually every river tested has shown some level of forever chemicals", which directly impacts rural water quality as impaired river sources hold the ability to pollute groundwater and private wells that rural areas primarily source their water supply from.

Out of the areas tested, the highest amounts of contaminated drinking water were within Darlington County, Lexington County, Richland County, and Sumter County. These areas are all classified as "rural", falling into a category of lower population and less "city" structure. Similarities to this occur across the state in various subregions and smaller towns, with an overall issue that is even more widespread across the country. Understanding why this emerges can be seen through a variety of disparities between urban and rural regions. Urban centers typically have higher household incomes, giving residents access to better water filtration systems than those available in rural areas. In contrast, rural communities, often located beyond major city jurisdictions, receive less consistent enforcement of EPA standards, with fewer inspections and weaker monitoring compared to urban regions where compliance is more rigorously maintained. In addition, rural areas within South Carolina rely heavily on private wells and groundwater sources for their primary water intake, which can pose challenges as private wells are not monitored by DHEC unless specifically asked by the private well owner (US EPA,OW).

Without proper water defense on this front, such as lacking protection against water contaminants in groundwater or not properly regulating safe drinking standards, contaminants can enter the water, which pose issues to the overall health of the consumer. Such harmful

contaminants, including lead, PFAS, and haloacetic acids, all pose a greater risk to adolescents who consume such products, given their positioning within a developmental stage. Overconsumption of these contaminants through sources of drinking water has been shown to negatively impact youth development, increase chronic illness risk, and pose greater health challenges upon entering later stages of life as toxins build within the body.

**Methods**

To solidify conclusions on South Carolina regional water inequalities, I began by analyzing various published scientific literature ranging from nationwide significance to local, statewide effects. Through this information, I developed significance between the level of water quality access and related demographic characteristics, including location, socioeconomic status, and population. I then collected publicly available data within South Carolina's Environmental Working Group (EWG) Tap Water Database, which provided levels of contaminants found in tested tap water sources throughout the state. This source also allowed for the comparison of water quality violations between the various tested locations. The significance of regional differences across the contaminant sources were amplified through collecting average income statistics from South Carolina's Revenue and Fiscal Affairs Office, allowing relationships to be built between the different levels of contaminants in each tested water source and their corresponding location's average socioeconomic status.

After comparing South Carolina regions and the differences in water quality violations, I drew conclusions on the groups most at risk for water-related health criticality, advanced among a similar countrywide understanding of at-risk groups. These conclusions were supported through published medical research into the effects of inadequate water quality consumption on the development of the adolescent population, which was identified to be most at risk. Analyzing the common regulatory differences between urban and rural areas from an enforcement and action perspective established a foundation upon which a root cause of these inequalities can be identified. Upon comparing factors such as water quality enforcement degree, community action, available resources and water sourcing, differences between urban and rural water quality can be positively attributed to correlating causes and both local and nationwide prospective solutions were curated in response.

**Results**

The data is stark: South Carolina's drinking water tells a story of disparity and neglect. According to South Carolina's EWG Tap Water Database, the state has identified within their utility testing a total upwards of 400 impaired tap water utilities featuring contaminants above federal guidelines, along with 3 utilities polluted above federal legal limits for the contaminants of Radium and Uranium (Environmental Working Group). Featuring 99 total contaminants, the impaired utilities presented a total of over 42 million impacts above federal guidelines between 2013 to 2024, with approximately 800 additional being above federal law. It can also be observed within this database the utility locations across the state that accrued the highest level

of state violations, in which it is shown that out of the top thirty highest violation utilities, 26 of the utilities were in regions classified as rural. This development is noted as a common trend when observing water quality disparities between urban and rural regions, detailed specifically within a country-wide water quality reflection completed by the U.S. Centers for Disease Control and Prevention (CDC), which ultimately concluded that patterns in tested water facilities"suggest that water quality improves as areas become more urban (or less rural)" (Strosnider et al.). In South Carolina, geography has become destiny, even in something as fundamental as the right to clean water.

Across South Carolina, there are ten different contaminants serving over three million documented citizens, along with 16 total contaminants serving over at least one million citizens (Environmental Working Group). The most detrimental of these contaminants include PFAS, nitrates, chromium, and Trihalomethanes; all of which are frequently consumed through water throughout the state. Rural areas, due to widespread agricultural focus and improper water disinfecting, are at an increased risk of the specific pollutant nitrate, which falls within the category of PFAS and emerges from agricultural runoff.

As shown within publicly available data on the South Carolina Revenue and Fiscal Affairs Office website, rural counties within the state commonly have lower average household incomes than do households belonging to urban areas of the state (Median Household Income by County 2011-2021 | South Carolina Revenue and Fiscal Affairs Office). Relating this to the discussion on water inequality, it was noted within the Journal of Exposure Science and Environmental Epidemiology that household income holds a direct correlation with access to adequate water quality opportunities, with areas of lower average household income often receiving less consistent access to proper water quality than areas of higher household income (Levin et al.). This relationship holds in the case of South Carolina's drinking water disparities, as regions with lower average household incomes, such as McCormick, Sumter, Aiken, and Chesterfield, contain higher reports of drinking water contaminants according to the EWG Tap Water Database.

These findings do not isolate themselves to South Carolina. Similarities are mirrored country-wide in relation to this correlation, as according to water and health researchers published within the Journal of Environmental Science and Technology, rural areas commonly have lower average incomes than do urban areas and corresponding lesser access to the standard quality drinking water that urban communities hold access to (Yang et al.).

Further building into the relation of income and country-wide water quality disparities, as identified within a study conducted by Boston University School of Public Health, a team of university researchers analyzed the frequency of water standard violations in four groups across the U.S: high-income urban, low-income urban, high-income rural, low-income rural. Their findings were compiled into a dataset of average violations per ten water systems, then graphed and compared through the water standard violations from the time period 1980-2015. Their findings highlight that rural areas, both falling into low and high income categories, consistently demonstrate greater levels of water quality violations in comparison to urban areas. It is clear

that when comparing these regions across the country, rural areas consistently demonstrate increased levels of violations over urban areas, even when these rural areas fall into a higher-income category.

Improper management of water directly relates to increasing levels of pollution among public waterways and water sources. Consuming water contaminated by pollutants directly fosters a range of health effects. According to the Environmental Protection Agency, consuming water containing levels of contaminants greater than their recommended limit directly relates to health effects including nervous system impairment, reproductive issues, and chronic illness (United States Environmental Protection Agency). In relation to the standards tested by the EPA across South Carolina waterways, the majority of contaminated water sources are within rural areas. This would indicate that more water quality-related illness emerge within areas classifying as rural than compared to areas classifying as urban. Urban areas of South Carolina are also demonstrated to have greater average household incomes than rural counterparts across the state, which not only reinforces the larger risk for water contamination within rural areas due to insufficient funding for proper water management, but amplifies the health effects rural communities face compared to urban areas. According to the U.S. Government Accountability Office, rural areas have greater difficulties accessing healthcare opportunities and affording payment necessary to meet optimal health conditions (U.S. Government Accountability Office). Relating the fact that rural areas in South Carolina face lower income, less medical opportunities, and greater levels of water contamination, it is evident that health related effects would be more severe in rural areas of the state than urban.

No group bears the cost of contaminated water more acutely than adolescents (Zborowski et al.). While both urban and rural areas can feature pollution related health effects on the adolescent population, given that South Carolina water quality is more heavily polluted in rural areas, the adolescents within this region would face greater health risks than compared to urban. When analyzing the effects of PFAS on childhood development, a direct relationship can be seen between poor water quality and negative health outcomes in adolescent maturation. A build-up of these chemicals within the body results in a variety of health related issues, including but not limited to impaired thyroid function, increased cancer risk and liver damage (Fenton et al.). Beyond the effects that harm all consumers of contaminated water, such as chronic illness, neurological disorders, and reproductive issues, adolescent development has been proven to hold increased risk due to the significance of hormonal balance and adequate nutritional intake for optimal growth. Through a study conducted by environmental health expert Ellen Silbergeld, Johns Hopkins researcher within the field of Environmental Health and Engineering, it was found that poor drinking water directly impacts the neurological development of adolescents, primarily through inducing neurotoxicity during development (Silbergeld). Neurotoxicity generates a variety of effects when afflicted amidst youth development, including impaired cognitive function, visible through lessened memory and iq attributes, and behavioral complications, manifested as increased likelihood for impulsiveness and addiction. Similar findings have been also reflected in numerous studies detailing analogous effects of PFAS on

childhood development, including impaired neurodevelopment detailed in (Ames et al) and compromised thyroid health presented in the research of (Oh et al). Given the rapid developmental stage of the adolescent age range, driven heavily by influence of the thyroid, neurological system, and related hormonal stimuli, it is evident that this group faces the most significant risk for long-term health consequences when consuming improper water. These findings make one truth undeniable: water quality isn't just an environmental issue, it's a developmental one.

**Findings/Conclusions(Change to something on health effects)**

After comparing urban and rural areas across South Carolina, rural areas consistently demonstrate increased numbers of water standard violations, impaired water sources, and contaminant totals. This issue does not relate to South Carolina alone, as across the United States a similar pattern emerges of shortcomings in rural water quality when compared to that of urban regions. Building upon this development, improper water quality has been proven to directly correlate with negative health effects, especially for the adolescent age range. Therefore, rural populations, given their higher levels of contaminated water and improper water defenses, are at greater risks for developing related health issues. Compounding the crisis, these rural communities often lack sufficient healthcare infrastructure, leaving the impacts of unsafe water more pervasive, more damaging, and far harder to escape.

**Proposed Solutions**

Water is the foundation of all life, and yet, for many South Carolinians, that foundation is cracking. The purpose behind this paper is to call attention to faults in South Carolina's drinking water quality enforcement, promoting steps in both governmental and local action towards preventing water quality health impacts. Through comparing publicly available online data on urban and rural areas of South Carolina, a conclusion can be drawn based around unequal enforcement of water quality standards and resulting adolescent health impacts in these areas. This issue is extremely important in the future vitality of not only the state, but the nation as a whole. With increasing industrialization levels and corresponding increases in country-wide pollution, steps must be taken locally, statewide, and federally to ensure proper water quality for all citizens. Starting now, future generations within the United States should be given access to higher qualities of life, living with less illness and experiencing proper adolescent development throughout their upbringing. Life is built upon water, and due to such, it is necessary to ensure that the water we build our society upon is at the highest quality possible.

The primary factor that fosters the inequality between urban and rural water quality is the level of enforcement enacted within these areas. As urban areas contain a higher population, higher average income, and increased government supervision, it is common that these areas receive significantly more direct enforcement of water quality standards than do rural areas. To address this, promoting increased governmental action towards equal enforcement of water quality standards would directly aid in the achievement of water disparity reduction. By targeting

proper enforcement of standards uniformly, states can effectively measure all areas and act properly to address each region's individual needs. On the local level, these standards can be enforced more strictly through campaigns and governmental offerings for private well testing, ensuring that consumers relying on these sources are able to gain access to the necessary requirements to both test their water quality and ensure it aligns with the enforced regulations.

Another primary influence in regional water quality disparities is a lower average income within these areas, decreasing the ability of rural areas to properly allocate necessary funding to secure proper water treatment within their areas. To address this, statewide grants could be provided on a basis of need within the varying regions across the state, ensuring all areas receive proper access to drinking water on par with the state-wide and federally set regulations. By promoting state action in the establishment and funding of rural drinking water sources, the issue of water quality management in rural areas can be further addressed. With direct state-level action within water sources among rural communities, proper tracking and management of these sources can be more easily documented within state records. While this solution does present drawbacks, including the adjustment of state-wide monetary resources and potential resistance from rural communities, it would be effective in addressing the issues of insufficient funding, improper state-wide regulation, and difficulties in the management of rural water quality.

To directly address the water quality consumed by adolescents, statewide school-led water testing can be promoted to ensure that the children relying on these public water sources are able to consume water aligned with the regulations. Enforcing greater water quality testing for public school systems in rural areas would ensure that these outlets are free of harmful contaminants that could affect youth development.

In conclusion, many different routes can be taken to mitigate the gap that is currently evident between rural and urban water quality. The effect of such inequalities is significant, as human vitality is built upon the catalyst of proper water intake. Through closing the gap between South Carolina water inequalities and ensuring proper water sourcing for all within the state, the adolescents of our future can be shielded from the effects of rapid industrialization and urbanization. The path forward is clear: protect the water, and we protect our future.

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**The Illusion of Objectivity: Is the concept of Objectivity Purely a Construct of the Mind?**
**By Jerry Wang**

**Abstract**

This paper makes the case that objectivity is essentially unachievable, both inside and outside of human experience. It investigates how all human knowledge is naturally filtered and constructed by perception, language, and cognition. Any comprehension of "objective" reality is mediated by subjective processes, as perception and language originate in the mind. Interpretation and bias continue to exist through language and mental frames, even in domains like science and mathematics that are thought to be very objective. The limits of epistemological theories that cast doubt on the existence or accessibility of an external reality, such as subjective idealism and solipsism, are further explored. In the end, the article comes to the conclusion that what we refer to as objectivity is only an ideal—a continuous effort to reduce bias—but by its very nature, it is still a human mental construct.

## 1. Introduction

The term objectivity is commonly defined as “expressing or dealing with facts or conditions as perceived without distortion by personal feelings, prejudices, or interpretations.” The definition mentions the absence of personal bias in perceiving and evaluating facts, which would imply that “objectivity” is independent of the mind, as the mind is the very source of bias. The question then arises: How can objectivity exist without a mind to create the truth that objectivity is based on? Does the concept of objectivity truly exist, or is it merely a construct of the mind?

This question is essential because it addresses whether our minds shape the objective truth we consider or if it exists independently of human perception. If we could establish this, it would fundamentally change the way we consider whether science, morality, or truth itself is actually absolute. Drawing on insights from psychology and philosophy, we can demonstrate that a perfect form of objectivity is inaccessible to us both within and beyond our perception. Therefore, all that we can access or discuss as “objective” is constructed by the mind.

## 2. Literature Review

### 2.1 What is within the mind?

To determine whether objectivity is possible in the mind, we must clarify what the mind contains. Within our anatomy, the brain is widely recognized as the organ responsible for all major cognitive processes, including perception and language (*Brain Anatomy and How the Brain Works*). Perception transfers raw sensory information into neural signals, which ultimately lead back to the brain (Cherry). Language, likewise, is rooted in specific neural structures such as the angular gyrus, Broca’s area, and Wernicke's area (*Speech & Language | Memory and Aging*

*Center*). Since these functions are rooted in brain activity, and the mind arises from the brain, it follows that perception and language are both products of the mind.

### 2.2 Philosopher's perspectives

Building upon these basic pictures of the mind, philosophers have long debated whether truth and objectivity can exist independently of these mental processes. During the early 1700s, George Berkeley proposed the theory of subjective idealism, stating that only minds and their perceptions exist in the world, and that the mind constructs everything we know (Downing). The theory is difficult to disprove, as it seems evident in our daily lives that our only way of knowing anything is through our perception. From Berkeley's point of view, what we call "reality" never appears to us apart from the mind, which already suggests that objectivity is deeply tied to mental experience.

Immanuel Kant's theory of phenomena and noumena acknowledges the existence of a world outside perception but asserts that this reality is fundamentally inaccessible to the human mind. He calls phenomena the world we access, and noumena a theoretical world beyond our perception. In contrast to Berkeley, Kant does not deny an external world; instead, he emphasizes that we can only ever know it as it appears to us, through the lens of our perception.

### 2.3 Filters of Reality

In understanding how perception shapes knowledge, psychological research has shown that the brain is a selective processor (*How the Brain Decides What We Perceive*), constantly deciding what information reaches consciousness. Even hallucinations—false sensory experiences—demonstrate that perception can generate convincing yet inaccurate representations of reality ("Hallucinations").

Language also plays a central role in constructing objectivity. The Sapir-Whorf hypothesis of linguistic relativity proposes that thought and perception are influenced by linguistic frameworks (Frothingham). Wittgenstein's statement, "The limits of my language are the limits of my world," further emphasizes that our capacity to describe or think about the world is bound to language itself (Rowe).

Together, these perspectives demonstrate that perception, language, and cognition are interwoven in all human understanding. They set the theoretical foundation for the central argument that follows: that objectivity cannot exist within or beyond the mind.

## 3. Discussion

### 3.1 Within perception (Kant's Phenomena)

Now that these theories and findings have been established, they point to a simple but unsettling conclusion: through our lenses, the mind is a medium through which all knowledge is filtered. Perception, language, and cognition are not neutral windows, but active filters that shape and limit what can appear in our daily lives. As commonly understood, objectivity is often taken

to be independent of any individual mind's biases. However, the constraints of human perception preclude objectivity. George Berkeley's idea of subjective idealism explains that our perception is the only existence; all knowledge, experience, and even scientific observation are limited to perception (Downing). We know nothing of the reality outside of our perception; as a result, the very concept of objectivity is flawed, as all human knowledge is filtered through perception and interpretation, rendering the possibility of unbiased knowledge impossible. Objectivity would require complete and perfectly unbiased access to all relevant facts, both within and beyond our perception, in other words, omniscience. This is inaccessible from a human perspective. In practice, the "objectivity" we achieve is merely an ideal, an attempt to minimize bias.

If our knowledge of facts is limited to what passes through the mind, some may argue that the perception we see is still reflective of the actual "objective" world. However, there is substantial evidence that perception is often unreliable. Brain scans reveal that "perception is highly selective; the brain constantly decides what information is important enough to reach our consciousness." Even if a reality exists outside of our perception, our minds still construct its appearance for us to perceive (*How the Brain Decides What We Perceive*). The point is further substantiated when examining concrete examples of perception being misleading. Hallucinations, for example, are described as: "false perception of sensory experience" ("Hallucinations"). Visual cues and biases, such as binocular disparity, also demonstrate that perception can deceive us in various ways (*Binocular Disparity - an Overview | ScienceDirect Topics*). Therefore, we cannot be certain perception is not misleading us about other aspects we consider "objective." Ultimately, because all knowledge is compromised through perception and interpretation, true objectivity is unattainable, and the mind will always limit our understanding of reality.

Furthermore, language is not merely a passive tool for describing reality, but an active construction of the mind; it is a human-made articulation of the world. Sapir-Whorf's theory of linguistic relativity emphasizes how people perceive and interpret the world through the framework of their language, and the categories within a language influence and constrain their thought processes (Frothingham). We can see this happen in a study, where English and Russian speakers performed a color-matching task in which they saw a blue square and had to choose which of two other blue squares matched it best, and because Russian distinguishes between *siniy* (dark blue) and *goluboy* (light blue) while English uses only "blue," Russian speakers were faster and more accurate, especially when the shades crossed the *siniy–goluboy* boundary, suggesting that language influences how sharply we perceive and discriminate colors (Green). Thus, what seems to be a straightforward, "objective" color difference is segmented more precisely for certain language users than for others, indicating that linguistic categories play a role in determining even fundamental perceptual distinctions rather than the environment alone. Philosopher Wittgenstein states: "The limits of my language are the limits of my world" (Rowe). The quote highlights how language often decides the way we view our world. Since language itself is a product of the mind, if no minds existed, there would be no linguistic structures and therefore no way to identify, formulate, or communicate anything as objective. There could be no

articulation, or even conception, of objectivity without mental processes for generating and interpreting words. Thus, perception is also bound to the limitations inherent in language; what counts as "objective" is a product of our linguistic and cultural framework. This suggests that any claim to objectivity is always already embedded in a particular language and form of life, rather than floating free as a neutral description of the world "as it is."

In addition, not only is the reality we see before us a creation of the mind, but we also cannot possibly perceive something without automatically introducing bias, rendering all "objective" statements subjective. "No matter how objective we believe we are, it is impossible to completely overcome the heuristics and biases that are hard-wired into the human brain" (Delbosca). Through our perception, the mind is automatically and unconsciously predisposed to create biased or subjective opinions when observing reality. Moreover, even when examining "truths", which supposedly negate bias, these truths are still grounded in belief in perceived facts. Philosopher Bertrand Russell says, "If there were no beliefs, there could be no falsehood, and no truth either" (McLaughlin). The statement further strengthens the argument that since perception shapes, creates, and distorts reality, anything that can be described as "objectively true" is reliant on the beliefs and thoughts about the perceived facts, which all rely on the mind. Such reasoning exposes the underlying flaw in the subjective-objective dichotomy, as objectivity is merely a type of subjectivity where we attempt to minimize bias; objectivity cannot exist within the frameworks of our perception. Considering that all subjectivity originates in the mind, the "objectivity" we know is also all in the mind.

To conclude, the mind is the inescapable bridge of all knowledge. What we call "facts" are always facts as perceived, and perception is selective and, at times, unreliable. Language, in turn, provides the framework through which we articulate and even conceive of objectivity, further shaping how reality is conveyed to us. On top of this, cognitive biases cannot be fully eliminated; they are built into the way our minds operate. These limitations show that we can never attain objectivity, at least not within the confines of our physical being.

**3.2 Outside of perception/mind (Kant's Noumena)**

Now that we have demonstrated that objectivity is impossible within our mind, due to the limitations of perception, we must now ask whether it could exist beyond the mind. We have no direct access to the world outside of our perception (if it even exists), so we can never know objectivity beyond our perception. Philosophies like subjective idealism go so far as to reject the idea of an external reality altogether, holding that the world is only a product of the mind (Downing). Immanuel Kant, meanwhile, acknowledges a world outside perception (the "noumena"), but argues that it is fundamentally inaccessible to us (Kamal). Both perspectives highlight the fact that the world outside of our perception is either unavailable or non-existent. This insight directly addresses the question of whether we can truly know "objective" reality as it is, rather than merely as it appears to us.

Extending this skepticism even further, the philosophy of solipsism poses a greater challenge to the possibility of objective knowledge, claiming that "the self can know nothing but

its modifications and that the self is the only existent thing." For the solipsist, only one's mind is sure to exist; everything else exists only as part of the content of one's consciousness. Despite being far removed from common sense, the theory is an essential perspective as it is not possible to disprove, and it challenges the very existence of all knowledge (Thornton). If solipsism is true, then "objective reality" is meaningless; only subjective experience is certain. We can never step outside our minds to verify an independent objective reality; the mind filters all knowledge. Thus, the very idea of objectivity collapses into subjectivity, since nothing beyond the mind can ever be fully known or proven. Ultimately, true objectivity outside of perception is unknowable and possibly meaningless.

Modern physics also shows us interesting observations about a world outside of the mind. Particularly in quantum mechanics, in the famous double-slit experiment, tiny particles such as electrons or photons are fired at a screen with two narrow openings (*Physics in a Minute: The Double Slit Experiment | plus.Maths.Org*). When no one checks which opening each particle goes through, they create a pattern on the final screen that looks like a wave, as if each particle went through both openings at once. But when scientists set up a detector to see which slit each particle passes through, the pattern changes: the particles now behave like little solid balls going through one slit or the other. This is what we call the "observer effect." Simply measuring or "looking" at the particles changes how they act. Scientists disagree on how to interpret this, but they generally agree that we cannot treat these particles as if they always had clear, fixed properties completely independent of how we observe them. The experiment challenges the simple idea that the world outside of our perception is always fully determined and just sitting there waiting to be neutrally recorded. Even at the level of quantum mechanics, what we call an "objective state" seems deeply tied to the way we choose to observe and describe it. The particles that make up our daily objects may be completely different from what we actually see.

**3.3 Counterargument: Mathematics**

With the evidence presented, objectivity seems inherently impossible for us. Despite this, there is one very popular idea that some argue is a unique and universal truth: mathematics, thought to be objective even beyond the mind. It's very hard to argue that one plus one isn't two, for example. Mathematician Eugene Wigner says, "The miracle of the appropriateness of the language of mathematics for the formulation of the laws of physics is a wonderful gift which we neither understand nor deserve," stating that the connection between mathematics and the physical world is so deep and precise that it seems to go beyond mere human invention or subjective perception (Wigner). Mathematical theories and concepts are thought to be discovered, not invented, by human minds; therefore, they were an intrinsic part of the universe already. If that were the case, then mathematics is perfectly objective.

However, even mathematics is formulated, understood, and interpreted by minds. Wittgenstein's famous philosophy of math stated that mathematics is just a "motley of techniques of proof" (Rodych). From this perspective, math is not a discovery of external truths, but rather a collection of rules and practices developed and sustained by human communities. Hence,

mathematical processes were invented and formed into axioms to comprehend coherent theories, by the logic of our reality. The same applies to scientific observations and any other concept that is claimed to possess objectivity beyond the mind. Therefore, neither math nor science can claim objectivity outside of the mind.

Additionally, there are instances when mathematics is not objective. The Bayesian prior perspective on possibilities considers the probability of an event before new data is collected, taking into account the individual's background knowledge and experience, and adopting a subjective approach (Hayes). These examples highlight the inescapable influence of subjective judgment, where even the most "objective" knowledge is ultimately constructed and given meaning within the context of the human mind.

**4. Conclusion**

In conclusion, objectivity is fundamentally inaccessible to us, both within and beyond our perception. All that we know, discuss, or label as "objective" is ultimately shaped by the frameworks of our minds, including our senses, language, and reasoning processes. Even our best attempts at objectivity, such as mathematics, remain limited by these mental structures. Nevertheless, striving for objectivity remains a valuable ideal. Our means of objectivity, then, is not absolute truth, but a continuous process of minimizing personal bias through reason and evidence. Thus, objectivity serves as a guiding ideal to reduce subjectivity; however, what we call objectivity is, in the end, nothing more than a useful construct of the human mind.

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**Advances in UAV–AI Systems for Precision Agriculture: Monitoring Soil, Nutrients, and Crop Stress By Dhruva Veldhurthi**


## Abstract

Recent advances in unmanned aerial vehicles (UAVs) and artificial intelligence (AI) have transformed precision agriculture by enabling fast, large-scale, and non-destructive monitoring of crop and soil health. Drone-based systems equipped with multispectral and hyperspectral sensors can assess soil moisture, nutrient levels, leaf chlorophyll, and water content, as well as map soil texture, providing farmers with detailed insights that traditional sampling methods cannot capture. These technologies allow for early detection of crop stress, more precise irrigation and fertilizer application, and improved overall resource efficiency. This paper synthesizes current research on UAV-AI systems in agriculture, highlighting their potential to enhance productivity, support sustainable farming practices, and shift crop management from reactive to predictive decision-making.


## Introduction

Agriculture has always depended on the ability to monitor soil and crop health, as soil quality directly determines yield and sustainability. Traditional methods of soil assessment, such as manual sampling and laboratory analysis, provide accurate data but are time-consuming, costly, and limited to specific points within a field. As a result, they often fail to capture the variability of soil conditions across large areas. In recent years, advances in remote sensing technology and artificial intelligence (AI) have provided new tools to address these challenges. Drones equipped with multispectral and hyperspectral sensors can capture detailed images of farmland, while AI models analyze this data to estimate key indicators such as soil moisture, nutrient levels, and crop stress. These multispectral sensors take images in a limited number of distinct bands of light, which are usually fast, good for quick health checks, and more affordable. Hyperspectral sensors, by contrast, take images in hundreds of narrow bands, providing far more detailed information but at a significantly higher cost.

Given these advancements, this paper explores the research question: How can AI-powered drones that measure soil and crop health support sustainable farming practices by improving efficiency and monitoring growth conditions? By offering precise, large-scale, and real-time monitoring capabilities, AI-powered drones represent a significant development in precision agriculture, with the potential to improve irrigation efficiency, conserve natural resources, and increase crop productivity.

## Body

Recent studies have demonstrated the effectiveness of drone-based systems for soil moisture monitoring, which is a critical factor in maintaining crop health. Traditional approaches, such as manual soil sampling, typically require extensive labor and can only provide information for limited locations within a field. By contrast, drones equipped with multispectral

and hyperspectral sensors are able to scan large areas quickly and generate detailed datasets. A 2024 study published in Agriculture, found that multispectral drone imagery, when analyzed with regression models, could estimate soil moisture to depths of up to 200 cm with less than 10% error. Similarly, research in Sensors (2025) showed that drones equipped with hyperspectral imaging and artificial neural networks were particularly effective in detecting soil moisture variations in water-stressed conditions, outperforming other machine learning methods. (Kudyba and Sun, 2025) These findings suggest that drone-based AI systems provide a reliable and scalable method for monitoring soil moisture, offering farmers valuable insights for improving irrigation management and overall crop performance.

Another dimension of drone-based crop health monitoring focuses on leaf-level indicators such as chlorophyll content, disease symptoms, and leaf area, which are early markers of stress often preceding visible reductions in yield. For example, drones efficiently monitor the health of corn (Phys.org, 2025) reports on research done in the University of Missouri where drone-mounted multispectral imaging was combined with AI to identify chlorophyll levels in leaves. This method enabled accurate prediction of nitrogen deficiency, which in turn supported more targeted fertilizer application and reduced environmental impact. Similarly, UAV-based remote sensing for estimation of leaf nutrient concentrations in citrus demonstrated that leaf spectral signatures could be used to non-destructively estimate nutrient status in citrus trees across different rootstock-scion combinations (Costa et al., 2022). These findings suggest that leaf-based drone monitoring provides valuable early indicators of crop health, enabling interventions before stress escalates.

In addition to moisture and nutrient monitoring, drone-based remote sensing has also proven effective in assessing soil texture and structural conditions, which directly influence water retention and root development. Hyperspectral imaging, paired with AI models, can detect subtle spectral differences linked to sand, silt, and clay content, allowing researchers to generate detailed soil texture maps without extensive ground sampling. A recent study using UAV-mounted hyperspectral sensors demonstrated that AI could accurately classify soil types and identify compacted or degraded zones within a field, supporting more precise soil management strategies (Flores Peña et al., 2025). By pinpointing areas that require aeration, organic amendments, or erosion control, these systems help farmers maintain long-term soil health while reducing resource waste.

Drone-AI systems also play a critical role in detecting early physiological stress in crops, such as reduced leaf water content or declining chlorophyll levels—both of which typically appear before visible signs of damage. In citrus orchards, researchers used multispectral UAV imagery with machine learning models to map chlorophyll and leaf water content across large areas, achieving strong prediction accuracy and revealing patterns of stress linked to irrigation variability (Zhang et al., 2025). By identifying stress hot early spots, farmers can adjust irrigation or nutrient application before yield loss occurs, ultimately, conserving water and improving overall crop resilience.

**Discussion/Analysis**

The findings across recent studies demonstrate that UAV-based remote sensing and AI-driven analysis have become central to modern agricultural monitoring, particularly in crops like citrus where nutrient balance, leaf condition, and soil texture directly affect yield and tree longevity. A consistent theme is that UAV imagery allows for faster, more spatially comprehensive monitoring compared to traditional ground-based sampling. However, each study highlights different limitations and technological strengths that shape the practical implications of drone-based monitoring in real agricultural environments.

One of the most striking insights is how effectively machine learning models can extract hidden nutrient-related patterns from aerial images. Costa et al. showed that UAV imagery combined with ML algorithms can estimate key leaf nutrient concentrations with strong accuracy, reducing the need for destructive leaf sampling (Costa et al., 2022). This is significant because nutrient deficiencies in citrus often present subtly before visual symptoms appear. Their study demonstrates that drone-based detection enables earlier intervention, which can prevent yield loss and reduce fertilizer waste. However, their approach also revealed sensitivity to lighting conditions and variability in canopy density, meaning that the accuracy of their models depends heavily on controlled imaging environments. This suggests that while UAV-based nutrient detection is promising, it must be implemented with strict field-level imaging protocols or robust preprocessing methods.

Similarly, Zhang et al. expanded this work by focusing on leaf water content and chlorophyll—two physiological indicators directly linked to drought stress and overall tree health (Zhang et al., 2025). Their integration of UAV sensing with model optimization techniques demonstrates how multi-spectral or hyperspectral data can capture biochemical properties that were previously measurable only through laboratory methods. This capability fundamentally changes how farmers manage irrigation, allowing them to identify water-stressed zones at high resolution. The study's modeling improvements showed significant gains in prediction reliability, but also emphasized that the precision of chlorophyll and water-content estimates still varies with sensor calibration quality and atmospheric interference. Together, these findings reinforce that UAV-based physiological monitoring can enable real-time precision agriculture but requires standardized calibration procedures to ensure consistent data quality across different orchards and seasons.

Expanding beyond plant-level physiology, Flores Peña et al. demonstrated that UAV-based hyperspectral imaging can also be used for soil texture classification, enabling more accurate mapping of soil variation across large fields (Flores Peña et al., 2025). Since soil texture affects water retention, nutrient mobility, and root development, this approach provides a foundation for variable-rate irrigation and fertilizer strategies. Their study also incorporated "robust AI algorithms," highlighting a shift from simple classifiers toward more complex, noise-tolerant computational methods. Unlike plant-focused monitoring, however, soil-based sensing faces deeper challenges: soil properties are heavily influenced by moisture, debris, and surface irregularities that distort spectral signatures. Thus, while UAV hyperspectral imaging

offers high spatial resolution, the reliability of soil texture prediction still depends on proper ground-truth sampling and periodic recalibration.

A unique dimension emerges from Kudyba and Sun, who explored the integration of drones with RF energy-harvesting sensor tags for autonomous field monitoring (Kudyba and Sun, 2025). Instead of relying solely on drone imagery, their system enables long-term field sensors to communicate data without traditional batteries. This represents a hybrid monitoring ecosystem, where drones act as airborne data collectors and power sources rather only than imaging platforms. The technological advantage is clear: continuous environmental monitoring without the labor of sensor maintenance. However, the study also acknowledges limitations in energy transfer efficiency and sensor placement, implying that real-world deployment requires careful design of flight paths, tag density, and sensor orientation. Still, when considered alongside UAV imagery studies, their work suggests that the most effective future systems will combine persistent ground sensors with periodic drone-based imaging to achieve a more complete understanding of crop and field conditions.

Taken together, these studies indicate a broader trend: UAV agriculture is shifting from simple aerial photography toward an integrated, multi-sensor, AI-powered ecosystem. The convergence of hyperspectral imaging, machine learning, autonomous sensing, and model optimization increases both the depth and precision of agricultural insights. However, they also reveal shared challenges—environmental noise, calibration issues, and model generalizability—that currently limit universal adoption. The evidence suggests that UAV-based monitoring is most effective when part of a larger data-driven management system rather than a standalone solution. As machine learning models become more robust and energy-harvesting sensors mature, farmers will likely depend on hybrid systems that integrate nutrient prediction, soil mapping, and real-time physiological monitoring into a unified decision-support platform.

Ultimately, the combined findings point toward a future where agricultural management becomes increasingly predictive rather than reactive. Early detection of nutrient deficiencies (Costa et al., 2022), precise estimation of chlorophyll and water content (Zhang et al., 2025), detailed soil texture maps for variable-rate inputs (Flores Peña et al., 2025), and autonomous sensing infrastructures (Kudyba and Sun, 2025) all reduce uncertainty and labor. The core challenge now lies not in the capability of UAV systems, but in harmonizing these diverse technologies into reliable, scalable workflows that agricultural producers can adopt without prohibitive cost or complexity.

**Conclusion**

The collective findings from recent UAV-based agricultural studies demonstrate that drone imagery and AI-driven analysis are becoming essential tools for improving precision, sustainability, and efficiency in modern citrus production. Across nutrient detection, physiological monitoring, soil texture mapping, and autonomous sensing, these systems consistently outperform traditional ground-based methods in both spatial coverage and early detection capability. Costa et al. showed that machine learning models paired with UAV imagery

can estimate nutrient concentrations before symptoms appear, offering farmers a powerful tool for preventative management (Costa et al., 2022). Zhang et al. further advanced this approach by demonstrating reliable prediction of leaf chlorophyll and water content, enabling early identification of drought stress and improving irrigation control (Zhang et al., 2025). Meanwhile, Flores Peña et al. expanded the role of UAV systems into soil diagnostics, showing how hyperspectral imaging and robust AI algorithms can map soil textures with high resolution, strengthening the foundation for variable-rate applications (Flores Peña et al., 2025). Finally, the energy-harvesting UAV–sensor hybrid system proposed by Kudyba and Sun highlights a promising direction for long-term, autonomous field monitoring that reduces maintenance barriers and expands continuous data collection (Kudyba and Sun, 2025).

Together, these findings suggest that UAV technologies are not merely supplemental tools but are evolving into central components of a comprehensive precision agriculture framework. While challenges remain—including calibration variability, environmental interference, data processing complexity, and system integration—each study demonstrates measurable progress toward more accurate, scalable, and automated monitoring solutions. The overarching trend points toward a future where crop management becomes increasingly predictive rather than reactive, supported by real-time, multi-sensor systems that integrate plant physiology, soil conditions, and environmental data. As UAV platforms continue to advance and AI models grow more robust, the agricultural industry will be equipped with increasingly powerful tools to optimize resource use, reduce environmental impact, and ensure long-term crop health. This research underscores that the continued development and integration of UAV-based technologies will play a critical role in shaping the next generation of sustainable and intelligent agricultural practices.

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**From Character to Character: Calligraphy in Imperial China By Angelina Chu**

**Abstract**

Originating in imperial China (221-907 CE), calligraphy served as more than a method of writing; it was an esteemed artistic tradition embodying the philosophical and spiritual ideals that underpinned China's transformation into the dominant regional power. As Chinese literacy became intertwined with the political imperative of Confucianism, calligraphy was a means of self-cultivation, conveying one's Confucian identity and enabling individuals to contribute to a greater societal order. In one of China's other dominant philosophical practices, Buddhism, calligraphy functioned as an avatar of self-contentment through the medium of scripture writing. These associations elevated Chinese literacy to a vehicle for cultivating oneself into a 君子 (*jūnzǐ*, "noble man"), the ideal Confucian citizen, and reaching 涅槃 (*nièpán*, "personal enlightenment"). As a means for moral development, the Confucian state used calligraphy as state-sanctioned propaganda to enforce a meritocratic society; however, as the art form became regarded as a symbol of prestige rather than a tradition of humanistic investment, calligraphy began to reinforce existing hierarchies in China. Through analysis of calligraphic and Confucian pedagogy in conversation with extant scholarly literature on imperial China's sociopolitical climate, the paper challenges the perception of calligraphy as a mere aesthetic pursuit. This paper ultimately addresses a scholarly divide, examining the myriad of significances calligraphy held in imperial China so as to contextualize the state's dominance as a byproduct of calligraphy's very versatility.

**Introduction**

The early imperial era of China, stretching from the Qin Dynasty (221-206 BCE) through the Tang Dynasty (618-907 CE), is often regarded as a Golden Age. After centuries of regional fragmentation and aristocratic rule, China's unification under a centralized state in 221 BCE marked the start of a new epoch. With physical expansion into Central Asia and parts of present-day Korea and Vietnam, China secured its position as the region's dominant entity. China's power in the Golden Age is akin to yet distinct from its modern reputation as a leader in global exports, captured in every "Made in China" sticker. Instead, Chinese dominance relied not only on commodities nor military conquest or geographic reach, but on the spread of ideas.

Within China, the advent of papermaking and a standardized writing system had given rise to literacy, and with it, a new intellectual elite. Unlike literary movements in other civilizations, which often confined themselves to academic inquiry or courtly entertainment, Chinese scholarship was conceived as an embodied way of life, anchored in service to the state and in the Confucian cultivation of moral character. Writing became the backbone of this embodied ideology. Calligraphy, rooted in Confucian ideals, embedded the state's imperial ambition into the rituals of daily life. This practice did not remain only within China's borders. As China expanded territorially, it also ideologically conquered surrounding regions, spreading the practice of calligraphy throughout the Sinosphere, China's span of cultural and political

influence, as a vehicle for other regions to develop their own intellectual vitality while simultaneously affirming China's continued dominance.

While this essay emphasizes developments from the Qin through the Tang, it also draws on later examples to show the endurance and adaptation of calligraphy's role in Chinese society. This essay first establishes how calligraphy's early artistic and orthographic evolution in form laid the foundations for its longevity in Chinese culture. This paper then demonstrates how Chinese writing became inextricable from its philosophical connotations in both Confucianism and Buddhism, exploring the implications these associations had on its role in society. From there, the essay examines calligraphy's role as intertwined with Confucian scholarship and bureaucracy before opening up to a broader analysis of its function as a social and political tool. This paper ultimately argues that, through both its form and function, calligraphy elevated literacy to a vehicle of the cultivated self, transforming—and being transformed by—Chinese society.

**Demystifying a Historical Enigma: The Origins of Calligraphy**

Fundamentally, though scholars are divided regarding a formal definition of calligraphy's form, calligraphy in early imperial China can be distinguished from standard writing in both its sophisticated aesthetics and practice. A useful term to consider when making this distinction is orthography. Through the lens of linguistics and art history, orthography refers to the degree to which writing adheres to the established form of characters in a given language. For instance, while two vertical and three horizontal strokes form the character 日 (*rì*, "sun"), the omission of the middle horizontal stroke produces an entirely different character 口 (*kǒu*, "mouth"). Exclusion of a singular stroke can entirely alter meaning and pronunciation, underscoring the utilitarian importance of orthography in reception of language. However, calligraphy complicates the conception of writing as a purely utilitarian act. As a medium for creative expression, calligraphy encompasses both the discipline of producing each stroke as well as the resultant aesthetic composition of each character. Calligraphy may record poems or essays, but the brushwork by which the literature has been written constitutes a work of art in its own right, with its visual form, as Xiongbo Shi notes, "embod[ying] the movement, rhythm, and the spirit of the myriad things."

Calligraphy is an extension of the artistry embedded in the innate form of Chinese characters. Common among many early writing systems, the Chinese language evolved from ancient pictographs, the earliest recorded versions of which were discovered in carvings on ceramic vessels from the Yangshao Culture period (5000-3000 BCE). However, Chinese legend credits a man named Cang Jie as the inventor of characters. Myths describe how he was "born with the capability of writing," creating characters based on his observation of the movements of stars, mountains, rivers, turtle shells, and bird feathers. Though this tale is regarded as fictional, it nevertheless highlights that pictographs served a similar purpose to that of other forms of visual art, which is articulated by Zhuzhong Qian and Desheng Fang: to encapsulate the activity of the natural world and use it to relay messages among humankind. Chinese is one of the few

languages that actively preserved the visual roots of pictographs in its modern characters. The Western alphabet, for example, was derived from Egyptian hieroglyphs; however, these pictorial origins became nearly undetectable by the time of its Greek standardization in the 8th century BCE due to phonetic and stylistic simplifications over time. For example, the Egyptian hieroglyph for "house," a clear floor-plan-like pictograph, eventually evolved into the Phoenician character bēt (𐤁), and then into the Greek letter beta (B), whose shape bore little resemblance to its original visual meaning. Due to such transformations, in which curves and details were stripped down into abstract lines optimized for speed and uniformity, the alphabet lost its pictorial legibility. By contrast, Chinese script retained a visible connection between characters and their pictographic roots; for instance, the character 山 (*shān*, "mountain") still resembles the jagged outline of peaks. One of the first skills taught to beginner Mandarin students today is the ability to recognize and write visual radicals, the remnants of pictographs, along with stroke types and order. It is therefore reasonable to infer that the inherent artistic demands of Chinese script laid the groundwork for the development of calligraphy as an art form.

The visual characteristics seen in early forms of calligraphy foreshadow its distinctive ability to imbue writing with aesthetic and spiritual meaning, a capacity that would eventually be realized by brush and ink. Carvings found on turtle shells and ox scapulas, also known as Oracle Bone Script, are considered the first examples of Chinese writing, dating back to the Shang Dynasty (1600-1050 BCE). These inscriptions, used to record the results of divinations, already exhibited variance in the thickness, count, and arrangement of strokes. Calligraphy soon extended to bronze vessels and weapons, where inscriptions were cast into molds. Amy McNair writes that some bronzes, such as those commissioned by the Shang queen Fu Hao, reveal how characters were deliberately manipulated into symmetrical and decorative arrangements. In such cases, legibility gave way to design, suggesting that calligraphy was already being valued as an object of aesthetic appreciation rather than mere record-keeping. By the Zhou Dynasty, calligraphy was also engraved in stone to commemorate treaties and ancestral rites. These inscriptions were "praised for their forceful strokes and structure," foreshadowing the assertive lines later produced with the brush. The emergence of the writing brush (c. 4th century BCE) and the invention of paper by Cai Lun in 105 CE, two pivotal innovations of China’s Golden Age, marked a turning point. Not only did these materials suggest accessibility, but their versatility ultimately created conditions for calligraphy to flourish into a sophisticated artform.

The simplistic tools traditionally used in Chinese calligraphy created an outlet for the practitioner to authentically give form to their ideas—and even to themselves—on paper. The brush, paper, ink, and inkstone, also known as the Four Treasures of the Study, each served a distinct purpose. A brush was composed of a tip made from bristles of animal hair, secured to a bamboo or wooden handle. The bristles were shaped like a teardrop, tapering from a thicker base to a fine point, enabling calligraphers to produce strokes of varying thicknesses depending on the pressure they exerted. Though oracle bones, ceramics, bronze, and silks were also used, paper became the primary medium on which calligraphy was written following its invention. Made from plant fibers such as bamboo and cotton, the paper used in calligraphy was smooth and

absorbent. Solid ink sticks were ground with water against small mortars called inkstones to form a thin substance that could glide across the page. Together, the fluidity of the ink and the flexibility of the bristles allowed the brush to take shape through the calligrapher's every move, recording even the slightest shift in motion or thought. The flatness of the paper created a surface where the brush tip could guide the ink effortlessly. The use of such receptive mediums ensured that the calligrapher's distinct choices and character were meticulously captured.

The practice of calligraphy was an intimate experience: one was required to be in close touch with the movement of their body and mind to allow their writing to become a mimetic representation of their inner self. This began before one even touched the brush. Calligraphers prepared to write by clearing their mind; just like the smooth paper was devoid of bumps or cracks that might disrupt the flow of the ink, one was to set aside any internal obstacles that could stand in the way of expressing their most authentic self, whether that be personal conflicts or worldly matters. This often catalyzed deeper self-reflection by the practitioner on whom they thought—or, aspired for—their authentic self to be. As a calligrapher internalized this identity, they would also begin to embody it. Traits such as confidence and righteousness might manifest in heightened posture and relaxed muscles, ideal conditions for steady writing, while self-doubt might lead to physical tension in the fingers, hindering one's ability to properly grasp the brush. The brush thus became an extension of the writer's physical posture, and their demeanor was embodied by the ink. For ideal results, one was to direct their entire focus to their practice, maintaining a steady hand to produce clean, balanced characters; even slight distraction might be exposed through crooked brush strokes or uneven spacing. Through the exercise of physical and mental discipline, calligraphers recorded characters that communicated not only the Chinese language or aesthetic artistry, but a cultivated identity.

Comparisons between calligraphy and other art forms, such as painting and music, illuminate not only the technical artistry required to produce calligraphy, helping to distinguish it from mere handwriting, but calligraphy's role in building morality. Scholars, including Kwo Da-Wei, have long recognized the brush and ink as vehicles for creative and moral expression in the discipline of painting. However, whereas in painting the artist does not aim for perfection in each individual stroke, but rather layers gestures in service of a greater image, in calligraphy the delicate, linear composition of characters makes each stroke central to the piece as every mark is visible in the final product. Writing neat calligraphy required intention and precision to avoid exposing the viewer to marks of insecurity. Po-Han Yang has also compared calligraphy to music. His description of the brush's movement as rhythmic refers to the temporal arrangement of calligraphic composition: a thicker, longer stroke may take longer to write, while a thin, shorter stroke can be created from a brief gesture. As each stroke leaves a temporal imprint, every movement becomes a record of the calligrapher's presence. The rhythm and variation of the brushwork not only demand technical mastery to imbue the language with character, but also reflect the calligrapher's moment-to-moment experience of embodied self-cultivation. Calligraphy thus provided a technical framework to transform inner manifestations into tangible expression. In Confucianism, calligraphy was used as a vehicle for advancing a new scholarly

ideal, ultimately rewarding adherence to this new, coveted status, and reinforcing the power of the state.

**Beyond Words: Redefining Literacy through Confucianism**

Calligraphy's development, and, by extension, the development of a cultivated self in the Chinese context, was closely tied to the philosophies and values that had shaped early imperial China: Buddhism, as a vehicle for personal devotion, and Confucianism, as a structure of social hierarchy. The terms *process* and *product* offer a useful framework to examine calligraphy's varying significance across Confucianism and Buddhism. While calligraphy in the Buddhist context is centered around the process of writing as meditative exercise, Confucianism is primarily concerned with the product of this act—the physical form of the ink on paper or engravings in stone, and the visual appearance of the writing—as an embodiment of character. To be clear, the application of these terms is not mutually exclusive between the two frameworks of thought, but it does shed light on the nuances of their differing priorities. Valued as a discipline that required many years of mastery, the process of writing Confucian calligraphy still required a high level of mental engagement and precision. Indeed, a Confucian scholar might have practiced calligraphy while he was alone and with great concentration, and in doing so, engaged in self-reflection. However, the diligence he used in writing—which he did in part because his work would ultimately be subject to the Confucian gaze of other intellectuals and measured by a distinct aesthetic idea—and the potential for social mobility prompted young Confucian calligraphers to understand that the final product that he produced was of the utmost importance. Ping Ho Wong expands on the risk of fixating on calligraphic aesthetics at the expense of integrity to the process: "Aesthetic enjoyment can be a by-product, so to speak, of pursuing the arts as means of self-cultivation, but allowing oneself to be side-tracked by the aesthetic enjoyment of calligraphy per se, for example, to the neglect of the primary task of moral edification will render calligraphic practice detrimental to self-cultivation." On the other hand, even when the products of sutra copying, the writing of Buddhist scriptures, would be circulated, they were seldom associated with the person who wrote them. Though one copying a sutra could aim for calligraphy that was elegant in appearance, this was not to attain merit in the eyes of another human, but in the eyes of the Buddha. In this way, sutra copying as a process was very intimate, functioning as an act of self-reflection and discipline, yet it was also estranged from the earthly self, as the product did not serve to express the thoughts of the scribe, but of the Buddha himself.

Calligraphy's development in the Confucian context is illustrative of Confucius' radical 6th century BCE assertion that, in the wake of the political instability of the Zhou dynasty (c. 1046-256 BCE), personal responsibility and moral discipline, not divine intervention, were the path to restoring harmony. Drawing from earlier intellectuals, such as the Duke of Zhou and Laozi, the founder of Daoism, the philosopher promoted an approach based on logic and observation of earlier Chinese dynasties, especially the Western Zhou, which he perceived as characterized by social and political order. Confucius reasoned that only after every individual

reached an adequate moral standard could they interact with those around them rationally and benevolently, allowing peace to be restored among the greater population. Education was central to this vision, as it forced individuals to think beyond themselves by engaging with the teachings of others: "If one learns from others but does not think, one will be bewildered. If, on the other hand, one thinks but does not learn from others, one will be in peril." Mastery of the Six Arts—a set of disciplines of both body and mind—taught scholars how to apply their cultivated virtue in practice, including 書 (*shū* "calligraphy"), alongside 禮 (*lǐ*, "rites"), 樂 (*lè*, "music"), 射 (*shè*, "archery"), 御 (*yù*, "equestrianism"), 數 (*shù*, "mathematics"). Of the Six Arts, calligraphy had a unique place in upholding this new moral standard through a novel conception: ethical literacy.

In Confucianism, brushwork served as a means of fostering in oneself the traits essential to becoming a 君子 (*jūnzǐ*, "noble man"), one who embodied the principled benevolence and respect for others that would contribute to a harmonious society. These traits made up 仁 (*rén*, "humaneness"), which ultimately fulfilled the "Silver Rule" of Confucianism: "Do not impose on others what you yourself to not desire." While compassion and empathy were cultivated through a practice of restrained brushwork, fostering modesty, patience, and internal focus through fluid, controlled lines, confidence and righteousness too were vital, with off-centered movement suggesting a lack of clarity or wavering intent. A *jūnzǐ* was expected to uphold values of kindness with inner clarity and moral courage. Confucian calligraphy thus balanced bold, solid strokes—not overly saturated or sharp, yet assertive nevertheless—with thin, delicate gestures to translate their moral character into a physical form. This combination cultivated a multi-dimensional character both on the page and off.

Calligraphy was so highly regarded as a reflection of one's inner morality that it gave rise to the Confucian practice of characterology, the art of judging a person's virtue through their handwriting. As Su Shi, a famous Song Dynasty (960-1279 CE) poet, observed, "either beautiful or ugly, a calligraphic work can tell the moral character of the calligrapher… beautiful brush-writing must be created by a noble person and ugly brush-writing must be created by a mean person." Especially among literati, calligraphy could secure or damage credibility, making its refinement both a personal and civic obligation. Indeed, as Richard Curt Kraus notes, "China's bureaucratic elite has long used its connoisseurship to criticize the calligraphy of those of whom it disapproves… Officials were frequently unhappy with their monarchs, yet feared to criticize them directly. No wonder that emperors have been a traditional target for this sublimation of political commentary by art criticism." Further, producing exemplary writing was seen as setting a moral example for others, fulfilling the Confucian duty to apply one's virtue in service to society. Whereas Confucian calligraphy ultimately cultivated the virtue of a greater Chinese society, Buddhist calligraphy directed cultivation toward the practitioner's individual spiritual pursuit.

Calligraphy functioned as a practice of Buddhism through the meditative isolation of the self, guiding both body and soul towards personal enlightenment. Buddhism is grounded in the belief that all suffering stems from attachment to one's periphery. This attachment may be literal, such as reliance on material goods, or metaphorical, such as desire for status or recognition. By

driving individuals to detach themselves from distractions and focus inward, calligraphy operated as a form of meditation, grounding practitioners in the present moment and helping them to separate from the periphery: as one study explains, it is "a practice of mindfulness for promoting self-reflection and self-cultivation, which leads practitioners to reflect with their mind and heart, and thus lead them to a harmonious relationship with others and the natural world." While the practitioner employed brush and ink in the act of writing, this was not a matter of dependence on external tools; rather, the flexible brush and flowing ink became extensions of the body, amplifying the practitioner's movements and leaving a record of their authentic self. As Jean F. Billeter explains, writing not only "enable[d] the calligrapher to 'give body' to the character" but allowed the written form to stand as "a representation of [the calligrapher's] body." The brush and ink thus granted the calligrapher agency over the identity they sought to realize and inscribe on the page, thereby reinforcing the Buddhist ideals of independence and self-conception. The same ideals of independence and self-conceptions were expressed in the visual qualities of Buddhist calligraphy.

Though there is not a set aesthetic ideal associated with Buddhism, calligraphy produced in Buddhist contexts was generally characterized by strokes that were simplistic in relation to Confucian ones. A compelling example of this is the writing of Li Shutong, a lauded scholar who renounced worldly renown to become a Buddhist monk at the age of 38. Peimin Ni describes the transformation of Shutong's calligraphy after this transition: "It became less 'pretty,' less elegant, and less appealing to the popular eyes. It obtained a chilly coldness and simplicity, indicating disinterest in earthly affairs. There are more blank spaces on the works. The characters display little variation, and the strokes move with such a calmness that there is absolutely no anxiety. What is shocking in those works is that they are done by such a talented master, and yet they look so easy going and so 'ordinary.'" Ni's explanation demonstrates that perhaps the lack of a set aesthetic ideal is precisely what characterized Buddhist calligraphy. Unlike in Confucian contexts, where calligraphy often served to impress an audience and conformed to societal ideals, Buddhist calligraphy expressed contentment within oneself. That even a master intentionally created calligraphy with "chilly coldness" and "simplicity" illustrates how skill was not meant to be exercised in Buddhist practice; it functioned to facilitate inner cultivation rather than an aesthetically pleasing product.

While Buddhist calligraphy encouraged practitioners to internalize Buddhist principles, they nevertheless helped to disseminate them to a broader audience. As Buddhism flourished in the 7th century, calligraphy became a common vehicle for spiritual connection. The primary example of this is sutra copying, in which individuals hand wrote sutras, or Buddhist scriptures, as an act of devotion. By copying sutras in calligraphy, individuals not only wrote but interpreted the spiritual teachings through the lens of their own experience. Instead of being written on paper, sutras were often engraved in stone for longevity, allowing their messaging to be circulated widely through temples, burial sites, public monuments, and even private altars. One example is the Fangshan stone canon at Yunjusi Temple, a Tang dynasty project that sought to preserve the entire Buddhist canon through carvings of the complete set of sutras into over

14,000 stone slabs. As with many other sutra-inscription projects, pilgrims could visit the temple to view or trace the inscriptions. In this way, sutra copying served as a means of disseminating Buddhist thought throughout the Chinese population. By inviting participation without restrictions of gender or status, this form of calligraphy reinforced Buddhism's role as a unifying force in early imperial China. On the other hand, Confucian calligraphy served the state through the cultivation of individual discipline.

**Made in China: A Confucian Manufacturing of Identity**

Students' instruction to write the character for 永 (*yǒng*, "eternity"), which comprises all of the basic stroke types used in any Chinese character, reflects the broader role of Confucian calligraphy: to provide a disciplined foundation for the pursuit of excellence. As Confucius himself emphasized, "To be studious is near to sensibility. To earnestly practise is near to benevolence. To possess the sense of shame is near to bravery. He who knows these three things knows how to cultivate his own character (xiushen)." The philosopher believed that through the rigorous study demanded by scholarship, students would build the discipline central to a *jūnzǐ*'s worldview. The process of learning calligraphy embodied this ethos: after learning how to hold and control the brush, students were made to repeat the writing of *yǒng* until mastery, a procedure comparable to spelling drills in a Western education. Just as the process of mastering *yǒng*—though painstakingly monotonous—guaranteed proficiency in every stroke type, giving students the means to write any character, so too did it instill the patience and benevolence necessary to help cultivate greater society. Confucius put this model into practice firsthand in his private academy—one of the first of its kind in China—where education was no longer restricted to aristocrats but open to all willing to dedicate themselves to study. In some cases, children continued their practice at home under their parents' guidance, a first step at applying their skills beyond the classroom. Eventually, they advanced to copying the works of revered masters. The pedagogy was ultimately tested in civil service examinations, where their mastery of calligraphy was directly linked to one's ability to contribute to society. Only after proving themselves in this rigid system did scholar-officials begin to develop their one distinctive style, a mark of both literary and artistic maturity.

In the civil service exams, candidates were judged on how their calligraphy took shape in conversation with Confucian morals, thereby reflecting how their character might be molded to serve the state. Formally established in the Sui Dynasty (581-618 CE), the civil service exams were an institutionalized Confucian challenge to the long-standing hereditary aristocracy by offering all men an opportunity to become government officials, the most esteemed status in early imperial China. The exams measured one's fitness to rule by testing their knowledge of Confucian teachings and their ability to apply them in practice. Successful candidates presented responses that referenced key teachings from the Confucian classics in the form of hand-written essays and poems. Characterology became one of the four criteria that the emperor assessed when selecting candidates for office beginning in the Han Dynasty, alongside the command of their stature, literary eloquence, and logic of their arguments. Similar to how one's tone of voice

might influence how their insights are received, the candidate's calligraphy functioned as a reflection of how the practitioner personally interpreted their written responses. While sharp, assertive strokes might have affirmed a sense of conviction or moral clarity, a product of self-reflection, softer, frayed lines could have signaled uncertainty. Ruyu Hung articulates the Confucian purpose of such self-cultivation: "Knowing how to cultivate his own character, [the candidate] knows how to govern other men. Knowing how to govern other men, he knows how to govern the kingdom with all its states and families." By illustrating a candidate's ability to exercise discipline in the service of self-cultivation, calligraphy ultimately measured their potential to apply this quality in governing the state. Thus, the exams were framed as a means to offer any individual a fair chance to become part of the government; however, closer scrutiny reveals that this comes with many complications.

Though calligraphy as a discipline upheld the Confucian ideal of meritocracy, this principle was not always realized in practice. Female elites who are recorded as having learned calligraphy through tutoring or family instruction were barred from civil service exams, and by extension, social mobility. Even among men, who would study their whole lives to secure an official title, some positions remained forever out of reach: scribes, for example, remained a hereditary position even after the establishment of the purportedly meritocratic civil service exams. Though ordinary citizens could indeed transform their lives by passing the exams, in many cases, the resources required to prepare for them—most often, Confucian schooling—still demanded a degree of privilege or sacrifice; even with proximity to calligraphy, one did not stand a chance at mastering the artform without basic literacy, an advantage in itself. As a result, calligraphy's exclusivity reinforced hierarchies entrenched in Chinese society. This reinforcement was not only literal, as the children of aristocrats used the resources available to them to follow in their parents' footsteps, but also psychological, through the prestige attributed to calligraphy. Kraus writes, "For the members of China's literate class, calligraphy has been one source of the tremendous self-confidence that has helped sustain them in power. Students of calligraphy are conscious of joining in an ancient tradition as they learn each stroke of the brush in precisely the same manner as their forebears." Thus, calligraphy's prestige was reciprocal: as members of China's literate class continued to write in calligraphy, they enforced its public reputation as a symbol of authority, and similarly, their fluency in such an esteemed art affirmed their own elite status. Calligraphy nevertheless helped to cement the tenet of meritocracy into China's cultural identity, even if this promise remained unrealized for many.

One's handwriting came to be regarded as an extension of the self not only among the aristocracy, but by a broader Chinese population. Judgements based on handwriting permeated everyday life. Kraus offers multiple examples of this: for example, at the start of the year, elementary students might judge their new teacher based on their writing of characters on the blackboard, extrapolating conclusions about how the teacher might act for the rest of the year. That young students applied this concept so instinctively demonstrates that characterology did not need to be formally taught to be internalized from an early age. Unlike civil service exam candidates, who wrote with precision, knowing their calligraphy would be evaluated, the teacher

likely wrote on the board for practical reasons alone. Yet her students still attributed moral value to her writing, turning a simple act of utility into one of performance. Even adults far removed from scholarly circles recognized calligraphy as a central part of one's identity. During a riot against the Ming calligrapher Dong Qichang, a group of illiterate peasant protestors slashed a stone tablet engraved with his calligraphy, crying, "Dong Qichang is cut to pieces!" Without the ability to read or visually analyze—skills that might be obtained from formal education—the protestors still treated the destruction of Qichang's writing as a symbolic destruction of the man himself. Though not a direct application of characterology, this episode reflects the cultural intuition that one's handwriting was inseparable from the writer. Just as ordinary people instinctively associated handwriting with character, the state institutionalized this principle by formalizing calligraphy as a model of scholarly virtue.

The state's promotion of Wang XiZhi's handwriting as the calligraphic ideal reveals how calligraphy became a tool for prescribing Confucian identity as opposed to a medium for authentic self-expression. Wang XiZhi (344-388 CE) is widely regarded as one of the greatest calligrapher-scholar in Chinese history. His most famous work, *Preface to the Poems Composed at the Orchid Pavilion*, is still celebrated today for its elegant structure and flowing semi-cursive script. Recognizing the excellence of Wang's calligraphy, Emperor Taizong of the Tang Dynasty (618-907 CE) actively promoted his script as the ideal model. With this state-recognition, Wang XiZhi's calligraphy became the primary reference point for aspiring scholar-officials as they began to learn the art form. Budding calligraphers were expected to learn from Wang not only by imitating his brushstrokes with precision, but to internalize the character they embodied. In copying the master's handwriting, scholars were bolstering both their technical skill and Confucian virtue. The idea of Wang XiZhi's script as the calligraphic standard—especially one set by the state—complicates the duality of calligraphy as both a state-sponsored practice and an individualistic pursuit.

In striving to meet the expectation of precisely imitating the revered calligraphy of Wang XiZhi, scholars were also manufacturing their own characters into copies of a state-sanctioned Confucian ideal. While students were ultimately encouraged to move beyond direct imitation, this standardized script remained foundational to their understanding of calligraphy. This raises a question: to what extent could calligraphy remain an "art" when creativity and individuality were restricted by formality? McNair addresses this tension: "The use of the 'Wang style' of regular script as a public standard reveals the same values that orthography does: orthodoxy, formality, and the authority of antique models. It is important to note that these values were accepted and promoted by both the state and private scholars." By elevating Wang XiZhi's writing to a universal ideal, the state blurred the line between calligraphy and orthography, stripping calligraphy of the personal in favor of the Confucian state. The emperor's endorsement of the Wang style ultimately demonstrates how literacy became a political tool that shaped Chinese culture. By prescribing an ideal identity through writing and elevating an aristocrat's hand as the model, the state used calligraphy to project values that ultimately reinforced its own power.

**Conclusion**

In redefining handwriting as a means of artistry, morality, and social capital, calligraphy stylized the mundane, rendering literacy both an aesthetic and political endeavor. This elevation set Chinese literacy apart from that of other cultures: in the West, written language became a vehicle for creativity through literature, whereas in China and the Sinosphere, writing itself was a form of art. In the intervening twenty two centuries, calligraphy has permeated the West through a process of assimilative commodification; whether manifested in stylized logos and fonts that exoticize Chinese culture or through adaptation into Western aesthetics via fonts that bear little resemblance to their Chinese predecessors, both forms flatten calligraphy into a superficial commodity. In so doing, they estrange the Western participant from comprehending the historical and cultural weight of the art, in addition to the principles it embodied. As such, calligraphy is not only a reflection of China's past but also its modern evolution.

From its conception, calligraphy has always served as a political tool, used to reinforce Chinese dominance within the state and beyond throughout the Sinosphere. Looking to today, however, the Western perception of calligraphy embodies a transformation in China's own cultural identity: one as a leader not in ideologies such as Confucianism and Buddhism, but in the global economy. China's embrace of manufacturing technologies has been just as revolutionary as their embrace of brush and ink in that it has streamlined accessibility to the *product*. As opposed to the years of individualized scholarly and mental discipline that underpinned the *process* of calligraphy, now the *product* is created through the clicks of buttons and impersonal, mindless contributions from hundreds of workers. The stylized art that was seen as the most prized possession has been replaced by mass produced handbags from the Guangdong Province, consumed by elites in China and globally. Calligraphy, like Chinese exports, has become commodified for a Western gaze, just as the Chinese national character, rather than promoting self-cultivation, has become associated with commercialism. Calligraphy thus reflects China's evolution as much as it reveals its cultural identity.

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**Corporate Social Responsibility and Firm Performance in Vietnamese SMEs: A literature Review By Tran Pham Minh Chau, Do Phan Truong An, Le Minh Ngoc & Supervisor By Prof. Dr. Nguyen Ngoc Thang**


## Abstract

Although there have been many advocates of CSR and its important role in improving firm performance, there is a paucity of studies in the context of Vietnam and SMEs. This study aims to investigate the impact of corporate social responsibility (CSR) on firm performance through two aspects: financial and non-financial performance and provide a framework for understanding this relationship. The study reviewed 12 articles regarding CSR in small and medium sized enterprises (SMEs) in Vietnam. The findings show that CSR enhances profitability, reputation and competitiveness while improving employee satisfaction and environmental performance. These factors contribute to stronger organizational commitment, operational efficiency and sustainable growth. As such, integrating CSR into long-term strategy is essential for SMEs to attain sustainable growth and a competitive advantage. The review offers new directions for future research that can motivate managers and practitioners to implement CSR into their enterprises.


## Introduction

In recent years, Corporate Social Responsibility (CSR) has become an increasingly vital component of business strategy, especially in developing economies such as Vietnam. With the growing emphasis on global sustainability standards and stakeholder expectations, companies—particularly small and medium-sized enterprises (SMEs)—are under increasing pressure to adopt socially and environmentally responsible practices. For these firms, CSR is no longer merely a moral obligation but a strategic instrument that enhances competitiveness, builds reputation, and drives sustainable growth. However, many Vietnamese SMEs still approach CSR primarily as a form of legal compliance rather than as an integrated strategy for improving firm performance. This gap highlights the urgent need to better understand how CSR initiatives influence both financial and non-financial outcomes in the Vietnamese context. Despite its growing popularity, CSR is still a relatively new idea in many developing nations, including Vietnam. Even though it is growing in popularity, its application frequently lacks total commitment since the potential advantages of CSR are not well highlighted. The difference illustrates how important it is to understand how CSR affects business success in these kinds of situations.

This study focuses on analyzing the overall impact of CSR on firm performance. CSR is considered a strategic tool that helps businesses enhance their reputation, build trust with customers and stakeholders, and thereby improve business performance. Implementing CSR activities not only contributes to creating a positive image but also provides a sustainable competitive advantage, enabling firms to achieve better long-term performance.

Given the growing significance of CSR in shaping organizational outcomes, it becomes essential to explore its specific influence within the Vietnamese business context. Therefore, this study seeks to address the following research questions: How does CSR impact firm performance in the context of Vietnamese SMEs?
The structure of this report is organized as follows:

- The Theoretical Framework section outlines the core concepts of firm performance and summarizes theoretical models connecting CSR to organizational outcomes.
- The Method section describes the literature review process and the criteria for selecting studies published between 2015 and 2025.
- The Findings section discusses the observed effects of CSR on financial performance, non-financial performance, employee satisfaction, and environmental outcomes.
- The Discussion section interprets these findings in the Vietnamese context and explores both theoretical and managerial implications.
- Finally, the Limitation and Future Research section identifies the main constraints of this study

**Firm Performance**

The importance of firm performance is recognised by everyone. It is an important indicator of the health of a company and is a key component to a company's success. Firm performance reflects how effectively a company utilizes its resources to achieve its objectives, generate profits, and sustain long-term growth. It can be assessed through both profitability and non-financial indicators, such as return on assets (ROA), return on equity (ROE); customer satisfaction, employee engagement, innovation, and social reputation. A strong firm performance not only enhances shareholder value but also strengthens a company's ability to adapt to market changes, attract investments, and maintain competitiveness in the industry.

**Theoretical Models Linking CSR to Firm Performance**

The knowledge and application of CSR to improving firm performance have become an important factor in the face of the rapidly changing environmental trends and societal expectations. Most companies invest in CSR initiatives because they believe it will result in higher firm performance. However, the theoretical framework linking CSR to firm performance has been subject to considerable debate. Phu Nguyen Ngoc, Dung Mai Viet and Thang Nguyen Ngoc proposed a framework that emphasizes how internal Corporate Social Responsibility (CSR) affects employees' organizational commitment (OC), with organizational attractiveness (OA) as a mediator and age as a moderator. According to their model, internal Corporate Social Responsibility implementation is a strong predictor for Organizational Commitment. Organizational Commitment is categorized into: Affective Commitment (AO), employees' emotional attachment to, identification with, and involvement in the organization; Normative Commitment (NC), stems from an employee's assessment of the respective costs and benefits of remaining with or leaving the organization; and Continuance Commitment (CC), the feeling of

obligation to remain with an organization. Nguyen Ngoc Thang and Yves Fassin developed a framework that also supports the relationship between internal corporate social responsibility (CSR) and organizational commitment. They stated CSR could be defined by five dimensions: Labor relation, Work-life balance, Social dialogue, Health and safety, Training and development. They saw that labor relations, health and safety, and training and education had a significant effect on organizational commitment whereas work–life balance and social dialogue have no significant association with organizational commitment.

Building upon these frameworks, Tuan Tran, Bui Van Vien, and Do Thi Tho expanded the understanding of CSR's impact by linking it to green marketing, corporate reputation, and competitive advantage within small and medium-sized firms in Hanoi. Their study demonstrated that CSR not only strengthens a company's ethical image but also serves as a driver for green marketing initiatives, which in turn enhance corporate reputation. The results revealed that CSR positively influences both green marketing and corporate reputation, while green marketing exerts a strong effect on corporate reputation. Moreover, corporate reputation was shown to contribute significantly to competitive advantage. These findings suggest that CSR can generate both direct and indirect effects on firm performance - particularly through its ability to improve reputation and marketing effectiveness, reinforcing the idea that socially responsible actions yield tangible competitive benefits.

Similarly, Tiep Le Thanh, Ngo Quang Huan, and Tran Thi Thuy Hong emphasized the mediating role of corporate reputation (CR) and corporate performance improvement (CPI) in the CSR-performance relationship. Their research indicates that CSR initiatives positively and significantly affect firm performance by enhancing reputation and internal capabilities. This suggests that CSR does not operate in isolation but rather through a chain of relational mechanisms - starting from improved stakeholder trust and public perception to enhanced internal efficiency and innovation.

Collectively, these theoretical and empirical studies converge on a shared understanding: CSR acts as a multidimensional construct that enhances firm performance not only by improving employee commitment and organizational attractiveness but also by elevating corporate reputation, marketing strength, and long-term competitiveness.

To summarize all of the frameworks discussed, a conceptual framework as shown in Figure 1 is formed. This study aims to measure the firm performance through CSR and compare them with the firm performance types such as Financial, Non-Financial and Others. Figure 1 shows that CSR has a direct effect on the overall firm performance. Firm performance is mediated by Non-financial factors that affect Financial Performance.

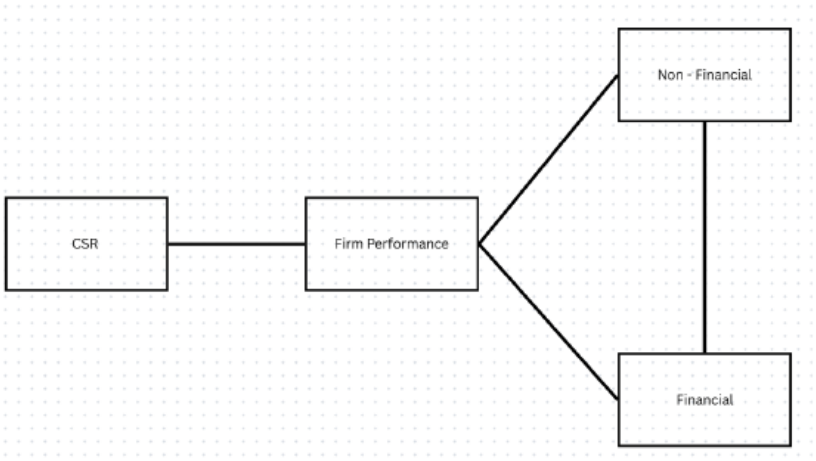



**Figure 1.** Conceptual framework of the study

**Methodology**

This literature review mainly focuses on research published in many different journals, from 2015 to 2025, that are related to Corporate Social Responsibility (CSR) in Vietnam. Major managerial or business journals (e.g. Journal of Asia-Pacific Business, Discover Sustainability, International Journal of Corporate Social Responsibility, Society and Business Review, Journal of Risk and Financial Management) were scanned for articles containing related information and data. In total, 12 studies were found that could be used for this purpose. All of the reviewed studies are presented in Table 1.

Table 1: Studies used

| No | Author/Study | Research method | Findings |
|---|---|---|---|
| 1 | Nguyen Ngoc *et al. Discover Sustainability* (2025) | - Physical surveys<br>- Purposive sampling techniques | - CSR has a positive impact on OC (β=0.3356, p<0.05) and on OA (β=0.7404, p<0.05)<br>- OA is positively related to OC (β=0.4971, p<0.05)<br>- OA significantly mediate the effect of CSR on OC (β=0.7404, p<0.05, LLCI and ULCI>0) |
| 2 | Nguyen Ngoc Thang & Yves Fassin (2017) | - Sampling<br>- Survey | Internal CSR is significantly related to AC (R2 = .18, F = 18.39, p < .01)<br>- health and safety had a significant effect on AC (β = .32)<br>- training and education had a positive and significant association with AC (β = .36)<br>Internal CSR has a significant association with CC (R2 = .15, F = 5.25, p < .01).<br>- health and safety had a significant effect on CC (β = .28)<br>Internal CSR has a significant effect on NC (R2 = .13, F = 4.41, p < .01)<br>- labor relations had a positive and significant effect on NC |

| | | | |
|---|---|---|---|
| | | | (β = .14) |
| 3 | N. Minh *et al.* (2025) | Multi-case study research design | - SMEs often do social CSR through charity work, usually monetary.<br>- Many SMEs support the disabled: provide job opportunities<br>- SMEs that help their employees not only through financial aid but also in transportation, accomodation, childcare, .... report having higher OC<br>- Environmental CSR includes: using eco-friendly inputs, conserving energy and water, reducing waste production, and minimizing the use of single-use plastic straws |
| 4 | Maitreyee Das *et al.* (2019) | Literature survey | Social and environmental practices are grossly neglected in SMEs more specifically in emerging markets. Existing literature mentions that collaborative mode of operation, government policy and facilitation, supporting organisation culture can positively influence SME's sustainability performance, and hence, improve their financial performance |
| 5 | Nguyen *et al. International Journal of Corporate Social Responsibility* (2018) | Critical review and analysis of literature | - While each firm's CSR approach differs based on its internal structure and mission, external factors such as national policies, economic conditions, and social norms create shared obligations across enterprises.<br>- Interactions among individual, organizational, and societal levels can lead to tension in adopting CSR practices, with traditional values playing a central role in shaping ethical responsibilities.<br>- The government strongly influences CSR through ideology, policy, and regulation, yet weak enforcement limits effectiveness. Meanwhile, globalization pressures Vietnam to align with international CSR standards and practices. |
| 6 | Society and Business Review | Qualitative systematic review of current literature | - CSR in Vietnam emphasizes social issues over environmental responsibility<br>- Ethic driven CSR: focus more on profit and economic growth, leading to unethical practices<br>- Socialist-driven CSR: government ensure equal distribution of wealth and access to education, basic health care, food and clothing; workers get treated better<br>- CSR identity: Vietnam mimicked and accept international standards for CSR due to pressures from foreign purchasers<br>- CSR integration: Vietnam more aware of CSR and is trying to practice it, however government manipulation of media and how the government control firms may paint a bad picture |
| 7 | Loan Thi Hong Van & Phuong Anh Nguyen | Survey | - CSR factors explain 65.2% of CSR implementation in SMEs<br>- Four independent variances (LĐ, MTNB, MTCT, and MTVM) with sig. <0.05 are linearly related with the dependent variance |

| | | | |
|---|---|---|---|
| | (2019) | | (CSR) |
| 8 | Angie Ngoc Tran & Søren Jeppesen (2015) | Institutional theoretical framework: fieldwork interviews | - Competitive market have the most influence due to the nature of the industry: 90% products are exported to US, Japan, Europe --> stakeholders pressure to uphold CSR<br>- SMEs depend on the society around them to grow and develope --> pressured to follow environmental protection (CSR) |
| 9 | Ta Huy Hung *et al.* (2025) | Analyse and in-depth interview | External motivations to practicing CSR:<br>- to comply with the environmental laws (100%)<br>- to build a good corporate image with stakeholders (80%)<br>- to become a good corporate citizen (70%)<br>CSR is not used to increase employee engagement, retainment, encouragement<br>Barriers to CSR implementation:<br>- (1) Lack of close connection between CSR activities and core business activities of the enterprise (100%); (2) Lack of participation and support of employees in the enterprise (80%); (3) Lack of time (70%); (4) Lack of information on good practices in the industry (70%) |
| 10 | The Tuan Tran, Bui Van Vien and Do Thi Tho (2025) | Survey<br>Data analysis (PLS-SEM) | - CSR activities positively impact the implementation of green marketing strategies in the context of SMEs in Hanoi ($\beta = 0.812$, $p < 0.01$)<br>- CSR activities positively impact corporate reputation in the context of SMEs in Hanoi ($\beta = 0.458$, $p < 0.01$)<br>- The implementation of green marketing strategies positively impacts corporate reputation in the context of SMEs in Hanoi ($\beta = 0.440$, $p < 0.01$)<br>- Corporate reputation positively impacts competitive advantages in the context of SMEs in Hanoi ($\beta = 0.794$, $p < 0.01$) |
| 11 | Tiep Le Thanh, Ngo Quang Huan & Tran Thi Thuy Hong (2021) | Data analysis (PLS-SEM) | - CSR positively significantly impacts corporate reputation (CR) (+0.475)<br>- CSR has a positive influence on customer purchasing intention (CPI) (+0.260)<br>- CR positively impacts CPI (+0.291)<br>- CR has a positive influence on firm performance (FP) (+0.300)<br>- CPI has a positive impact on FP (+0.330) |
| 12 | Vuong Khanh Tuan (2020) | Descriptive survey method | |

The articles have different approaches to firm performance, like how Ta Huy Hung (2025) looked through the financial lens while The Tuan Tran, Bui Van Vien and Do Thi Tho (2025) investigated the environmental aspects. The studies also explore different areas of SMEs,

from the textile to the service industry. Overall, the lack of consistency in approaches and measurements proves a challenge to writing this review.

**Effects of CSR on Financial Performance**

Based on the framework of analysis above, the research results consistently indicate that CSR positively affects firms' financial performance in Vietnam.When businesses implement activities such as reducing emissions, managing waste effectively, using sustainable raw materials, conserving energy and water, and adopting eco-friendly production processes, these actions not only minimize their negative environmental impact but also generate tangible economic benefits. Nguyen Minh et al. (2025), found improving environmental performance helps businesses significantly reduce operational costs through resource conservation, process optimization, and waste reduction. These factors directly contribute to increasing profit margins, stabilizing cash flow, and strengthening competitiveness in the market. Nguyen Ngoc, Mai Viet, and Nguyen Ngoc (2025) found that internal CSR practices significantly improve employee commitment, which indirectly enhances productivity and overall firm profitability. Das, Rangarajan, and Dutta (2019) further demonstrated that companies with integrated CSR strategies experience improved long-term financial outcomes through operational efficiency and reduced risk exposure. Another important aspect is that environmental performance expands market access and resource opportunities. As environmental standards become mandatory in many global supply chains, firms that comply gain a competitive advantage in partnering with international companies, accessing "green" financing, and benefiting from policy incentives. Meeting ESG (Environmental, Social, and Governance) requirements also helps reduce legal risks, avoid penalties, and prevent operational disruptions due to regulatory violations. These factors contribute to greater business stability and strengthen long-term competitiveness. As a whole, these findings confirm that CSR not only fulfills social and environmental responsibilities but also serves as a strategic tool for improving firm performance and financial resilience.

**Effects of CSR on Non-Financial Performance**

Recent studies on internal CSR and organizational commitment (OC) in Vietnam demonstrate a strong positive relationship between CSR activities and non-financial performance outcomes, particularly in the form of enhanced OC and employee well-being. Research in the construction industry reveals that internal CSR significantly improves OC both directly and indirectly through organizational attractiveness (OA), with OA mediating the relationship between CSR and OC ($\beta = 0.7404$, $p < 0.05$) (Nguyen Ngoc, 2025 ). In a similar manner, evidence from Vietnamese service firms shows that aspects of CSR such as health and safety, training and education, and labor relations contribute positively to affective, normative, and continuance commitment ($R^2$ values ranging from .13 to .18, $p < .01$) (Nguyen Ngoc Thang & Yves Fassin, 2017). These findings suggest that CSR initiatives not only strengthen employees' psychological attachment to their organizations but also enhance perceptions of workplace safety, development opportunities, and relational trust. As such, CSR serves as a key driver of

non-financial performance in Vietnamese SMEs by fostering internal cohesion, talent retention, and organizational loyalty, all of which are factors essential for sustainable competitiveness in developing economies.

**a) Employees satisfaction**

Employee satisfaction is a critical factor influencing firm performance, especially in the context of CSR implementation in Vietnamese SMEs. When businesses ensure safe working conditions, fair welfare policies, and transparent labor relations, employees develop stronger commitment, motivation, and loyalty. According to *Vuong Khanh Tuan (2020)*, employee satisfaction derived from CSR practices enhances workforce engagement and improves organizational productivity. Similarly, *Angie Ngoc Tran & Søren Jeppesen (2025)* emphasize that decent working conditions and respect for workers' rights lead to higher morale, job satisfaction, and competitiveness in labor-intensive industries. In addition, *Loan Thi-Hong Van & Phuong Anh Nguyen (2019)* highlight that maintaining a satisfied and stable workforce helps SMEs meet international CSR standards, secure global partnerships, and strengthen their reputation. Overall, employee satisfaction is both a driver and an outcome of CSR, contributing to stronger organizational capacity and better firm performance.

**b) Environmental performance**

The result indicates that environmental performance has a positive and significant impact on firm performance, especially for SMEs in the context of sustainable development. Specifically, according to *Nguyen Minh, Majid Khan, Jo Bensemann, and Rahizah Sulaiman (2025),* activities such as reducing emissions, managing waste, conserving energy, and using sustainable materials help businesses lower operating costs, optimize resources, and improve profit margins. In addition, environmental performance enhances corporate image and reputation, supporting customer attraction and market expansion. These findings are also consistent with the study by *Tran The Tuan, Bui Van Vien, and Do Thi Tho (2025),* which shows that investing in green technology and innovation not only improves operational efficiency but also creates a sustainable competitive advantage. Overall, these factors confirm the strategic role of environmental performance in strengthening competitiveness and promoting long-term growth for SMEs in Vietnam.

**Discussion**

As expected, CSR has a variety of positive effects on the financial and nonfinancial firm performance. These effects might be much broader than the results of many previous studies suggest. It means that these effects are of considerable importance in terms of both theory and managerial implications. Therefore, it is necessary to identify and develop potential ideas for discussion and provide suggestions and directions for future research on this topic. The findings from this research reinforce the growing consensus that CSR is not an ethical obligation but a strategic investment that enhances firm financial performance. The significance of these results

lies in their implications for developing economics like Vietnam, where CSR is usually viewed as a legal compliance (Nguyen et al. 2018). The results can motivate companies to strengthen their CSR initiatives that can offer a competitive advantage.

The findings from the reviewed studies also highlight that CSR plays a crucial role in strengthening non-financial performance in Vietnamese SMEs, particularly through its influence on organizational commitment and employee-related outcomes. This relationship aligns with social exchange theory, which suggests that when firms demonstrate care and responsibility toward their employees, workers reciprocate with loyalty, motivation, and greater engagement. In the Vietnamese context, internal CSR practices such as providing safe working conditions, fair labor relations, and opportunities for training serve as a vital mechanism to enhance employee satisfaction and retention. Moreover, the mediating role of organizational attractiveness, as demonstrated in Nguyen Ngoc (2025), emphasizes that CSR initiatives not only improve employees' internal experiences but also shape external perceptions of the firm as an ethical and desirable workplace. This is particularly significant for young and skilled workers, who value employers that prioritize well-being and corporate responsibility.

In addition, it is discovered that a firm's success is significantly influenced by its environmental performance. Investments made by a company to support safe and equitable working conditions frequently result in increased employee commitment, trust, and motivation, all of which boost overall productivity. This is consistent with the findings of Vuong Khanh Tuan (2020). Loan Thi-Hong Van and Phuong Anh Nguyen (2019) contend that upholding CSR compliance helps export-oriented SMEs to meet international labor standards and maintain partnerships with global buyers, while Angie Ngoc Tran and Søren Jeppesen (2015) emphasize that respect for labor rights and decent working conditions boost employee morale and competitiveness. However, Nguyen Ngoc Thang and Yves Fassin (2017) highlight that financial constraints continue to limit the adoption of CSR in Vietnamese SMEs. However, as emphasized by Nguyen Ngoc Thang and Yves Fassin (2017), CSR implementation in Vietnamese SMEs is still limited due to financial and managerial constraints.

**Limitation and future research.**

The limitation of this report is that the scope of the research focuses solely on Vietnam, which may not fully reflect the impact of CSR in different economic and social contexts. In addition, the report is based on the synthesis and analysis of only 12 studies, which limits the generalizability of the findings.

Furthermore, the research mostly covers only secondary sectors such as textiles and manufacturing. Primary sectors, such as agriculture, fishing, mining and tertiary sectors like banks and healthcare are not studied and covered. This limits the scope of the result only to secondary sectors, specifically the manufacturing sector.

The research doesn't consider other factors that might influence firm performance, such as firm size and age, market dynamics, or political environment. This lack of external factor analysis may lower the ecological validity of the result.

The results only capture the impact of CSR at a single point of time which does not allow the researchers to observe long-term outcomes.

Considering all the limitations, future research should expand the scope to include multiple countries and incorporate more diverse empirical data and literature to help strengthen and clarify the relationship between CSR and firm performance. A variety of different firms and sectors would also be beneficial. In addition to expanding the scope of research, multiple external factors and time frames should be considered to ensure the validity of the result.

**Conclusion**

This study provided a literature review on how CSR affects firm performance in the context of Vietnamese SMEs, and it developed a framework for analyzing the impact of CSR on financial and non-financial performance of a firm. CSR has a positive influence on a firm's financial performance, which is shown in enhanced profitability and competitive advantage. In addition, through enhancing employee satisfaction, commitment, and organizational reputation, CSR is the key to non-financial success. Environmental performance also plays a role in enhancing competitiveness through cost reduction, innovation, and improved reputation. Therefore, SMEs should incorporate CSR into their long-term strategy in order to sustain these benefits. The review offers new directions for future research that has potential to guide managers and practitioners to implement CSR into their enterprises.

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# A Dietary Exploration of Neurodegenerative Processes in Alzheimer's Disease

Ananya Dhagat By Ananya Dhagat

## Abstract

Alzheimer's disease is a neurodegenerative disorder characterized by progressive memory loss. It currently has no known cure, making strategies for prevention and management of the disease quite necessary. According to the CDC, over 55 million people worldwide are living with dementia, with Alzheimer's accounting for around 60-70% of these cases. Different dietary patterns, such as the Western, Mediterranean, and MIND diets, have been well-researched in their means of influencing cognition. These diets vary in their components, including specific nutrients, fats, antioxidants, and micronutrients that impact brain function and cellular processes. They also influence factors linked to cognitive decline, such as inflammation, the gut microbiome, and the neurophysiological pathway. Dietary patterns may therefore have an important role in slowing Alzheimer's progression by supporting neurological health over time and contributing to wider strategies for minimizing the disease's impactfulness. This literature review explains and compares these dietary approaches in depth, showcasing their potential in benefitting the disease's management approaches.

## Introduction

Alzheimer's disease is a progressive neurological disorder that slowly impairs memory, thinking, and behavior. It is the most common type of dementia, accounting for 60-80% of all cases. Alzheimer's currently affects almost 7 million Americans, a number expected to double by 2060, according to the Centers of Disease Control and Prevention (CDC, 2024). As the American population continues to age, Alzheimer's has become a public health challenge, having negative implications on healthcare systems. While age and genetic factors are obvious risk factors, recent research has helped advocate that diet can potentially reduce the risk of Alzheimer's disease.

What we eat can influence major body systems, including immune health and responses, the cardiovascular system, metabolic function, and most relevant, cognitive health. Nutrients from food can impact processes such as oxidative stress, inflammation, the integrity of the blood-brain barrier (BBB), neuroplasticity, and neuronal health, all of which can play a role in the development or prevention of cognitive decline (Więckowska-Gacek et al., 2021).

The Western diet, characterized by an abundance of processed foods, is typically high in refined carbohydrates, salt, saturated fatty acids, and cholesterol. This form of consumption is commonly associated with fast food, sugary beverages, packaged snacks, and processed meats, all of which are low in essential, healthy nutrients. It is linked to many health problems including diabetes, obesity, and hypertension. These conditions are not only major risk factors for cardiovascular issues but also for cognitive impairment. Research links the diet to impairments in the BBB, the protective lining that regulates what substances enter the brain from the bloodstream, increased neuroinflammation, and oxidative stress, which may accelerate cognitive

decline and promote the development of Alzheimer's disease (Wieckowska-Gacek et al., 2021). Disruption of the BBB allows harmful substances and inflammatory molecules to reach the brain's tissue, while chronic inflammation and oxidative stress can destroy and impair communication between neurons.

In opposition to the Western diet, the Mediterranean diet emphasizes eating fruits, vegetables, whole grains, legumes, fish, and olive oil, with low consumption of red meat and saturated fats. This dietary pattern, inspired by traditional foods of countries like Greece, Italy, and Spain, is rich in fiber, antioxidants, polyphenols, and healthy fats such as omega-3 fatty acids. This diet is known for its antioxidant and anti-inflammatory properties, and has been associated with improved cerebral blood flow, synaptic plasticity, and neuronal cell function. Improved cerebral blood flow enhances oxygen and nutrient delivery to the brain, supporting energy and brain tissue repair. Synaptic plasticity, or the ability of neurons to modify the strength of their connections, is crucial for memory and learning, and is positively influenced by nutrients found in the Mediterranean diet. These neuroprotective effects contribute to the Mediterranean diet's potential in slowing cognitive decline and reducing the risk of Alzheimer's disease. Studies have shown that individuals who adhere closely to this diet experience a lower chance of developing dementia in later life (Fekete et al., 2025).

The MIND (Mediterranean-DASH Intervention for Neurodegenerative Delay) diet combines aspects of the Mediterranean and DASH (Dietary Approaches to Stop Hypertension) diets to specifically support brain health. It was developed with the goal of reducing the risk of Alzheimer's disease by targeting food components known to impact brain aging. It focuses on foods such as leafy greens, which are rich in vitamin K and folate, and berries, specifically blueberries and strawberries, containing antioxidants called flavonoids that support healthy aging. It also emphasizes nuts, whole grains, and fish while limiting saturated fats and sugar. Studies suggest that even moderate adherence to the MIND diet can significantly reduce the risk of Alzheimer's disease (Calil et al., 2018). The diet also encourages the use of olive oil as the primary cooking fat and includes moderate wine consumption, especially red wine, due to its content of natural plant compounds, including flavonols, anthocyanins, and phenolic acids (Omar, 2019). To summarize, while poor dietary choices commonly associated with the Western diet may increase the risk of cognitive decline, healthier eating choices like the Mediterranean and MIND diets offer promising strategies for delaying the onset of Alzheimer's disease.

**Western Diet**

The Western diet, typically high in processed foods, added sugars, unhealthy fats, and red meat, has been linked to numerous health issues. Following a Western diet may contribute to various conditions, including diminished cognitive performance. For instance, a study conducted by Attuquayefio et al. in 2017 presented the first experimental human evidence proving that consumption of saturated fats and excess sugar negatively affects performance on hippocampal-based memory tests. The researchers utilized assessments including the Hopkins Verbal Learning Test (HVLT), Logical Memory (LM), and the National Adult Reading Test

(NART), and results showed significantly lower recall ability in the experimental group (Attuquayefio et al., 2017). Furthermore, a 2013 investigation done by Gibson et al. reported findings revealing that consuming more fat, especially saturated and trans fats, was linked to poorer performance on memory and visuospatial learning tasks, including the verbal recognition memory (VRM), delayed matching to sample (DMS), and paired associate learning (PAL) tasks. These changes occurred even after accounting for age, physical activity, and verbal IQ. These effects were still seen regardless of how many total calories participants ate (Gibson et al., 2013). In 2017 Attuquayefio et al. reported interesting findings on cognitive performance and change in blood glucose across experimental meals. They found that a short diet manipulation of saturated fat and added sugar intake leads to poorer performance on tests such as the Hopkins Verbal Learning Test (HVLT), a memory test for hippocampal performance (Attuquayefio et al., 2017).

Poor dietary habits and obesity also have a major effect on cognition. Using data across seven years, the 2008 study by Baranowski et al. found that Alzheimer's disease death rates increased nearly twice as much in rural counties compared to urban ones. Rural areas also showed higher rates of obesity and type 2 diabetes, conditions commonly linked to the Western diet, suggesting that dietary patterns may be contributing to the rise in Alzheimer's in these regions (Baranowski et al., 2008). In addition, results from a 2012 trial by Fitzpatrick et al. showed that being obese in midlife increased the risk of dementia, but after age 65, a higher BMI was linked to a lower risk. The highest dementia risk was seen in older adults who were underweight. This suggests that BMI's impact on dementia risk changes as people age. Together, these findings show how diet and body weight across one's lifespan can impact cognition (Fitzpatrick et al., 2012).

Animal research has provided significant evidence that high-fat and processed diets can have damaging effects on brain function and overall metabolic health. In 2019 Crawford et al. fed Sprague-Dawley rats a high-fat diet and found that consumption led to inflammation of the cecum, the release of lipopolysaccharides into the bloodstream, and fat buildup. These effects lead to digestive problems including bloating, pain, and altered bowel movements, and promote an inflammatory immune response, which is linked to chronic diseases such as type 2 diabetes and cardiovascular issues. Their findings indicate that extended intake of a high-fat diet is associated with increases in gram-positive bacteria which negatively impact metabolic health (Crawford et al., 2019).

Inflammation from poor diet can be systemic and affect other organ systems and even the brain. Neuroinflammation is one of the key deleterious neurological problems linked to such diets. A study conducted by Badrah Saeed Alghamdi in 2020 fed rats a high-fat diet to investigate its effects on neuroinflammation. Results showed higher concentrations of pro-inflammatory cytokines, including IL-1β, IL-6, TNF-α, and NF-κB, in the prefrontal cortex. This indicates activation of microglia, the brain's primary immune cells, which release these cytokines during an neuroinflammatory response. Prolonged or excessive activation of the microglia can damage neurons and disrupt normal brain function. Chronic inflammation in the brain also contributes to the formation of amyloid-beta plaques and tau protein tangles, key

features of neurodegenerative diseases like Alzheimer's. In the prefrontal cortex, these changes impair cognition, emotional regulation, and decision-making (Alghamdi, 2020). Additionally, research carried out by Jena et al. in 2018 used wild-type, male mice in order to investigate the effects of a processed foods diet on bile acid function and inflammation. The researchers showed that processed food consumption impaired bile acid production and disabled bile acid signaling in the brain which had a detrimental effect on synaptic plasticity and inflammatory responses throughout the whole body (Jena et al., 2018). Synaptic plasticity is essential for learning and memory. When it is decreased, the brain has difficulty strengthening or modifying the connections between neurons that encode new information. As a result, the brain becomes less capable of adjusting to new situations, solving problems, or recovering from injury or stress.

Beyond structural and cognitive impairments, Western dietary patterns have also been shown to influence oxidative stress and immune activity in the brain. In 2009 Studzinski et al. fed APP × PS1 mice (an Alzheimer's disease genetic model) a short-term Western Diet and noticed an elevation in oxidative stress, independent of amyloid-beta deposition. This implied that other means could be capable of increasing oxidative stress in the brain; oxidative stress activates cellular apoptosis, and leads to neuronal death (Studzinski et al., 2009). Similarly, research carried out by Shaftel et al. in 2007 showed that IL-1β, a molecule increased by the Western diet, can cause long-lasting immune cell buildup in the brain without directly damaging neurons. Their findings suggest that IL-1β plays a key role in ongoing brain inflammation by continuously attracting white blood cells like neutrophils (Shaftel et al., 2007).

Other studies have focused on structural and cognitive impacts. An investigation done by Stranahan et al. in 2009 studied how excessive caloric intake could negatively impact hippocampal structure and function in middle-aged rats. They observed a decrease in dendritic spine density and adverse effects on synaptic plasticity. Dendritic spines are tiny protrusions on neurons where synapses form, and their density is linked to the brain's capacity for learning and memory. A reduction in these structures results in weakened synaptic connectivity and impaired neural communication (Parkins et al., 2023). The decrease in dendritic spines coincided with lower levels of BDNF (brain derived neurotrophic factor), a protein meant to support the health of neurons, which in turn weakened learning abilities. In addition to these cognitive deficits, excessive caloric intake also elevated serum lipids and increased blood sugar levels, suggesting overall metabolic dysfunction systemwide (Stranahan et al., 2009). These kinds of metabolic imbalances are associated with insulin resistance and chronic low-grade inflammation, both of which can further impair brain function**.** In a 2010 study by Kanoski et al., rats maintained on a high-energy diet for 90 days showed impairments in the feature negative (FN) discrimination task, while performance in the feature positive (FN) discrimination task remained unaffected. The feature negative (FN) task tests the ability to inhibit a learned response when a specific cue signals no rewards, relying on hippocampal function. The feature positive (FP) task involves learning when a cue predicts a reward only in the presence of another stimulus and is less dependent on the hippocampus (Kanoski et al., 2010).

Emerging evidence also suggests that the Western diet can compromise the brain's structural defenses, such as the BBB. A report from Kanoski et al. in 2010 found that rats fed a high-energy diet demonstrated a reduced expression of tight junction proteins, specifically Claudin, in both the choroid plexus and BBB. Claudins aid in the selective restriction of substance passage, so this diet is seen to potentially allow harmful substances to penetrate the brain and impair neuronal function.

**fMRI/MRI Evidence**

In a 2019 study by Roelofs et al., researchers examined brain activity in rats before and after sucrose consumption using magnetic resonance imaging (MRIs). Before consumption, both the group allowed to eat freely (ad-libitum fed) and the group with food restriction showed strong brain connectivity, particularly within the frontal cortex. After sucrose tasting, connectivity dropped in both groups. This trend suggests that a common caloric component of the Western diet, sucrose, may have negative cognitive effects (Roelofs et al., 2019). Similarly, in 2016, researcher Chirico and others fed Apolipoprotein E-deficient (ApoE) mice a high-cholesterol diet to observe the occurrence of vascular abnormalities in the brain through MRIs. The imaging revealed vascular sequelae, an effect resulting from blood vessel damage, and iron deposits, possibly from bleeding or cellular activity. In addition, the imaging indicated a bright, enhanced region once gadolinium, a contrast agent, was injected into the bloodstream. Gadolinium's presence in the brain tissue highlighted a leaky, disrupted BBB (Chirico et al., 2016).

Research carried out by Patkar et al. in 2021 utilized positron emission tomography (PET) scans in order to examine the possible effect of sucrose on cognition. In the group of rats consuming a 5% sucrose solution three times a week, the presence of translocator proteins (TSPO) increased in the brain, indicating heightened neuroinflammation and reactive microgliosis, which is the vast activation of microglia (Patkar et al., 2021).

**Gut Microbiome:** The Western diet also has severe implications on the composition and diversity of the gut microbiome. In a 2016 study conducted by Agus et al., one group of mice was fed a high-fat diet over a period of 18 weeks, while another was fed a conventional diet. Results concluded that the group of mice given food rich in fats and sugars had higher levels of fecal Lipocalin-2. Fecal Lipocalin-2 is a protein found in feces, serving as a biomarker for intestinal inflammation and gut dysbiosis, or imbalance in the function of gut bacteria (Agus et al., 2016). Similarly, Turnbaugh et al. discovered fecal changes in mice on the Western diet in 2010. Specifically, the abundance of *Bacteroidetes*, a beneficial gut bacteria, was reduced, implying increased risk of inflammatory bowel disease (IBD) and obesity (Turnbaugh et al., 2010). To add on, multiple trials have revealed significant findings regarding the diversity of various bacterial species. A study performed by Kim et al. in 2012 found that mice that consumed a high-fat diet experienced an increase in *Firmicutes,* efficient in absorbing calories from food, and is known to pose a risk of developing obesity and metabolic disorders. The mice

also faced a decrease in *Bacteroidetes* and *Proteobacteria,* which can contribute to impaired fiber fermentation and reduced short-chain fatty acid production (Kim et al., 2012).

**Mediterranean Diet**

Unlike the Western diet, the Mediterranean diet tends to support cognitive function and protect against neurodegeneration associated with aging. The diet is mainly composed of fruits and vegetables, whole grains, legumes, seeds and nuts, fish, various herbs and spices, olive oil, and red wine. Adherence to the Mediterranean diet has been associated with reductions in Alzheimer's-related biomarkers, including amyloid-beta accumulation and changes in amyloid ratios linked to disease progression. A study conducted by Vassilaki et al. in 2018 found that older adults who followed a Mediterranean-style diet, especially those who ate more vegetables and drank red wine in moderation, had lower levels of beta amyloid plaque in the brain. Higher intake of vitamin A and beta-carotene from food also showed similar trends, but not all were statistically significant (Vassilaki et al., 2018). Additionally, in a 2021 clinical research trial by Hoscheidt et al., the Mediterranean diet lowered amyloid-β40 levels and changed the amyloid ratio in a way that corresponded with a lower risk of developing Alzheimer's. Consumption also increased cerebral perfusion, the process of blood flow through the brain's vasculature, in normal cognition adults. The opposite pattern was observed in consumption of the Western diet (Hoscheidt et al., 2021).

Alongside the context of aging populations, several studies suggest that these components of the Mediterranean diet may directly enhance memory and support the formation of new brain cells. In a study done by Joseph et al. in 2004, aged rats given a blueberry-enriched diet showed a notable increase in the growth of new precursor cells in the dentate gyrus of the hippocampus, an area important for learning and memory, compared to those on a standard diet. This increase was linked to better memory performance, as rats with fewer new cells made more errors in the radial arm water maze (RAWM) task. These results suggest that blueberries may help improve memory in older animals by boosting the growth of new brain cells in the hippocampus (Joseph et al., 2004). Moreover, a 2012 study by Kim et al. showed that the conversion of DHA, a type of omega-3 fat, to DEA was an important process in hippocampal development. DEA promoted neurite outgrowth, synapse formation, and increased the expression of synapsins and glutamate receptors, which are key for synaptic transmission and brain signaling (Kim et al., 2012).

In both clinical and population studies, the Mediterranean diet has been linked to better performance in specific cognitive domains such as language, memory, and spatial awareness. Participants in a study conducted by Berr et al. in 2009 showed lower chances of cognitive decline in visual recall and ease of verbal expression during consumption of olive oil (Berr et al., 2009). Similarly, research carried out by Anastasou et al. in 2017 found that cognitive skill areas including memory, language, frontal lobe functions, and spatial awareness showed a positive relationship with the Mediterranean Diet score, a numerical value that measures how closely a person's diet matches the Mediterranean diet. To assess these cognitive skills, participants completed tests such as the Greek Verbal Learning Test (GVLT) for memory, the Boston Naming

Test (BNT) for language the Trail Making Test for attention and executive function, and the Benton Judgment of Line Orientation Test (BLO) for spatial awareness. The results indicated that individuals with higher Mediterranean Diet scores tended to show better performance in these cognitive domains, suggesting the link between the diet and improved brain health (Anastasou et al. 2017).

Certain lifestyle factors commonly seen in Mediterranean dietary patterns, such as wine consumption, may also contribute to reduced Alzheimer's risk. Findings from 2002 by Truelsen et al. concluded that moderate wine consumption, whether monthly or weekly, was correlated with a lower risk of developing dementia compared to complete avoidance (Truelsen et al., 2002). In addition, in a 2007 clinical trial conducted by Micallef et al., it was found that moderate red wine consumption increased serum antioxidant capacity and decreased plasma malondialdehyde (MDA) in both the young and elderly, protective factors that reduce oxidative stress. These changes indicate that red wine's polyphenols can help shield the brain from oxidative damage, slowing decline (Micallef et al. 2007).

Finally, the Mediterranean diet also supports a healthier gut microbiome, which plays a critical role in influencing brain function indirectly. A study conducted by Hidalgo et al. in 2017 found that hypertensive rats fed a diet enriched in EVOO, a compound found in olive oil, showed three main results. The rats had more beneficial gut bacteria, especially Lactobacilli and clostridia XIVa, along with an overall higher amount of bacterial genetic material. The higher abundance of Clostridia XIVa was linked with lower blood pressure, and vice versa. Finally, the rats fed EVOO had a more diverse mix of gut bacteria compared to those on a standard diet. Increased beneficial gut bacteria like *Lactobacilli* and *Clostridia XIVa* are known to produce short-chain fatty acids (SCFAs), which can reduce inflammation and support the integrity of the BBB, indirectly benefiting brain function.

**fMRI/MRI Evidence**

Various imaging techniques have proved useful in showcasing neurological effects of the Mediterranean diet. In a 2022 clinical trial conducted by Kaplan et al., brain structure volumes of participants were measured by MRI brain scans using hippocampal occupancy volume (HOC). 66% of participants following solely healthy dietary guidelines showed a decrease in HOC, especially prevalent in older adults. However, those following a Mediterranean diet higher in polyphenols and lower in processed meat (Green-MED diet) did not have a significant change in HOC after the 18-month intervention. A 2018 study conducted by Berti et al. utilized Statistical Parametric Mapping (SPMs), a computational analysis method for neuroimaging, to display Aβ deposition in participants with low versus high Mediterranean diet adherence. Results showed higher rates of Aβ deposition in various parts of the brain in participants with lower adherence.

**MIND Diet**

The MIND diet, a combination of the Mediterranean and DASH diets designed to promote brain health, emphasizes foods like leafy greens, berries, nuts, whole grains, fish, and

olive oil, while limiting red meat, butter, and sweets. Long-term adherence to the MIND diet has been linked to both improved cognitive performance and a reduced risk of developing dementia, even with individuals with more prevalent risk factors. For instance, a study carried out by Crom et al. displayed that better adherence to the MIND diet in 1989-1993 was linked to lower dementia risk early on, but the effect faded over time. In contrast, adherence between 2009-2021 was mainly tied to lower risk, although the impact gradually decreased over time. Similarly, in a trial performed by Barnes et al. in 2023, elderly people with a family history of dementia consumed either the MIND diet or a control diet with some caloric restrictions. Results showed that both diets led to better performance in 12 cognitive function tests that spanned five domains (episodic memory, semantic memory, executive function, perceptual speed, and attention).

One of the MIND diet's main features, high vegetable intake, has been linked to slower neurodegeneration. A study conducted by Kang et al. in 2005 discovered that consuming vegetables, specifically green leafy and cruciferous vegetables, was linked to less cognitive decline in aging women. Cognitive function was assessed using six standardized tests, including the Telephone Interview for Cognitive Status (TICS), immediate and delayed recalls of the East Boston Memory Test, category fluency (animal naming), delayed recall of a 10-word list, and digit span backward. A global composite score was calculated by averaging Z-scores from all six tests for participants who completed them. Furthermore**,** an elderly, population-based study conducted by Morris et al. observed that higher intake of vegetables slows down neurodegeneration, specifically with the consumption of green leafy vegetables. Participants completed a food frequency questionnaire and were assessed at baseline, 3-year, and 6-year follow-ups. Cognitive function was evaluated using the average Z-score from four standardized tests: the East Boston Tests of immediate and delayed recall, the Mini-Mental State Examination, and the Symbol Digit Modalities Test. The researchers found that consuming more than 2 vegetable servings per day was comparable to being 5 years younger.

Although the MIND diet incorporates elements of both the DASH (Dietary Approaches to Stop Hypertension) and Mediterranean diets, research suggests it may offer greater protection against neurodegeneration than either diet by themself. In a 2018 investigation by Calil et al., it was found that only the highest level of adherence to the DASH or Mediterranean diets was related to a lower risk of developing Alzheimer's. Because of this, it was concluded that the MIND diet has a greater amount of protection against neurodegeneration than both diets alone. Likewise, a 2018 report by Rainey-Smith et al. looked at how following the Mediterranean diet and eating specific foods affected the buildup of amyloid-beta (Aβ) in the brains of older Australian adults over 36 months. All the participants were cognitively healthy but showed signs of early Aβ buildup linked to Alzheimer's. The results showed that those who followed the Mediterranean diet more closely had slower Aβ accumulation, especially those with higher fruit intake. These findings suggest that sticking to a healthy diet like the Mediterranean diet, or similar diets like the MIND diet, may help protect brain health and slow early changes related to Alzheimer's disease.

Studies have shown that dietary patterns like the MIND diet may help reduce the buildup of Alzheimer's-related biomarkers, specifically amyloid-beta, by influencing both production and clearance. Results of a trial conducted by Barnes et al. in 2023 showed that both the MIND diet and control groups had increased white-matter hypertensive volumes, markers of small vessel disease, and decreased brain volumes, indicative of age-related brain atrophy. In addition, results of a 2009 trial carried out by Nishida et al. found that in Ttpa-/- mice, both brain and blood clearance of amyloid-beta were reduced. Since amyloid-beta production in the brains of Ttpa-/- mice didn't increase, the data suggested that the buildup of Aβ was likely due to problems with its removal rather than its production. As well, in a 2001 study conducted by Yamada et al., daily doses of idebenone and α-tocopherol, the most active form of vitamin E, significantly improved learning and memory problems in rats that had been given a continuous dose of amyloid-beta. The improvements were seen in how quickly the rats learned to find a platform in water maze tests. Together, these studies suggest antioxidants of diets may hinder Alzheimer's pathology by improving amyloid-beta clearance and reducing cognitive decline.

Currently, there is no published research focused on the effects of the MIND diet on BBB integrity, fMRI outcomes, or in animal models. Current works primarily focuses on cognitive performance and risk reduction in human populations, with little evidence other than diet manipulation studies.

**Discussion**

Through a combination of all findings, a relationship was clear between diet and cognitive health, mainly in considering age-related neurodegeneration. While the Western diet is attributed with neuroinflammation, oxidative stress, and poor cognitive function, both the Mediterranean and MIND diets harbor neuroprotective effects that may reduce the risk of developing Alzheimer's and if present, the disease's progression.

As stated previously, the Western diet, with a large presence of saturated fats, sugars, and processed foods, contributes to disturbances in pathology-related body aspects and functions. These include chronic inflammation, disrupted BBB integrity, altered gut microbiota, insulin resistance, and elevated oxidative stress. Animal and human studies have shown that this dietary pattern serves as a detriment to hippocampal-dependent memory and allows for the accumulation of biomarkers such as amyloid-beta plaques and tau tangles. These processes explain cognitive impairments and larger Alzheimer's prevalence in populations that often consume Western components.

Contrastingly, the Mediterranean and MIND diets have been found to improve cognitive performance, reduce Alzheimer's pathology, and reduce its prevalence. These diets are rich in antioxidants, anti-inflammatory ingredients, vitamins, fiber, and omega-3 fatty acids. All of these components have been shown to support the health of the brain by reducing inflammation, promoting synaptic plasticity, enhancing cerebral blood flow, and maintaining the integrity of the BBB, particularly true for the Mediterranean diet. Several clinical and population-based studies show that individuals who closely adhere to the Mediterranean and MIND dietary patterns tend

to perform better on memory and executive function tests. Furthermore, these diets also support a healthy gut microbiome, which has a beneficial impact on the function of the gut-brain axis.

The role of the gut microbiome has proved to be prominent in regards to diet in this review. Diet-related changes in gut microbiome composition can influence inflammation, the absorption of nutrients, the body's immune responses, and the production of neurotransmitters and short-chain fatty acids. The Western diet was found to decrease microbial diversity and increase the abundance of pro-inflammatory substances, while the Mediterranean and MIND diets aided in adding beneficial bacteria such as *Lactobacilli* and *Clostridia XIVa* to the gut's environment. These results suggest that gut health acts as a sort of pathway through which diet and cognitive health hold a connection.

While the evidence of this literature review utilizes strong evidence that links diet and Alzheimer's disease, several limitations exist in current research. The main limitation is that most studies revolving around this topic are observational or correlation, meaning cause-and-effect is not fully feasible. Few of these studies involve random assignment, so this furthers the difficulty of determining the direct impact diet adherence has on cognition. Lastly, because Alzheimer's disease is shaped by a variety of factors, including genetics, environment, and lifestyle, diet alone cannot account for all factors involved in the disease's progression.

**Conclusion**

This paper has explored how dietary patterns influence cognitive health and the progression of neurodegenerative mechanisms, particularly concerning Alzheimer's disease. The contrast between pro-inflammatory and neuroprotective effects in different diets highlights how nutrition can impact neurology through aspects of their nutritional components. Continued research into the connection between diet and neurodegeneration may help shape more targeted, preventative, and personalized dietary strategies to support cognitive aging.

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**Maintaining the Ad Valorem Tobacco Tax in the United Kingdom: Estimating the Additional Number of Smokers Who Would Have Quit**

**By Oliver Litchfield & Mentored By Samir Soneji**

**Abstract**

In the United Kingdom (UK), tobacco is taxed in three parts: first a tax per pack, then an ad valorem tax, and finally a value added tax (VAT). In 2011, the ad valorem tax for tobacco decreased from 24% to 16.5%. In this study we calculated the number of additional smokers who would have quit smoking if the ad valorem tax had remained at the 2011 rate of 24% instead of decreasing to 16.5% or if the ad valorem tax was raised back to 24% from 16.5% in one of the years after 2011. We utilized UK census data, smoking prevalence data, tobacco taxation and pricing data, and published prevalence elasticity studies. To calculate the additional number of cigarette smokers who would have quit in a given year, we developed a stochastic simulation model based on these parameters. In 2011, we estimated an additional 60,500 (95% confidence interval [CI]: 7,700 to 113,300) smokers who would have quit had the ad valorem tax rate remained at 24%. This additional number of smokers who would have quit peaked in 2012: 62,400 (95% CI: 8,300 to 115,200). It then would have subsequently decreased. By 2023, we estimated an additional 23,000 (95% CI: 3,100 to 42,400) smokers would have quit. The results highlight the importance of tax in decreasing cigarette consumption and consequently lowering smoking prevalence and, ultimately, the burden of smoking-related disease.

**1. Introduction**

Smoking prevalence in the United Kingdom (UK)— a nation consisting of England, Scotland, Wales, and Northern Ireland (1) — decreased from 45.6% in 1974 to 14.5% in 2020 for all persons aged 16 or older (2). This decrease in the prevalence resulted from public health efforts (e.g., warning labels on cigarette packs, bans on tobacco advertising), the growing awareness of the health effects of smoking, and government regulation through taxation (3). In this paper, we focus on government regulation through taxation and its impact on smoking prevalence.

The law of demand states that there is an inverse relationship between the price of a good and the quantity demanded of that good (4). The price elasticity of demand measures how responsive the consumption of a good is to a change in the price of that good. It is calculated by dividing the percent change in quantity demanded by the percent change in price (4). The price elasticity of prevalence for cigarettes indicates the percent reduction in the number of smokers due to an increase in price. Farrelly and Bray and Pryce et al. each calculated the price elasticity of prevalence for cigarettes to be -0.15 and -0.169 respectively (5, 6). Knowing the prevalence elasticity helps us calculate the relationship between an increase in the UK tobacco tax and smoking prevalence.

In the UK, tobacco is taxed in three parts (7). First, a tax per pack is added to the pre-tax price. Next, an ad valorem tax is added. Lastly, a value added tax (VAT) is added. In 2011, the ad

valorem tax for cigarettes decreased from 24% to 16.5% (8). This reduction in the ad valorem tax was accompanied by an increase in the tax per pack. The UK government reduced the ad valorem tax and increased the tax per pack to narrow the gap between the post tax price for all cigarettes of different prices, making the difference in the price between cheap and expensive cigarettes smaller (9).

Cigarette smoking has substantial negative impacts on physical health, mental health, and financial health. Smoking cigarettes is the leading cause of lung cancer, responsible for over 70% of incident cases (10). Smoking also increases risks of dementia, rheumatoid arthritis, heartburn, and other medical issues (11). While smoking is commonly thought to relieve stress—and while it does in the short term—in the long term smoking can actually increase anxiety (12). Furthermore, smokers incur a large financial burden from smoking (11). To mitigate these harmful effects, what if the price of a pack of cigarettes was increased through an increase in taxation?

We do not know the impact on cigarette smoking prevalence if the ad valorem tax had not dropped to 16.5% and instead remained at 24%. Specifically, we do not know how many additional smokers would have quit smoking in a given year because of the higher prices of a pack of cigarettes through the higher ad valorem tax (i.e., 24%).

This study addresses this public health question by developing a stochastic simulation model that varies the prevalence elasticity based on published literature and estimates the number of additional smokers who would have quit smoking if the ad valorem tax had remained at the 2011 rate of 24% instead of decreasing to 16.5% or if the ad valorem tax was raised back to 24% from 16.5% in one of the years after 2011. This study provides timely empirically-based results to UK policy makers and public health officials.

## 2. Methods

**2.1 Data.** Our study utilizes demographic, smoking, economic, and taxation data (Table 1 of Appendix). First, we collected total population counts for the United Kingdom from the Human Mortality Database between 1977 and 2023. Second, we collected annual smoking prevalence from the Office for National Statistics between 1974 and 2023. Third, we collected the Consumer Price Index (CPI) from the Office for National Statistics between 1988 and 2025. Fourth, we collected the average price per pack of cigarettes from the Office of National Statistics between 1987 and 2025. Fifth, we ascertained the prevalence elasticity from published studies. Finally, we collected the value added tax (VAT), ad valorem tax rate, and tax per pack from GOV.UK between 1978 and 2024.

**2.2 Statistical Analysis.** First, we calculated the total number of smokers in the UK per year as the product of the population count and smoking prevalence. Second, we linearly interpolated the ad valorem, VAT, and tax per pack for any missing years. Third, we assumed a normal distribution for prevalence elasticity with a mean of -0.16 and standard deviation of 0.07

based on empirical studies (5, 6). Fourth, we inflation-adjusted the average price per pack of cigarettes. Fifth, we calculated the following quantities: [a] the net price in inflation-adjusted pounds less the VAT, less the tax per pack, and less the ad valorem tax rate and [b] the counterfactual price in inflation-adjusted pounds, which equaled the sum of [a] and the tax per pack and the product of [a], the ad valorem rate of 24%, and 1 plus the VAT. Sixth, we calculated the percent change in price between the counterfactual inflation-adjusted price and the observed inflation-adjusted price. Seventh, we estimated the percent change in smoking prevalence as the product of this percent change in the price and the prevalence elasticity. Finally, we randomly drew from the distribution of prevalence elasticity N=10,000 times to calculate a distribution of the percent change in smoking prevalence and resulting number of additional cigarette smokers who would have quit in a given year had the ad valorem tax rate been 24% (See Table 2 of Appendix for further details on the calculation).

## 3. Results

**3.1 Smoking Prevalence & Ad Valorem Tax Rate Over Time.** In the UK, smoking prevalence decreased from 40.2% in 1978 to 11.9% 2023 (Figure 1). In 1978, the ad valorem tax rate equaled 30%. It remained at 21% between 1978 and 1992. In 1993, the rate decreased to 20% in 1993 and eventually increased to 24% in 2009. Finally, in 2011, it decreased to 16.5%.

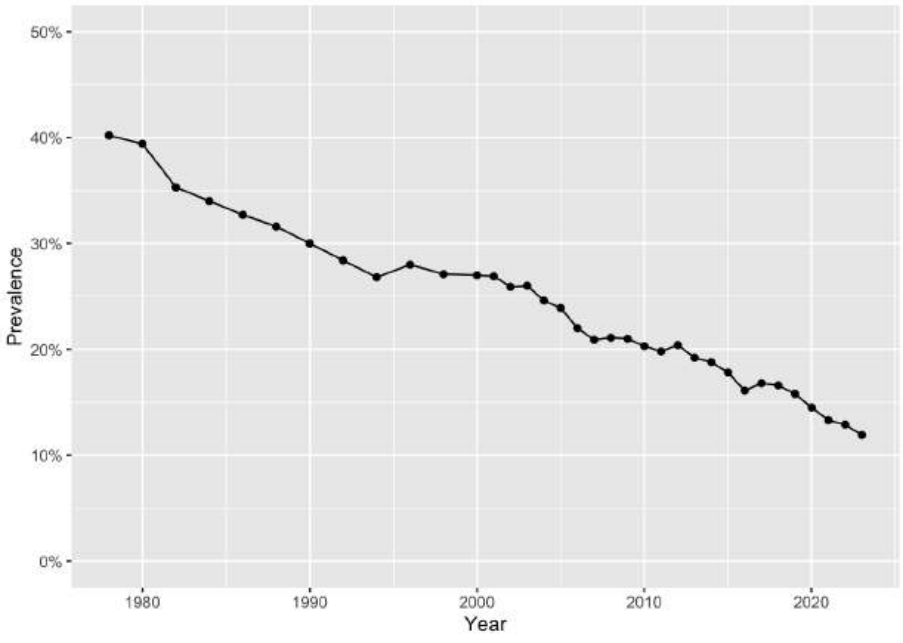



Fig 1: Smoking Prevalence in the UK, 1978–2023

**3.2 Counterfactual Number of Additional Smokers Who Quit.** We estimated an additional 60,500 (95% confidence interval [CI]: 7,700 to 113,300) smokers who would have

quit had the ad valorem tax rate remained at 24% in 2011 (Figure 2). This additional number of smokers who would have quit peaked in 2012: 62,400 (95% CI: 8,300 to 115,200). It then subsequently decreased. If the ad valorem was raised to 24% in 2023, we estimated an additional 23,000 (95% CI: 3,100 to 42,400) smokers would have quit.

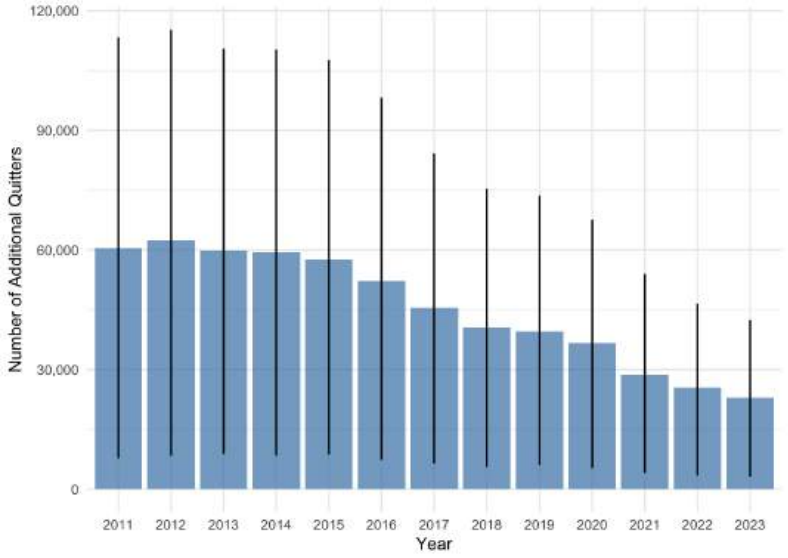



Fig 2: Number of Additional Quitters in a Given Year and 95% Confidence Intervals (Thousands), 2011-2023

**3.3 Observed & Counterfactual Number of Smokers.** If the ad valorem tax rate had remained at 24% in 2011, we estimated the total number of smokers in the UK in 2011 would have decreased from 9.82 million to 9.76 million (95% CI: 9.70 to 9.81 million). Likewise, if the ad valorem tax was raised to 24% in 2023, we estimated the total number of smokers in 2023 would have decreased from 6.42 million to 6.39 million (95% CI: 6.37 to 6.41 million).

## 4. Discussion

In this study, we reached two central findings. First, if the ad valorem tax had remained at 24% after 2011, instead of decreasing to 16.5%, an additional 45,000 additional smokers in the UK would have quit per year on average between 1998 and 2023. Second, the impetus of the reduction in the ad valorem tax—to narrow the post tax price gap between cheaper and more expensive cigarette brands—led to an unintended public health consequence.

Overall, taxation is an effective way to decrease cigarette consumption. A study by Chaloupka et al. revealed how tobacco excise taxes are a successful way to decrease cigarette consumption, and that it is most effective for the elderly and poor (13). Additionally, Gardner et al. concluded that 47% of current smokers from an English household survey said that they would support a 20 pence increase of the price of a pack of cigarettes if the revenue went to tobacco control funds (14). Similarly to our study, Goodchild et al. calculated that if the excise tax for cigarettes were to be raised by 1 international dollar per 20-cigarette pack then the daily smoking prevalence for adults would drop by 9% resulting in 66 million fewer smokers

worldwide in 2014 (15). There are also other methods to attempt to reduce cigarette consumption. A study by Breton et al. investigates the effectiveness of the UK's implementation of plain packaging for cigarette packaging. They found out that despite increasing the price of cigarettes, there was no significant drop in sales (16).

In 2025-2026, it is estimated that the UK Government will collect £8.1 billion pounds from tobacco duties (7). Decreasing the ad valorem tax from 24% to 16.5 % while increasing the specific £ per 1,000 sticks tax was favorable to expensive cigarette producers (9). This is because now their products are less expensive to consumers relative to cheaper cigarettes because the specific £ per 1,000 taxes are the same for everyone, while ad valorem taxes are higher the more expensive the cigarette (9).

We note several strengths in this national-based study. We used prevalence elasticities from published studies and drew from the range of calculated elasticities. We also note a key limitation, too. We could not assume that each additional cigarette smoker who quit would maintain quitting and not return to smoking at a later time.

In conclusion, while the intention for decreasing the ad valorem tax in 2011 for tobacco from 24% to 16.5% was to narrow the price gap between less and more expensive cigarettes, this policy change may have unintentionally led to fewer cigarette smokers quitting. This study contributes to our knowledge of the effectiveness of taxes in reducing cigarette consumption through the use of a real world example. The results highlight the importance of tax in decreasing cigarette consumption and consequently lowering smoking prevalence and, ultimately, the burden of smoking-related disease.

## 5. Appendix

| Category | Quantity | Years | Source |
|---|---|---|---|
| Population | Total UK Population | 1977 to 2023 | (17) |
| Smoking Prevalence | Annual UK Smoking Prevalence for all people aged 16+ (1974-2020) and all people aged 18+ (2021-2023) | 1974 to 2023 | 1974-2020 (2)<br>2021 (18)<br>2022 (19)<br>2023 (20) |
| CPI | CPI Index, base year=100 | 1988 to 2025 | (21) |
| Average Price Per Pack of Cigarettes | Average price of cigarettes 20 king-size filter | 1987 to 2025 | (22) |
| Prevalence Elasticity | Two Prevalence Elasticites | 1998 and 2023 | (5)<br>(6) |
| Taxes for tobacco in the UK | Value Added Tax (VAT), ad valorem tax, and tax per pack | 1978 to 2024 | (8) |

Table 1: Data Sources of Parameters

| Category | Variable | Value |
|---|---|---|
| Tax (Actual) | Ad Valorem Tax | 16.5% |
| | Tax Per Pack | £3.099 |
| | Valued Added Tax (VAT) | 20% |
| Net Price (Actual) | Net Price | £9.35 |
| | Net Price - VAT | £7.79 |
| | Net Price - VAT - Tax Per Pack | £4.69 |
| | Net Price - VAT - Tax Per Pack - Ad Valorem | £4.03 |
| Counterfactual | Ad Valorem | 24% |
| | Net Price | £9.71 |
| Additional Quitters Calculation | % Change in Price | 3.88% |
| | Prevalence Elasticity | -0.16 |
| | % Change in smoking prevalence | -0.62% |
| | Additional Quitters | 61,442 |

Table 2: Example Calculation: 2011

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**Beyond Stereotypes: An Ethnographic Study of Yi Traditional Food Culture By Joy Liang**

**Abstract**

This ethnographic study examines Yi traditional food culture in the Cliff Village of Daliang Mountain, Sichuan, China, challenging external stereotypes of ethnic minority practices as "uncivilized." Through ten days of participant observation and in-depth interviews with Yi community members, cultural inheritors, and elders, this research applies theories of symbolic anthropology and structural functionalism to analyze Yi food culture across three dimensions: institutional norms, symbolic meanings, and cultural inheritance. Findings reveal that Yi food practices embody sophisticated social systems, profound spiritual meanings, and remarkable cultural resilience. The institutional analysis demonstrates how food-related rituals maintain social order and relationships through material symbols. The symbolic analysis illustrates how animals serve as sacred mediums connecting humans with ancestors, nature, and faith. The cultural inheritance analysis shows Yi people's selective adaptation strategy, preserving core cultural elements while flexibly integrating modern influences. These findings challenge simplistic characterizations of minority cultures and offer insights into how traditional cultures can adapt to modernization while maintaining cultural integrity.

**Keywords**

Yi culture, food anthropology, symbolic anthropology, structural functionalism, cultural inheritance, ethnic minorities

**Introduction**

In a Yi family home in the Cliff Village of Daliang Mountain, Sichuan, China, I witnessed for the first time the traditional process of making tuotuo meat and shared a meal with the host family. When I observed the family sitting on the ground, eating with their hands, and casually discarding gnawed bones onto the floor, I experienced an instinctive sense of cultural shock and discomfort as a city dweller accustomed to dining tables and utensils. As a Han researcher who has lived in urban areas since childhood, I could not prevent the automatic formation of judgments in my mind—that the Yi people's eating practices appeared uncivilized and unrefined. However, during the following ten days of fieldwork, through deep engagement with the local Yi community, cultural inheritors, and elders knowledgeable about traditional food culture, I discovered that once I moved beyond this biased first impression and examined their culture more carefully, what initially seemed "uncivilized" was actually deeply rooted in Yi cultural heritage, embodying rituals and values passed down through generations.

This paper employs participant observation and in-depth interviews to apply theories of symbolic anthropology and structural functionalism in analyzing how the seemingly "rough and casual" Yi traditional food culture actually manifests profound ethnic cultural significance. The analysis proceeds through three dimensions: institutional norms, symbolic meanings, and cultural inheritance, demonstrating that Yi food practices are far more sophisticated and meaningful than external stereotypes suggest.



Fig 1: Yi people sharing baked potato on the floor

**Institutional Norms and Social Order**

The selection of dishes, dining standards, and distribution rules in Yi traditional food culture all reflect meticulous social systems and regulations, demonstrating that Yi culture is fundamentally different from what superficial observations might suggest. When hosting guests, the Yi determine dishes and banquet scale based on the visitor's identity and social relationship with the host. Different occasions—from weddings and funerals to neighborhood gatherings—require carefully corresponding preparations. When I inquired about specific institutional norms, Amo, a villager in the Cliff village, explained, "Yi people are very respectful in our hospitality. The larger and more numerous the animals used to accommodate guests, the more it demonstrates the host's respect. For major events like weddings and funerals, we slaughter cattle or pigs. For ordinary gatherings, we usually prepare chickens, at most sheep."

From the perspective of structural functionalism (Lumen Learning, n.d.), such explicit social norms not only provide individuals with clear understanding of their relationship with others and society as a whole, but also reflect a core characteristic of Yi society: maintaining social relationships and order through material symbols. The scale of a meal represents social status, interpersonal relationships, attitudes toward specific events, and broader social and cultural values (State Ethnic Affairs Commission, n.d.). Through repeated practice in daily life, these rituals continuously reinforce each member's understanding and adherence to behavioral norms. Every act of hospitality conducted according to established norms reaffirms existing social relationships and emphasizes Yi social structure. This repeated reinforcement significantly ensures the stability of Yi social structure's transmission across generations. What might appear as simple etiquette actually plays a crucial role in ensuring cultural transmission and social order, thus reflecting the profound connection between ritual, food, and societal stability.



Fig 2: Yi people sharing steamed buckwheat cakes

**Symbolic Meanings and Spiritual Significance**

In Yi culture, food functions as a medium for expressing ancestor worship, predicting fortune and misfortune, and transmitting cultural identity (Banyuetan, 2013). Animals in particular do not merely serve as food sources but constitute an indispensable component of Yi cultural and spiritual life. Yi tradition requires that many special occasions must be observed with great ritual significance according to customary practices. The New Year and weddings or funerals represent the most common examples. Whether celebrating the New Year or before a couple's marriage, rituals must be performed to predict whether coming days will be auspicious or inauspicious. In these rituals, villagers slaughter a pig and observe the color and shape of its liver and pancreas. According to

The Collection of Five Ethnic Issues—Chinese Minorities (2008), "If the gallbladder is clear yellow and the pancreas large and straight, it is auspicious; if the pancreas is curled, it is inauspicious, meaning the match cannot proceed" (as cited in State Ethnic Affairs Commission, n.d.). After the ritual, the pig's kidneys, liver, pancreas, and tongue must first be cooked and offered to ancestors before the pork can be consumed (Li, 2013). In the Yi worldview, this pig determines the harvest of the coming year and even the future of marriages.

From the perspective of symbolic anthropology, this ritual illustrates the multifaceted role of food in Yi culture. People use the pig to predict future fortune, indicating that the Yi believe the pig carries an important function beyond being mere sustenance: it serves as a medium connecting humans with nature and the divine. Through this expression of respect for the past and expectations for the future, the ritual sustains people's motivation for life, allowing them to maintain hope for the coming year while respecting behavioral norms and preserving traditions. Not only pigs, but also cattle, sheep, and chickens—though eventually consumed as food—are considered sacred in Yi culture, serving as vital carriers of cultural and spiritual heritage.

For instance, specific cooking and distribution rules govern chicken preparation: similar to pigs, after slaughtering, the bimo (priest in Yi culture) must first divine using the chicken's head, comb, and tongue. If the divination result proves favorable, the chicken will be consumed; if not, it cannot be eaten. Moreover, because meat was historically precious, a chicken's two wings had to be offered specifically—one to the bimo who communicates with the gods, another to the host. Whether treating the chicken as a sacred animal capable of divination or demonstrating significant respect and trust toward the bimo, these customs fully demonstrate the deep symbolic meaning of food in Yi culture. These food traditions carrying profound cultural significance now face dual challenges of preservation and transformation in contemporary society.



Fig 3: Yi people roasting chicken carefully following traditional procedures

**Cultural Inheritance and Adaptive Resilience**

Under the impact of social modernization, Yi traditional food culture demonstrates a capacity for selective adaptation: it retains core cultural elements while flexibly integrating modern influences into daily life, reflecting the ethnic group's strong cultural resilience and spiritual vitality (China National Geographic, n.d.). First, many important Yi traditional festivals and customs remain completely preserved and transmitted. The grandest celebrations, such as the Torch Festival and the Yi New Year, still strictly follow traditional norms, including hospitality standards, food preparation rules, and distribution systems mentioned previously (Banyuetan, 2013). The fact that such detailed traditional customs continue to be comprehensively and rigorously practiced indicates that Yi society still maintains its characteristic of transmitting culture and preserving social structure through emphasis on social rules. The ongoing execution of these ritual practices demonstrates that the Yi continue to uphold respect for food, ancestors, and deities.

However, the Yi people's preservation of traditional culture is selective, as many Yi families are gradually embracing certain influences from modern society. Unlike the traditional Yi food culture which emphasizes the pure, natural flavor of ingredients, Yi families living closer to towns and cities now purchase basic seasonings such as soy sauce and salt to enhance food

taste. During visits to Yi households in less remote areas of Daliang Mountain, I observed that modern processed foods—including bread, beverages, and ice pops—had also become part of daily consumption. In interviews, a young Yi man named Xiao Wu, who works in Xichang City, explained that even though he has become accustomed to eating oily and salty food in the city, during the New Year or festivals he must return home to eat according to traditional dietary norms and cannot break food customs due to modern tastes.

This selective transformation reveals the essence of Yi cultural adaptability: distinguishing between the "core" and the "form"—strictly preserving rituals and traditional norms with deep cultural significance while allowing behavioral forms in daily life to flexibly adapt to modernization. This balance between "preserving tradition" and "adapting to modernity" not only protects the valuable cultural characteristics of the Yi as an ethnic minority but also facilitates cultural transmission to a considerable extent while keeping Yi society connected to contemporary life, enabling younger generations to integrate into modern society. Therefore, the Yi's strong resilience allows them to maintain their core culture while autonomously choosing methods to adapt to modernization, providing valuable reference for the cultural preservation of other ethnic minorities.

**Conclusion**

Through in-depth field research, this study finds that Yi society and its traditional food culture are entirely different from external stereotypical judgments of being "rough and uncivilized." Instead, they present a highly intricate and meaningful cultural system. At the institutional level, the Yi use food to symbolize social relationships and reinforce social and cultural stability through repeated ritual practice. At the symbolic level, the Yi regard food as a sacred medium connecting ancestors, nature, and the divine, preserving food traditions with profound cultural meanings. At the cultural inheritance level, the Yi demonstrate remarkable cultural resilience by balancing selective adaptation between tradition and modernization.

These findings not only challenge external stereotypes of ethnic minority cultures but also, by revealing possibilities for traditional culture's adaptation to modernization, provide valuable insights for the inheritance and protection of other ethnic minority cultures. Due to time and geographic limitations, this study was unable to investigate deeply the views of different age groups within the Yi community regarding current methods of cultural inheritance, which represents an important direction for future research. Additionally, comparative studies with other ethnic minorities' food cultures could further illuminate patterns of cultural adaptation and resilience in modernizing contexts.

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**The Influence of Steroid Hormones on Breast Cancer Progression By Yiyun (Athena) Cai**

## Introduction

Breast cancer is the second most common cancer worldwide and the most common cancer in women, remaining a leading cause of cancer-related deaths (Łukasiewicz et al., 2021; Wilkinson & Gathani, 2022). Despite major advances in research, diagnosis, and treatment, breast cancer continues to pose a significant global health challenge.

Historically, breast cancer was classified based on histopathological features, separating cases into invasive ductal carcinoma (IDC) and invasive lobular carcinoma (ILC). While this system helps identify tumour origin, it does not fully explain how tumours behave or which treatments they respond to. For this reason, breast cancer is now more commonly classified using molecular characteristics, leading to four major subtypes: Luminal A, Luminal B, HER2-enriched, and Basal-like breast cancer, also known as Triple-Negative Breast Cancer (TNBC). Luminal A and Luminal B tumours are both hormone-sensitive, meaning they express high levels of estrogen receptors (ER). Luminal A tumours tend to grow more slowly and are considered less aggressive, whereas Luminal B tumours show higher proliferation rates. HER2-enriched breast cancers lack hormone receptors but overexpress the HER2 protein, which drives rapid tumour growth. TNBC is defined by the absence of ER, PR, and HER2, making it the most difficult subtype to treat because it does not respond to hormone- or HER2-targeted therapies (Akram et al., 2017; Tsang & Tse, 2020).

A variety of clinical treatments are currently used to manage breast cancer, and while no single therapy guarantees complete elimination of cancer cells, these approaches aim to slow tumour growth, kill cancer cells, and prevent metastasis. Standard treatments include surgery, chemotherapy, radiation therapy, hormone therapy, and targeted therapy. Surgery is usually the first option for localized breast cancer and involves removing the tumour and nearby lymph nodes. Chemotherapy uses cytotoxic drugs to kill fast-dividing cells and is commonly used for aggressive subtypes such as TNBC. Radiation therapy uses high-energy rays to shrink tumours or prevent further growth. Hormone therapy works by blocking hormones from binding to their receptors, preventing cancer cells from receiving growth signals, highlighting the importance of steroid hormones in breast cancer biology. Targeted therapies differ from chemotherapy by acting on specific molecular pathways unique to cancer cells, making treatment more precise (Maughan et al., 2010; Xiong et al., 2025).

## Roles of Hormones in Breast Cancer and Their Clinical Applications

### Estrogen

As mentioned earlier, breast cancer growth can be strongly influenced by steroid hormones such as estrogen and androgens. Estrogen is primarily produced in the ovaries, with smaller amounts synthesized in the adrenal glands. It plays an essential role in regulating the female reproductive cycle and secondary sexual characteristics. In the context of breast cancer,

estrogen can stimulate the growth of hormone-sensitive tumors, especially Luminal A and Luminal B subtypes. These tumors express estrogen receptors (ERα and ERβ), which are proteins located inside the cell that activate gene expression when estrogen binds to them. This binding initiates estrogen-driven signaling pathways that promote cell growth and division, making ER signaling a major driver of proliferation in these cancers (Kim & Munster, 2025).

A key enzyme involved in estrogen production is aromatase, which converts androgens into estrogen. After menopause, the ovaries stop producing estrogen, so aromatase activity, mainly in adipose tissue, becomes the primary source of estrogen in the body. Because estrogen strongly influences breast cancer growth, aromatase inhibitors are commonly used in postmenopausal women to block estrogen synthesis and slow tumor progression. Another major class of endocrine therapy consists of selective estrogen receptor modulators (SERMs), such as tamoxifen. SERMs bind to estrogen receptors and prevent estrogen from activating them, reducing tumor growth signals. Tamoxifen is widely used in both premenopausal and postmenopausal patients and helps lower the risk of recurrence. Overall, therapies that target estrogen production or ER activation are essential in managing hormone-sensitive breast cancers and significantly improve patient outcomes (Clusan et al., 2023; Kwa et al., 2016).

**Androgen**

Androgens, including testosterone and dihydrotestosterone (DHT), are steroid hormones responsible for male reproductive and secondary sex characteristics. In females, they are produced mainly in the adrenal glands and ovaries. Similar to estrogen binding ER, androgens bind to the androgen receptor (AR), which regulates gene expression when activated. In ER-positive breast cancers, AR activation can sometimes counteract estrogen-driven proliferation. In these cases, androgens may act in a protective or inhibitory manner by reducing the tumor-promoting effects of estrogen (Kono et al., 2017).

However, the role of AR changes dramatically in AR-positive TNBC. Because TNBC lacks ER, PR, and HER2, these tumors do not respond to typical hormone therapies. In this subtype, AR signaling often becomes pro-tumorigenic, actively promoting growth and progression. This makes AR-positive TNBC more aggressive and harder to treat. As a result, researchers are increasingly interested in AR-targeted therapies. Drugs such as enzalutamide, which blocks AR activation, and abiraterone, which inhibits androgen synthesis by targeting CYP17, are being explored for their potential to treat AR-positive breast cancers. Although originally developed for prostate cancer, these drugs represent promising targeted approaches for managing breast tumors that rely on androgen signaling (Bleach & McIlroy, 2018; Kolyvas et al., 2022).

**Progesterone**

Progesterone is another important steroid hormone in breast cancer biology and plays a major role in regulating the menstrual cycle. Like estrogen and androgen, progesterone binds to its corresponding receptor, the progesterone receptor (PR). However, PR activation has a more complex and sometimes contradictory role in breast cancer. Depending on the biological context,

progesterone signaling can either support or suppress estrogen-driven tumor growth. In some cases, PR activation promotes cell proliferation, while in others, it appears to inhibit estrogen-mediated pathways (Horwitz, 1987).

Clinically, PR status is an important prognostic marker. Tumors that are positive for both ER and PR tend to respond more effectively to endocrine therapies such as tamoxifen or aromatase inhibitors. As a result, PR expression is routinely used to help guide treatment decisions. Despite its importance, the detailed mechanisms underlying progesterone's dual role in tumor progression and its influence on treatment response remain unclear. More research is needed to fully understand how PR signaling contributes to breast cancer development and how it might be targeted therapeutically (Li et al., 2022; Trinca et al., 2018).

Because different breast cancer subtypes rely on distinct molecular pathways, understanding how specific hormones influence cancer cell behavior is important for both basic biology and potential therapeutic applications. Hormone-sensitive cancers, such as Luminal A (e.g., MCF7 cells), depend heavily on estrogen signaling for growth, while triple-negative cancers (e.g., MDA-MB-231 cells) lack these receptors and must rely on alternative pathways for survival. However, hormones other than estrogen, such as androgens, glucocorticoids, and adrenal precursors like DHEA, may still affect cancer cells through different receptors and signaling networks. Studying how these hormones change cell proliferation and key signaling pathways can provide insight into why certain breast cancer subtypes respond well to hormone-based therapies while others do not. Therefore, the goal of this study was to examine how estradiol, DHT, cortisol, and DHEA influence proliferation and signaling protein expression in two breast cancer cell lines with distinct receptor profiles: MCF7 (hormone-sensitive) and MDA-MB-231 (triple-negative).

**Methods**

For this experiment, several steroid hormones were used to treat breast cancer cells, and their biological functions are summarized below.

Estrogen, specifically estradiol, is a major female sex hormone responsible for regulating reproductive tissues and secondary sexual characteristics. Estradiol is especially important in breast cancer biology because it binds to estrogen receptors (ERα and ERβ). Once activated, these receptors act as transcription factors that activate genes involved in cell growth, proliferation, and survival. Because ER activation can lead to increased cell division and tumor progression, understanding how estrogen influences proliferation is essential (Miziak et al., 2023).

Cortisol is not a sex hormone but is still relevant in this study due to its strong effects on cell metabolism and stress responses. Cortisol is a glucocorticoid hormone produced in the adrenal cortex, and it binds to glucocorticoid receptors (GR). GR activation regulates immune function, metabolism, and the cellular response to stress. In cancer cells, cortisol signaling can influence survival pathways, making it important to investigate in the context of breast cancer behavior (Posani et al., 2024).

Androgens, such as DHT, were also examined. DHT is a potent male sex hormone derived from testosterone and is responsible for male secondary sexual characteristics. DHT binds to the AR, which then activates genes involved in cell growth and differentiation. In AR-positive breast cancer cells, DHT stimulation can enhance cell proliferation, making androgen signaling another important pathway to evaluate (Lin et al., 2009).

Lastly, DHEA (dehydroepiandrosterone) is a precursor hormone produced by the adrenal glands. It can be converted into active estrogens or androgens, allowing it to indirectly influence hormone signaling pathways. Although DHEA has weaker direct activity compared to other hormones, its ability to convert into ER- or AR-binding hormones means it may still affect cell signaling, growth, and proliferation (Holst et al., 2004; Lin et al., 2025).

**Cell culture and cell treatment**

Breast cancer cell lines MCF7 (Luminal A) and MDA-MB-231 (Triple-Negative Breast Cancer), obtained from the American Type Culture Collection (ATCC), were cultured in Dulbecco's Modified Eagle Medium (DMEM) supplemented with 10% fetal bovine serum (FBS) and 1% Penicillin–Streptomycin. Cells were maintained in a 37°C incubator with controlled humidity and $CO_2$ to support optimal growth.

For hormone treatment experiments, cells were seeded into appropriate culture plates and allowed to adhere overnight. The medium was then replaced with fresh DMEM containing 10% FBS, and cells were treated with 1 μM of each hormone: estradiol, DHT, cortisol, or DHEA. Dimethyl sulfoxide (DMSO), the solvent used to dissolve the hormones, served as the vehicle control. Treatments were performed for varying durations (3 hours, 4 hours, 3 days, or 4 days) depending on the experimental requirement. After treatment, cells were processed for either proliferation assays or protein expression analysis.

**Cell proliferation assay**

To quantify the effects of hormone treatment on cell growth, a crystal violet staining assay was performed (Feoktistova et al., 2016). Cells were cultured in 96-well plates and, following treatment, washed twice with phosphate-buffered saline (PBS). They were then fixed with 50 μL of methanol for 20 minutes. After removal of the fixative, 50 μL of crystal violet solution was added to each well and allowed to stain the cells for 20 minutes. Excess stain was removed, and the wells were gently washed with PBS to eliminate residual dye (handled with caution due to the toxicity of crystal violet).

To quantify cell proliferation, the crystal violet retained in the cells was solubilized with methanol. Absorbance was measured using a microplate reader, and higher absorbance values indicated higher cell numbers. The resulting measurements were analyzed to determine how each hormone affected proliferation across the two breast cancer cell lines.

**Western Blots**

Western blotting was used to examine changes in protein expression following hormone treatment. After the designated treatment period, cells were washed with PBS and lysed in an ice-cold RIPA buffer containing protease and phosphatase inhibitors. Lysates were collected, centrifuged to remove debris, and the supernatant containing total protein was mixed with Laemmli sample buffer.

A total of 20 μL of protein per condition was loaded onto SDS-PAGE gels for electrophoresis, using molecular weight markers as references. Gels were run at 90 V for approximately 90 minutes. After separation, proteins were transferred onto PVDF membranes at 82 V for 60 minutes. Membranes were then blocked overnight in a blocking buffer to prevent non-specific antibody binding.

Following blocking, membranes were cut to appropriate sizes and incubated with primary antibodies. The following antibodies (from Cell Signaling Technology) were used: vinculin (loading control), phospho-AKT (P-AKT), phospho-ERK (P-ERK), phospho-S6 (P-S6), SOD2, and AR. After primary antibody incubation, membranes were washed three times with TBST, followed by incubation with HRP-conjugated secondary antibodies for 1 hour. Membranes were again washed three times with TBST before imaging.

Protein bands were visualized and quantified using the LI-COR Odyssey CLx Imaging System. Band intensities were normalized to the control lane on each membrane, and the normalized values are reported below the corresponding blots.

## Results

### Estradiol Strongly Promotes Proliferation in ER-Positive MCF7 Cells but Not in Triple-Negative MDA-MB-231 Cells

To study how different hormones affect breast cancer cell growth, I used two cell lines: MCF7 and MDA-MB-231. MCF7 cells belong to the luminal A subtype, which expresses estrogen (ER) and progesterone (PR) receptors. Because they have these receptors, they are expected to respond to hormones like estradiol. In contrast, MDA-MB-231 cells are a triple-negative breast cancer (TNBC) subtype. They do not express ER, PR, or HER2, which means they usually do not respond to most hormone treatments and are generally harder to treat. In my experiment, DMSO (the solvent) was used as the control, and the treatment groups included estradiol, DHT, cortisol, and DHEA.

After 3 days of treatment, MCF7 cells showed a strong increase in growth when treated with estradiol. Their absorbance values were more than twice as high as the DMSO control, showing that estrogen greatly boosted their proliferation. DHT caused only a small increase, while cortisol and DHEA did not noticeably change cell growth compared with the control (Figure 1A).

By day 4, the absorbance levels slightly decreased in all groups, but estradiol continued to show a clear growth-promoting effect, reaching about 150% of the control. DHT still

produced a mild increase, and cortisol and DHEA again showed little to no change. Overall, estradiol consistently promoted the strongest growth in MCF7 cells (Figure 1B).

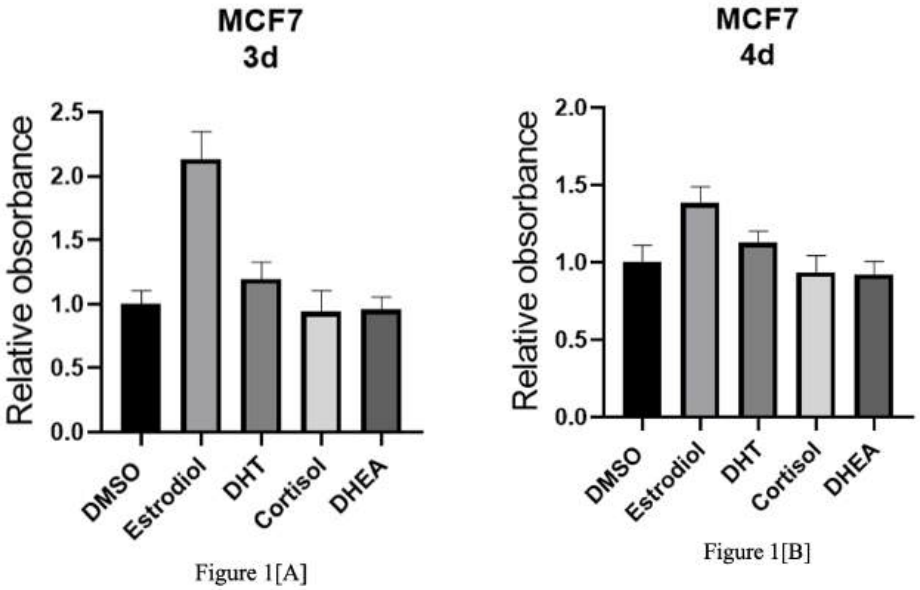



Figure 1 Effect of Steroid Hormone Treatment on MCF7 Cell Proliferation

**A.** Relative absorbance of MCF-7 breast cancer cells after 3 days of steroid hormone treatment. Cell viability was measured using a standard cell proliferation assay, where higher absorbance indicates greater cell growth. The x-axis shows the different hormone treatments (with DMSO as the control), and the y-axis shows the relative absorbance.

**B.** Relative absorbance of MCF-7 breast cancer cells after 4 days of steroid hormone treatment. Absorbance was measured using the same cell proliferation assay. As in panel A, the x-axis displays the hormone conditions (DMSO control), and the y-axis represents the relative absorbance values.

Because MDA-MB-231 cells do not have hormone receptors, I expected that hormones such as estradiol and DHT would not affect their growth. After 3 days, this expectation was confirmed: absorbance levels for estradiol- and DHT-treated cells were almost identical to the control. Cortisol led to a slight increase, while DHEA caused a small decrease, but neither effect was large (Figure 2A).

By day 4, these trends became a bit more noticeable. Cortisol-treated cells showed a clearer rise in absorbance, while DHEA-treated cells showed a more obvious decrease compared with the control. Estradiol and DHT again showed almost no effect. These results show that hormone treatments have minimal impact on MDA-MB-231 cells, which is consistent with their triple-negative status (Figure 2B).

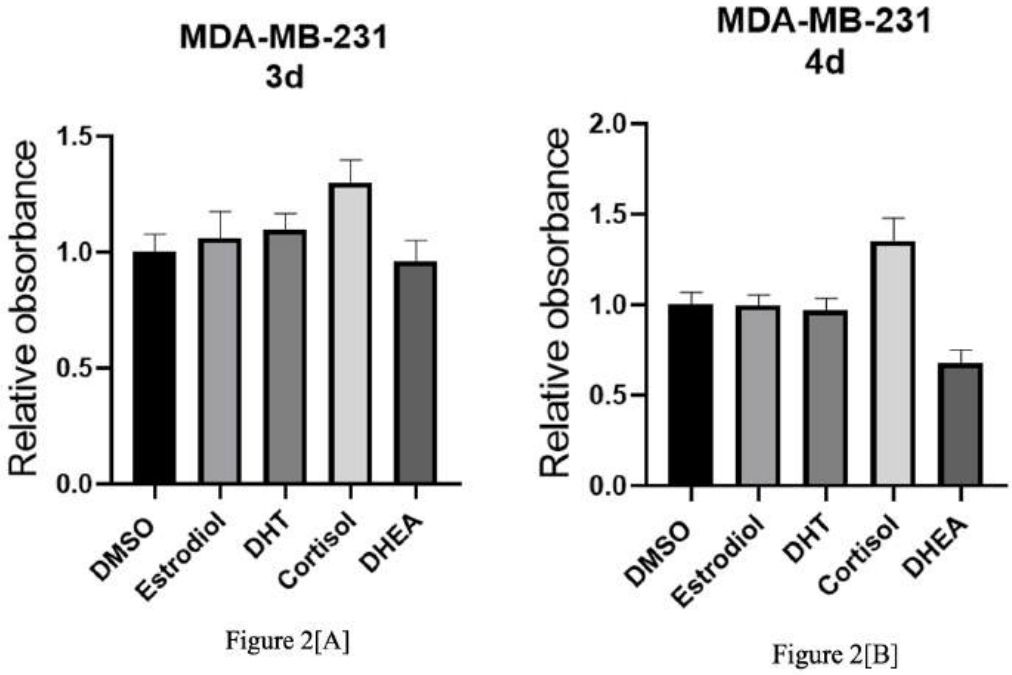



Figure 2 (Effect of Steroid Hormone Treatment on MDA-MB-231 Cell Proliferation)

**A.** Relative absorbance of MDA-MB-231 breast cancer cells after 3 days of steroid hormone treatment. Cell viability was assessed using a standard cell proliferation assay, where higher absorbance reflects increased cell growth. The x-axis shows the different hormone treatments (with DMSO as the control), and the y-axis indicates the relative absorbance.

**B.** Relative absorbance of MDA-MB-231 breast cancer cells after 4 days of steroid hormone treatment. Absorbance was measured using the same cell proliferation assay. As in panel A, the x-axis displays the hormone treatment conditions (DMSO control), and the y-axis represents the relative absorbance values.

**Different Hormones Activate Distinct Signaling Pathways in MDA-MB-231 and MCF7 Breast Cancer Cells**

To examine how various hormones influence metastasis-related signaling pathways, several antibodies were used in western blotting. Their functions and biological implications are summarized here. Vinculin is a cytoskeletal protein involved in cell adhesion and was used as a loading control to ensure equal protein amounts in each sample. P-AKT (phosphorylated AKT), the activated form of AKT, reflects activity in the PI3K/AKT pathway, which promotes cell survival, proliferation, and resistance to apoptosis; higher P-AKT suggests pathway activation, while lower levels suggest inhibition (Rascio et al., 2021). P-ERK (phosphorylated ERK) indicates activity in the MAPK pathway involved in proliferation and differentiation. High P-ERK represents strong MAPK signaling, whereas low levels indicate pathway suppression (Guo et al., 2020). P-S6 (phosphorylated S6 ribosomal protein) is a downstream target of the mTOR signaling pathway, which regulates cell growth and protein synthesis (Ruvinsky &

Meyuhas, 2006). Increased P-S6 means active mTOR signaling, while reduced levels indicate mTOR inhibition. Finally, SOD2 is a mitochondrial antioxidant enzyme that protects cells from oxidative stress; high SOD2 implies greater resistance to oxidative damage, while low SOD2 suggests increased oxidative stress. Because treatment times were short, the results mainly compare phosphorylation levels rather than total protein expression.

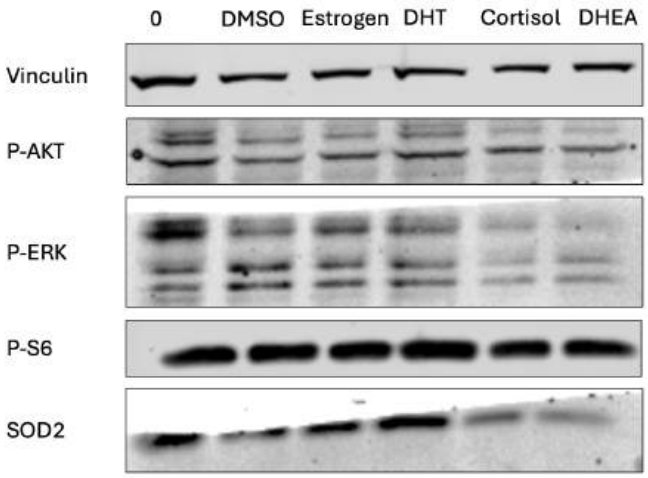



Figure 3[A]

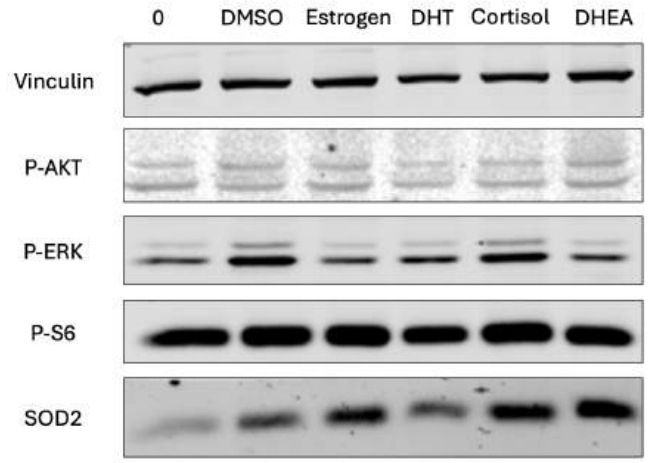



Figure 3[B]

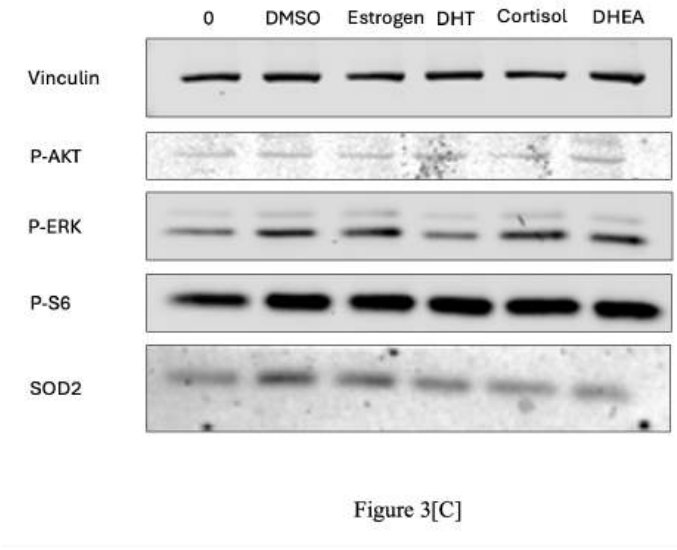



Figure 3[C]

Figure 3. Western Blot Analysis of Hormone-Treated MDA-MB-231 Cells

**A.** MDA-MB-231 cells were treated with the different hormones for 3 hours, and total protein was collected. Western blots were used to measure the phosphorylation levels of AKT, ERK, and S6, as well as the total protein level of SOD2.

**B.** MDA-MB-231 cells were treated with hormones for 4 hours, followed by protein collection and western blot analysis of phosphorylated AKT, ERK, S6, and total SOD2 levels.

**C.** MDA-MB-231 cells were treated with hormones for 3 days. Total proteins were then collected, and western blots were performed to examine the phosphorylation of AKT, ERK, and S6, along with SOD2 protein expression.

Regarding MDA-MB-231 cells, after 3 hours, P-AKT bands were darker in the estrogen- and DHT-treated groups, while cortisol and DHEA produced weaker bands compared to the DMSO control. For P-ERK, estrogen and DHT bands were similar to the DMSO control but lighter than the no-treatment lane, whereas cortisol and DHEA bands were much fainter. P-S6 remained strong in all hormone-treated groups, with estrogen and DHT darker than the control. SOD2 increased under DHT treatment but decreased in the cortisol and DHEA groups (Figure 3A).

After 4 hours, the vinculin loading control indicated that fewer DHT samples were loaded compared with other groups. P-AKT remained elevated with estrogen treatment, while cortisol and DHT bands appeared lighter than the control. P-ERK showed an opposite pattern: the cortisol-treated sample produced a stronger band than the control, while estrogen, DHT, and DHEA bands remained similar to or slightly lighter than the DMSO control. P-S6 continued to show strong expression across all treatments, with estrogen and cortisol both slightly above the control level. For SOD2, DHT produced a lower band than the DMSO control, while estrogen, cortisol, and DHEA showed elevated levels (Figure 3B).

After 3 days, phosphorylation signals were generally reduced across all groups. P-AKT bands were faint in every condition, with no clear increases or decreases. P-ERK levels were also low overall, although DHT showed a noticeable reduction and cortisol showed a slight increase relative to the control. P-S6 bands remained comparable to the DMSO control, indicating little long-term change in mTOR-related signaling. SOD2 levels were also reduced across treatments, with estrogen showing a small elevation but still lower than the control (Figure 3C).

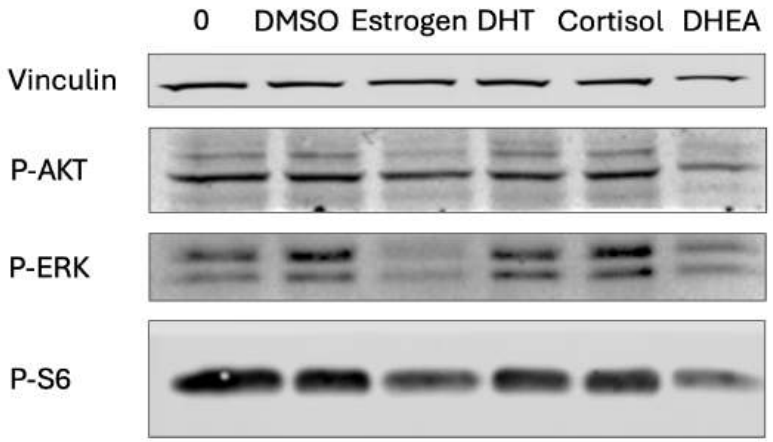



Figure 4[A]

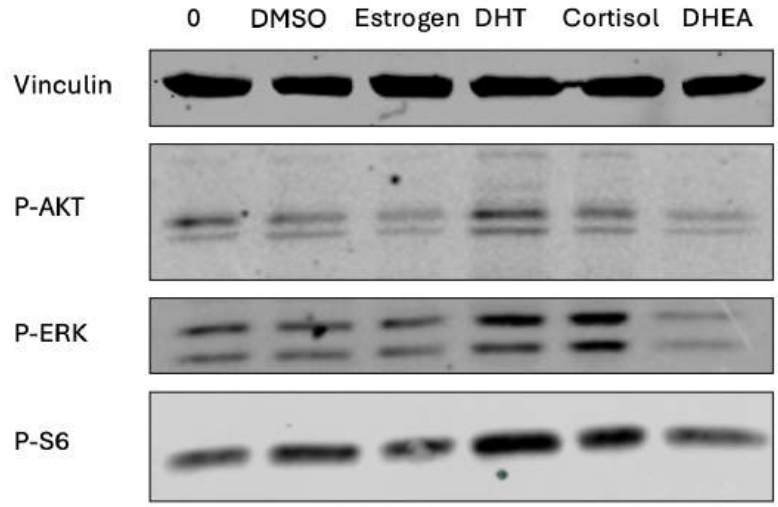



Figure 4[B]

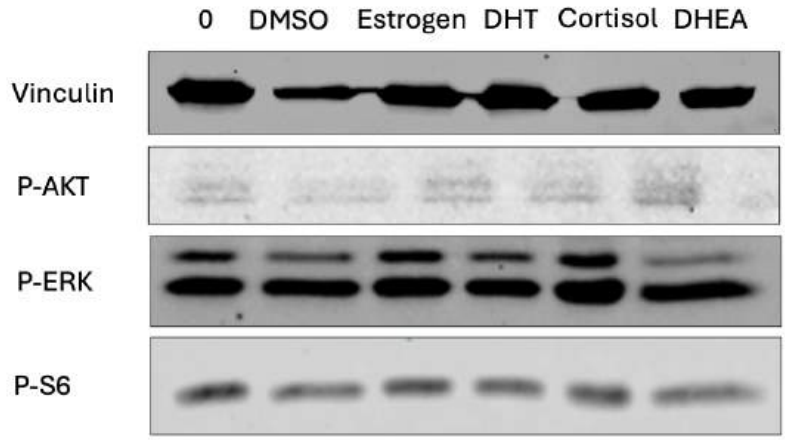



Figure 4[C]

Figure 4. Western Blot Analysis of Hormone-Treated MCF-7 Cells

**A.** MCF-7 cells were treated with the different hormones for 3 hours, and total protein was collected. Western blots were used to measure the phosphorylation levels of AKT, ERK, and S6.

**B.** MCF-7 cells were treated with hormones for 4 hours, followed by protein collection and western blot analysis of phosphorylated AKT, ERK, S6.

**C.** MCF-7 cells were treated with hormones for 3 days. Total proteins were then collected, and western blots were performed to examine the phosphorylation of AKT, ERK, and S6.

In the MCF7 cells, P-AKT showed the strongest band under estrogen treatment, followed by DHT, while DHEA produced a lighter signal compared with the controls. P-ERK levels increased with DHT and cortisol, but estrogen treatment resulted in a noticeably lower band. For P-S6, estrogen and DHEA bands appeared faint, whereas DHT and cortisol produced stronger signals. SOD2 decreased under estrogen treatment, while other hormone-treated samples were similar to the control (Figure 4A).

By 4 hours, DHT produced the darkest P-AKT signal, followed by cortisol. For P-ERK, DHT showed the highest expression compared with the control, estrogen remained similar to control, and DHEA showed reduced levels. P-S6 was elevated in the DHT- and cortisol-treated samples and decreased under estrogen and DHEA. SOD2 data were not available for this time point (Figure 4B).

After 3 days, the vinculin loading control indicated fewer DMSO samples were loaded than hormone-treated samples. Estrogen appeared to show the highest expression overall compared with other treatments. P-ERK bands were similar across treatment groups, with estrogen and cortisol appearing slightly elevated. For P-S6, estrogen- and cortisol-treated samples showed modest increases over the control. SOD2 data were unavailable for this time point (Figure 4C).

## Discussion

### How Different Hormones Affect Cell Proliferation

**MCF7** (How Different Hormones Affect MCF-7 Cell Proliferation)

#### 3-Day Treatment

The strong proliferative response seen in MCF7 cells after estrogen treatment aligns with the biology of luminal A breast cancer, which is characterized by high estrogen receptor (ER) expression. The weaker but noticeable response to DHT suggests that MCF7 cells may also express androgen receptors, although androgen signaling appears far less influential than estrogen signaling. Cortisol and DHEA did not significantly stimulate proliferation, indicating that these hormones have minimal impact on MCF7 growth. Overall, these results highlight the dominant role of estrogen signaling in luminal A breast cancer and demonstrate that MCF7 proliferation is highly hormone-specific.

#### 4-Day Treatment

By day 4, the decrease in relative absorbance across hormone conditions suggests that MCF7 cells may have approached a growth plateau. While estrogen still promoted proliferation, its effect was less pronounced than on day 3, likely due to limited space or nutrient availability as the culture reached higher density. DHT continued to cause a modest increase in cell growth, supporting the idea that androgen receptor activity is present and that DHT remains stable in culture over several days.

#### Comparison: Day 3 vs. Day 4

Together, these observations show that MCF7 cells were more metabolically active at day 3 and had slowed by day 4 as they neared confluence. Estrogen's effect decreased as the cells approached maximum density, whereas DHT maintained a subtle but consistent stimulatory effect. Cortisol and DHEA showed little change at either time point, further confirming that they do not play a major role in regulating MCF7 cell proliferation.

**MDA-MB-231** (How Different Hormones Affect MDA-MB-231 Cell Proliferation)

#### 3-Day Treatment

The minimal proliferative response observed in MDA-MB-231 cells after 3 days of hormone treatment is consistent with their triple-negative status, as these cells lack ER, PR, and HER2 and therefore do not rely on sex hormone signaling for growth. The slight increase in absorbance in cortisol-treated cells may indicate that glucocorticoid receptor (GR) signaling can promote a mild survival or proliferative response. In contrast, the reduced absorbance in DHEA-treated cells may reflect a potential inhibitory or stress-related effect. Overall, the results show that hormone-driven proliferation is largely absent in this cell line.

**4-Day Treatment**

By day 4, these trends became more noticeable. Cortisol-treated cells showed the highest absorbance values, suggesting a sustained role for GR-mediated signaling in promoting cell survival or mild proliferation. Estradiol and DHT remained similar to control levels, as expected from a hormone-insensitive TNBC line. DHEA showed an even greater reduction compared with day 3, indicating progressively slower growth or decreased viability.

**Comparison: Day 3 vs. Day 4**

Comparing both time points, MDA-MB-231 cells showed no time-dependent increase in proliferation in response to estradiol or DHT, confirming their lack of sensitivity to these hormones. Cortisol's effect became stronger by day 4, supporting the role of GR signaling in maintaining cell survival under stress. Meanwhile, DHEA consistently produced the lowest absorbance values, with a marked decline by day 4, suggesting that DHEA may inhibit cell proliferation or impose metabolic stress. These findings contrast sharply with the hormone-responsive behavior of MCF7 cells, highlighting key biological differences between luminal A and triple-negative breast cancer subtypes.

**How Different Hormones Influence Key Growth and Stress Signaling Pathways in Breast Cancer Cells**

**MCF7**

**3 hours**

The darkened P-AKT band following estrogen treatment suggests activation of the PI3K/AKT pathway, consistent with estrogen-driven survival and growth signaling in luminal A cells. The moderate response to DHT indicates weaker PI3K/AKT activation through androgen signaling, while the reduced P-AKT levels under DHEA suggest minimal or potentially inhibitory effects. For P-ERK, the elevated levels in DHT- and cortisol-treated samples indicate activation of the MAPK/ERK pathway, whereas estrogen-treated cells showed reduced P-ERK, suggesting possible suppression of MAPK signaling at this early time point. A similar pattern is seen with P-S6: DHT and cortisol increased mTOR pathway signaling, while estrogen and DHEA produced reduced P-S6 levels. The decrease in SOD2 expression under estrogen may reflect altered oxidative stress regulation, while the relatively unchanged SOD2 levels across the other treatments suggest minimal effects on mitochondrial antioxidant responses.

**4 hours**

After four hours, P-AKT levels increased under DHT and cortisol, suggesting that androgen and glucocorticoid signaling may dominate AKT pathway activation at this time point, which is somewhat unexpected for an ER-positive cell line. Elevated P-ERK and P-S6 levels under DHT and cortisol further indicate activation of the MAPK and mTOR pathways. In contrast, estrogen and DHEA treatments continued to show reduced MAPK/mTOR engagement,

with DHEA in particular suggesting a potential inhibitory effect on proliferative signaling. These patterns show that non-estrogen hormones can transiently override estrogen-driven pathways in MCF7 cells, depending on timing.

**3 days**

After three days of treatment, estrogen again induced the strongest P-AKT signal compared with other hormones, consistent with its known role in long-term growth signaling in luminal A cells. Interestingly, DHEA also showed relatively elevated P-AKT levels, which is unexpected given its typical association with inhibitory effects. P-ERK levels were similar across all treatments, with slight increases under estrogen and cortisol, indicating modest MAPK pathway activation. Likewise, small increases in P-S6 under estrogen and cortisol suggest mild upregulation of mTOR signaling and protein synthesis. SOD2 data were not available for this time point.

**MDA-MB-231**

**3 hours**

The darker P-AKT signals under estrogen and DHT suggest some engagement of the PI3K/AKT pathway; however, because the bands do not show a strong increase over the DMSO control, the pathway activation appears minimal. Reduced P-ERK levels in cortisol- and DHEA-treated samples indicate inhibition of the MAPK pathway, while estrogen and DHT had little effect. Strong P-S6 bands across all conditions imply that mTOR activity is largely hormone-independent in these cells, with estrogen and DHT contributing only mildly. Elevated SOD2 levels under DHT suggest enhanced oxidative stress response, whereas lower SOD2 levels under cortisol and DHEA imply reduced antioxidant signaling.

**4 hours**

Sustained P-AKT activity under estrogen indicates continued growth signaling, while cortisol and DHT showed reduced P-AKT levels, suggesting weaker activation. In contrast, the elevated P-ERK band in cortisol-treated cells highlights glucocorticoid-driven stimulation of the MAPK pathway at this time point. P-S6 remained high in all samples, with estrogen and cortisol showing slightly increased levels, reflecting active mTOR signaling and protein synthesis. SOD2 expression decreased only under DHT, suggesting increased oxidative stress, while estrogen, cortisol, and DHEA elevated SOD2, potentially providing greater protection against oxidative damage.

**3 days**

By three days, overall reductions in phosphorylation across all treatments indicate that AKT signaling is not sustained during prolonged hormone exposure in MDA-MB-231 cells. Reduced P-ERK under DHT suggests suppression of MAPK signaling, while the elevated cortisol response implies continued glucocorticoid-driven activation. P-S6 levels remained

similar across all treatments, suggesting that long-term mTOR signaling is not significantly altered by any of the hormones tested. The general decline in SOD2 across treatments further indicates that prolonged hormone exposure does not maintain antioxidant or stress-protective pathways. Together, these findings reinforce the limited long-term influence of steroid hormones on key signaling pathways in triple-negative breast cancer cells.

**Conclusion**

The results from both the cell proliferation assays and western blot analyses show that steroid hormones influence breast cancer cell behavior in distinct ways depending on receptor status. In hormone-sensitive MCF7 (luminal A) cells, estradiol produced the strongest proliferative response, especially after 3 days, confirming that estrogen signaling drives rapid growth through ER activation. DHT also stimulated moderate proliferation, suggesting that the androgen receptor may contribute secondarily to cell growth in this subtype. In contrast, cortisol and DHEA had little effect on MCF7 proliferation, indicating that glucocorticoid and pro-hormone signaling do not strongly impact cell division in ER-positive breast cancer.

In triple-negative MDA-MB-231 cells, which lack estrogen, progesterone, and HER2 receptors, the overall proliferative response to hormones was minimal. As expected, estradiol and DHT had no significant impact on growth due to the absence of hormone receptors. However, cortisol treatment led to a noticeable increase in proliferation and increased signaling protein expression, especially after 3–4 days. This pattern suggests that glucocorticoid receptor (GR) activation may promote survival or stress-adaptation pathways in TNBC cells. In contrast, DHEA consistently decreased absorbance and lowered pathway activity, indicating a potential inhibitory or stress-related effect on this aggressive subtype.

Together, these findings highlight the hormone-specific and subtype-dependent nature of breast cancer cell responses. They reinforce the idea that receptor status is a crucial determinant of hormonal sensitivity: luminal A cells are highly responsive to estrogen and partially to DHT, while triple-negative cells show little response to sex hormones but remain sensitive to cortisol-mediated signaling. This study demonstrates how differences in receptor expression shape hormone responsiveness and may contribute to distinct growth behaviors among breast cancer subtypes.

Understanding how different hormones affect breast cancer cells can provide insight into how stress, endocrine changes, or hormonal therapies might influence tumor progression. For example, the strong stimulatory effect of estrogen in MCF7 cells underscores why anti-estrogen therapies (like tamoxifen) are effective in ER-positive breast cancer. The cortisol-induced growth seen in MDA-MB-231 cells raises questions about how stress hormones may influence TNBC progression, and whether targeting the glucocorticoid receptor could serve as a therapeutic strategy. DHEA's inhibitory effects may also warrant further study as a potential suppressor of growth in certain breast cancer subtypes.

While this study provides meaningful insight, several improvements could strengthen the conclusions. Increasing the sample size and using multiple biological replicates would make the

results more statistically reliable. Testing additional time points could help determine when hormone-induced signaling begins and how long it persists. Including total protein levels (not only phosphorylated forms) would allow clearer interpretation of pathway activation. It would also be valuable to test additional hormone concentrations to determine dose-dependent effects. Finally, expanding the study to include more breast cancer subtypes or performing follow-up assays, such as apoptosis assays, migration assays, or gene-expression analysis, could offer a more complete picture of how hormones regulate cancer cell behavior.

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**More Accessible World Wide Web By Om Sandip Patel**


## Abstract

The World Wide Web is very important and an integral part of people's everyday life, providing a deep ocean of information. However, we still face significant challenges of accessibility for visually impaired individuals (Abu Doush et al., 2017). Currently, we have some solutions, like screen readers and browser extensions, that offer partial assistance for navigating and consuming web content (Borodin et al., 2010). These extensions still aren't up to par. My research here presents a new integrated approach combining speech recognition and text-to-speech navigation by keystrokes instead of mouse clicks. So, I built a chrome extension and a python application that allows visually impaired individuals to browse the web and understand website content. The findings in one of the research work highlights the need for more inclusive web technologies and demonstrate a potential of combining open-source libraries and browser APIs to bridge accessibility gaps (Bigham et al., 2011). My work contributes to ongoing efforts of making a more accessible digital world, empowering visually impaired individuals to navigate, search, and consume web content with greater autonomy.


## Introduction

The world wide web was invented by Tim-Berners Lee in 1989. The purpose of it was to compile text documents and open documents in different "tabs ("A Short History of the Web" 2019)." Today, over 6 billion people use the world wide web to search for information and open hyperlinks. However, the world wide web is not designed for people with untreatable visual impairments. The actual definition of visually impaired is to have a reduced level of vision that standard eyewear cannot treat. In the U.S, there are about 7-8 million visually impaired people, and 338 million across the whole world.

The current website-browsing solutions for the visually impaired include the chrome screen reader extension and chrome read aloud feature. These accessibility tools are available for free on operating systems like Mac. However, these available tools often require users to click on specific page elements before the element's text is read aloud. This task is difficult for visually impaired individuals to perform. The findings in one research paper highlights the need for more inclusive web technologies and demonstrates the potential of combining open-source libraries and browser APIs to bridge accessibility gaps (Bigham et al., 2011).

From the gap in the current extensions, I found an opportunity to improve web search accessibility for the visually impaired individuals. There are Braille keyboard stickers available for a minimal price that allows visually impaired people to press specific keys easily. So, I built a chrome extension that extracts text from each page element. From there, users can navigate the extracted text one by one by pressing the TAB key for the forward direction and SHIFT+TAB key for the backward direction. However, the question still stands, how does a person without sight open the chrome browser and search something on the web? To solve this, I implemented a Python application that works parallelly to the chrome extension. By leveraging Python's speech

recognition capabilities, this system will listen to the voice command “Search”. If you say “Search News,” it will open the chrome browser and search “News” on the web. Then, they can press the TAB keys and my chrome extension will read the text elements one by one, tab by tab.

**Methods**

My goal for my chrome extension is to make the web more accessible for the visually impaired. The app I developed allows the visually impaired to use voice commands to navigate a web page and make searches. It has two main components, a python script and a chrome extension. The user first runs the python app. Then, using the chrome extension, they can speak to make a search. Finally, the user can press tab or shift+tab to navigate through the web page.

First, I developed a Python application with a voice command interface. The Python script utilizes the `speech_recognition` library to capture and interpret voice commands (Lazzaro & Roland, 2011; Almalki et al., 2016).When a user says "Search ..." followed by their query, the script extracts the search term and opens the default web browser(needs to be set as chrome) and lands to Microsoft Bing’s search results page with the search term results. The code that runs these functions can be found in figure 1 below.

```
import speech_recognition as sr
import webbrowser
import urllib.parse
import time

def listen_for_command():
    recognizer = sr.Recognizer()
    mic = sr.Microphone()

    print("🎤 Listening... say something like 'Search Data Graph'")

    with mic as source:
        recognizer.adjust_for_ambient_noise(source)
        audio = recognizer.listen(source)

    try:
        text = recognizer.recognize_google(audio)
        print(f"🗣️ You said: {text}")
        return text.lower()
    except sr.UnknownValueError:
        print("❌ Sorry, I couldn't understand the audio.")
        return None
    except sr.RequestError as e:
        print(f"⚠️ Could not request results; {e}")
        return None

def process_command(command):
    if command and command.startswith("search "):
        # Extract search term after 'search'
        search_term = command.replace("search ", "").strip()
        encoded_query = urllib.parse.quote_plus(search_term)
        url = f"https://www.bing.com/search?q={encoded_query}"
        print(f"🌐 Opening: {url}")
        webbrowser.open(url)
    else:
        print("ℹ️ Please say a command starting with 'Search', e.g. 'Search Data
Graph'.")

def main():
    stop = False
    while not stop:
        command = listen_for_command()
        stop = process_command(command)
        time.sleep(0.5)  # small pause to avoid immediate re-trigger

if __name__ == "__main__":
    main()
```

Figure 1. Code for the python application

For the chrome extension, instead of using python, I used javascript. Using python for the chrome extension was not supported. The code scans the active tab for visible elements and extracts text from it. Then it enables navigation using the `Tab` or `Shift+Tab` keys. Each time you press the key, the action triggers Chrome's SpeechSynthesis API to read aloud the extracted text. The open source libraries and technologies I have used include `speech_recognition` for voice commands, `webbrowser` for automated browsing, and java script browser APIs for text extraction and speech output. This integrated system ensures that users can initiate searches and listen web content without the need of sight or mouse-based actions. The code for the chrome extension can be found in figure 2.

```
console.log("Content script loaded.");

let currentIndex = -1;
let elementsWithText = undefined;

function getElementsText(el) {
  const result = [];
  const excludedTags = ["script", "style", "noscript", "select"];

  el.childNodes.forEach((node) => {
    // Only process element nodes
    if (node.nodeType === Node.ELEMENT_NODE) {
      const style = window.getComputedStyle(node);

      // Skip hidden or invisible elements
      if (style.display === "none" || style.visibility === "hidden") return;

      // Skip script, style, and noscript
      const tag = node.tagName.toLowerCase();
      if (excludedTags.includes(tag)) return;

      // Only include direct text nodes of this element
      node.childNodes.forEach((child) => {
        if (child.nodeType === Node.TEXT_NODE) {
          const text = child.textContent.trim();
          if (text) {
            result.push({ type: tag, text, node: child });
          }
        }
      });

      // Recursively process child elements
      result.push(...getElementsText(node));
    }
  });
  return result;
}
```

```
document.addEventListener("keydown", async function keyEvent(e) {

  elementsWithText = elementsWithText ?? getElementsText(document.body);

  if (e.key === "Tab") {
    e.preventDefault();

    if (e.shiftKey) {
      currentIndex = (currentIndex - 1 + elementsWithText.length) %
elementsWithText.length;
      console.log("Shift + Tab pressed → move backward");
    } else {
      currentIndex = (currentIndex + 1) % elementsWithText.length;
      console.log("Tab pressed → move forward");
    }

    console.log("Reading text element at index = " + currentIndex);
    const elObj = elementsWithText[currentIndex];
    const elNode = elObj.node; // the element containing text

    if (elNode.nodeType === 1) { // make sure it's an element
      if (!elNode.hasAttribute("tabindex")) elNode.setAttribute("tabindex", "-1");
      elNode.focus({ preventScroll: false });
      elNode.scrollIntoView({ behavior: "smooth", block: "center" });
    } else if (elNode.parentElement) {
      // fallback if el is a text node
      const parent = elNode.parentElement;
      if (!parent.hasAttribute("tabindex")) parent.setAttribute("tabindex", "-1");
      parent.focus({ preventScroll: false });
      parent.scrollIntoView({ behavior: "smooth", block: "center" });
    }

    // Read text aloud
    await new Promise((resolve) => {
      const utterance = new SpeechSynthesisUtterance(elObj.text);
      utterance.rate = 1;
      utterance.pitch = 1;
      utterance.volume = 1;
      utterance.onend = () => setTimeout(resolve, 1000); // 1-second pause
      speechSynthesis.speak(utterance);
    });
  }
});
```

```
async function readElements(elements) {
  for (const el of elements) {
    el.el.focus({ preventScroll: false });
    el.el.scrollIntoView({ behavior: "smooth", block: "center" });
    await new Promise((resolve) => {
      const utterance = new SpeechSynthesisUtterance(el.text);
      utterance.rate = 1;
      utterance.pitch = 1;
      utterance.volume = 1;
      utterance.onend = () => setTimeout(resolve, 1000); // 1 second pause
      speechSynthesis.speak(utterance);
    });
  }
}
```

Figure 2. Code for the chrome extension.

## Discussion

## Conclusion

This project aims to improve web accessibility for visually impaired users, as it is crucial for digital inclusion and autonomy (Abu Doush et al., 2017). The presented system in this paper demonstrates a practical solution by combining technologies like python and java script for voice-activated search with sequential text-to-speech reading. It removes many barriers posed by existing tools (Borodin et al., 2010; Bigham et al., 2011). The approach here is specifically

important because it empowers visually impaired users to independently search and navigate the web, rather than relying on sighted assistance or limited interaction models.

**Limitations**

Limitations of the current system include the inability to use Google Search due to Google-related restrictions on speech synthesis, so we are using Microsoft Bing search. More research is required on highly or non-standard web wages; for example, Google forms, surveys, typing, emails, etc. Despite these constraints, my project lays the groundwork for a more accessible web search experience. Also it highlights the importance of developing adaptable solutions in modern assistive technology for inclusion of the visually impaired community (Almalki et al., 2016).

**Future Work**

My future ambition for this project is to include more voice commands that allow for more computer control, such as opening specific applications, navigating between tabs, or interacting with form elements. My first target would be to dive into opening email applications like Gmail and reading the inbox/promotions emails loudly. In the long term, my vision is for my extension to be integrated into common applications (Google, Apple, etc.), allowing visually impaired individuals to easily access and utilize it.

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**Sleep Deprivation-Induced Endocrine Dysfunction and Its Cardiovascular Sequelae in Middle Age By Su Su Yati Zaw**


## Abstract

Global public health concerns have emerged about sleep deprivation and its consequences on endocrine function and cardiovascular well-being. Sleep deprivation disrupts the homeostatic balance of various hormonal systems and this can lead to elevated cortisol levels, decreased insulin sensitivity, and altered release of hormones regulating growth and appetite; together, they create an environment that promotes the development of metabolic syndrome and the associated risk factors (hypertension, endothelial damage) that contribute to the decline of cardiovascular health (Chen et al.; Buxton et al.; Van Cauter et al.). Middle-aged adults are especially at risk due to age related decreases in hormone production and their ability to recover physiologically from the effects of chronic sleep loss. Sustained sleep loss increases the occurrence of atherosclerosis, dyslipidemias, myocardial infarctions, and cerebral vascular accidents (Anagnostis et al.). This study will review current studies to describe how inadequate sleep causes disruptions in hormonal regulation as a pathway to long term cardiovascular disease (Lisco et al.). The literature also emphasizes the need for interventions that target behavioral aspects of sleep hygiene and the biological consequences of disrupted hormonal regulation in middle aged adults to prevent declines in cardiovascular health.



**Key words** Sleep deprivation, endocrine system, cortisol, cardiovascular health, middle age


## Introduction

Our modern world has produced a degree of pressure on sleep never before experienced. Sleep has become a commodity subject to negotiation, as opposed to being considered essential to the body's biological functioning. There are many systems affected by sleep deprivation, but none are as susceptible as the endocrine system. Hormone-based signaling pathways control metabolism, immune function and blood vessel health; therefore, disruptions to this system result in widespread, long-lasting consequences (Van Cauter et al.).

One way that sleep loss can lead to long term health issues is through the disruption of the hypothalamic-pituitary-adrenal (HPA) axis. The HPA axis is responsible for regulating the body's stress response. Activation of the HPA axis leads to increased levels of cortisol, which is elevated for extended periods of time when individuals experience chronic stress, causing a multitude of physiological problems including hyperglycemia, insulin resistance, visceral obesity and vascular damage (Guyon et al.; Buxton et al.). Furthermore, sleep restriction causes disruptions to insulin signaling and the balance of hormones and proteins that affect the regulation of hunger and energy stores leading to increased caloric intake and subsequent weight gain and arterial inflammation. These physiological changes create many of the characteristics of metabolic syndrome, which is a major predictive factor of cardiovascular disease (Anagnostis et al.).

Middle-aged individuals represent a unique population where multiple risk factors converge. In middle age, an individual's ability to buffer against the effects of aging is declining, and they may be experiencing maximum amounts of occupational stress and family responsibilities that could already be causing disruptions to their natural circadian rhythms (Hu et al.). However, most studies examining the relationship between sleep and endocrinology are either focused on adolescents or the elderly, creating a significant gap in the current literature regarding how sleep-endocrine interactions occur in middle-aged adults who may still appear to be healthy. Since there is typically a long latency period between the initial manifestation of endocrine dysfunction and the development of cardiovascular disease, the dysfunction is frequently identified after the damage has been done (Willemars et al.). Therefore, further research is needed to determine how variations in sleep duration correlate to early biomarkers of cardiovascular risk in healthy adults. Additionally, identifying measurable endocrine and physiological indicators (e.g., cortisol-related changes in heart rate, blood pressure, and perceived stress) would help to support earlier identification and potentially allow for targeted lifestyle interventions. Improved scientific understanding and public awareness of sleep related endocrine dysfunction occurring during middle age may provide the opportunity to prevent the progression toward chronic cardiovascular disease prior to the onset of clinically apparent symptoms.

This study will make contributions to this knowledge gap by assessing the relationship between differences in nightly sleep duration and markers of cardiovascular and endocrine function in a group of middle-aged adults. The study will seek to confirm previous theoretical work as well as inform prevention strategies that incorporate sleep medicine into metabolic and cardiovascular health.

**Literature Review**

Sleep deprivation is increasingly being associated with significant disruptions in the HPA-axis (the primary physiological mechanism for responding to stress) through controlled research trials. The results of this work have demonstrated that sleep restriction of just seven days can cause an increase of up to 50% in evening cortisol concentrations (Chen et al.). This demonstrates a prolonged state of hyper-vigilance independent of the amount of time spent awake. Hyper-cortisolism (chronic elevation of cortisol levels), has been shown to lead to elevated vascular tone, decreased ability to dilate the endothelium and increased systemic inflammation (Guyon et al.). These factors combined result in stiffening of arteries, increased blood pressure and are precursors to long term cardiovascular disease (Anagnostis et al.).

Additionally, sleep deprivation was found to impair glucose tolerance by reducing insulin sensitivity by 20-30% in previously normal individuals. This impairment in glucose clearance from the blood causes compensatory overproduction of insulin and contributes to development of insulin resistance. Insulin resistance is known to increase the risk of developing Type II diabetes and is a precursor to the development of dyslipidemias (abnormal lipid profiles) (Van Cauter et al.). Dyslipidemias typically consist of high levels of triglycerides and low-density

lipoproteins (LDL). Both conditions promote the acceleration of atherosclerosis, especially in individuals whose metabolic function is declining due to age.

Restrictive experimental sleep of middle age populations consistently changes both the timing and levels of cortisol, particularly increasing levels of evening cortisol after several nights of severe restrictions; a pattern related to the increase in vascular stiffness and the decrease in endothelial function. An experimentally controlled laboratory study demonstrated that multi-night restrictions increased cortisol in the later part of the day, demonstrating an ongoing stress signal at a time the body is in recovery and should have lowered blood vessel tone. Evening cortisol elevation has been associated with elevated vascular tone and decreased nitric-oxide-mediated dilation; these effects provide a reasonable link between sleep deprivation and elevated blood pressure and arterial aging (Guyon et al.).

In addition to cortisol, sleep curtailment increases energy use during required wakefulness and disrupts autonomic function. Increased sympathetic activity and metabolic demand during the biological nighttime creates vascular stress at a time normally reserved for vascular repair and explains why individuals who are short sleepers demonstrate high resting heart rate and poor endothelial function (Shaikh et al.). Sleep deprivation also impacts other endocrine functions including suppression of nocturnal growth hormone secretion; an important component of tissue repair and lipid metabolism. Additionally, sleep deprivation disrupts the homeostatic equilibrium of leptin and ghrelin; hormones involved in controlling hunger and caloric consumption. Suppression of leptin and elevation of ghrelin result in increased hunger and caloric consumption leading to obesity, which is yet another major cardiovascular risk factor (Tsou et al.). Additionally, sleep deprivation results in increased production of pro-inflammatory cytokines such as interleukin-6 and tumor necrosis factor-alpha which enhance vascular inflammation and plaque formation (Shaikh et al.).

While the field as a whole appears to be somewhat homogenous, a recent systematic review and meta-analyses found that acute sleep deprivation was not significantly raised in total cortisol levels across different methods and matrices; however, a number of serum based measures were significantly elevated—which suggests that timing, type of assay used and level of restriction can be important factors that are contributing to conflicting results and highlight the importance of the pattern and chronicity of sleep loss rather than just one night of being awake

In summary, these data suggest a network of endocrine disruptions that ultimately lead to the erosion of cardiovascular resilience. Due to the gradual declines in hormones associated with aging, middle-aged individuals will be less capable of adapting to these perturbations and therefore more susceptible to progression of chronic diseases (Anagnostis et al.).

**Research Design**

The design of this study was a correlational, cross-sectional design that examined the relationship between the amount of time participants slept at night (the independent variable) and multiple physiological and psychological factors of cardiovascular and endocrine health: resting heart rate, systolic blood pressure, diastolic blood pressure, and perceived stress. In addition to

these variables, Body Mass Index (BMI) and age were also collected in order to statistically control for the potential influence of metabolic and age-related variables on the relationships of interest.

A correlational design was selected in order to examine the relationship between naturally occurring sleep variability and its effects on biological functioning in a realistic and non-restrictive way. This type of design allows researchers to measure multiple variables simultaneously in a "real-world" setting without introducing artificial constraints such as those present in a laboratory setting (Hu et al.). This design was also selected for its feasibility and ethics.

**Procedure**

Data collection occurred over a one-week period. Prior to the start of the data collection week, volunteers were given a brief instruction sheet on how to correctly log and track their sleep hours each night, using a smart-watch sleep tracker. On the morning of each day for one week, volunteers reported how many hours and minutes they slept the preceding night.
On the seventh day of data collection, all physiological and psychological measures were collected between 6:30 AM and 8:30 AM in a quiet, well-ventilated room. Volunteers were instructed to avoid consuming any products containing caffeine, alcohol, or to engage in any strenuous physical activity twelve hours prior to testing. Each volunteer's resting heart rate and blood pressure were measured using a validated automatic digital monitor (Omron M3 series) after a two minute seated rest. The average of the two measurements was used to minimize measurement error.

Perceived stress was assessed using a shortened version of the Perceived Stress Scale (PSS-10). Volunteers rated ten items that described their emotional experiences during the previous week (e.g., "I felt nervous or stressed") on a five-point Likert-type scale (0 = never to 4 = very often). Total scores were obtained by summing ratings across all ten items, resulting in a maximum score of 40; with higher scores indicating greater stress. All data were entered manually into a spreadsheet and then reviewed by a second rater for transcription accuracy.

**Sampling and Methodology**

Thirty-two middle-aged adults (16 males and 16 females), ranging from forty to sixty years of age (M = 48.9 years, SD = 5.3), volunteered to participate in this study. Volunteers were recruited through announcements, and social media parent group posts. None of the volunteers had been diagnosed with a sleep disorder (i.e., insomnia, sleep apnea) nor worked night shift or rotating shifts. Additionally, none of the volunteers were taking antihypertensive, corticosteroid, or beta-blocker medications nor suffered from a recent major illness or surgical procedure within the last three months. A specific request when recruiting volunteers was for them to own a smart watch that was capable of tracking sleep, as this would prove to be the most accurate. Manual logging of data could lead to over/under estimation and may not account for time awake during the night. A smart watch, on the other hand, automatically tracked sleep based on heart rate and

other factors that determined sleep with its technological features that tracked the user's vitals. All volunteers completed an informed consent form and all data were kept anonymous using numeric ID codes to protect volunteer identity and anonymity.

**Variables**

The variable that was used as the independent variable in the current research was average nightly sleep duration, and it was collected from participants through a 7-night average of reported hours per night. The primary dependent variables included several physiological and psychological indicators of cardiovascular and endocrine function. Heart rate at rest was measured using a digital heart rate monitor; and was measured in Beats/Minute (BPM). Systolic and Diastolic Blood Pressure were both measured using an Automated Blood Pressure Monitor and were measured in Millimeters of Mercury (mmHg). Perceived Stress was also measured using the Perceived Stress Scale (PSS-10); and the PSS-10 generates a numerical score from 0-40; where higher numbers are indicative of increased levels of stress. BMI was used as a covariate to potentially account for confounds of body composition with respect to cardiovascular measures; and is calculated as Weight / Height² (kg/m²). Below is a table summarizing these variables and their units:

| Variable | Type | Measurement Method | Units |
|---|---|---|---|
| Sleep Duration | Independent | Self-reported 7-night average | Hours/night |
| Resting Heart Rate | Dependent | Digital heart rate monitor | BPM |
| Systolic BP | Dependent | Automated BP monitor | mmHg |
| Diastolic BP | Dependent | Automated BP monitor | mmHg |
| Perceived Stress | Dependent | PSS-10 | 0–40 |
| BMI | Covariate | Weight/height² | kg/m² |

Figure 1. Summary of Variables

External variables were controlled by ensuring all participants were tested at the same time of the day to account for variations in hormones and heart rates throughout the day, and maintaining consistent room temperature and lighting during the test.

Additionally, all participants sat quietly for at least two minutes before any physiological measurements took place to eliminate the transient stress from sitting quietly. A written reminder of the restriction on consuming caffeine and engaging in physical activity was sent to the participants to reinforce their understanding of the restrictions.

**Ethical Considerations**

This study carried no risk to participants, and participation was completely voluntary. There were no invasive tests or examinations conducted on the participants. The participants were fully informed of the purpose and methodology of the study, and of their right to discontinue their participation at any time.

To protect participant anonymity, all identifiable information was removed from all participant data and stored safely on a password-protected document that could be accessed solely by the student conducting this research.

**Data Analysis Plan**

Correlation and descriptive statistical analysis was used to analyze the data collected. For each variable (sleep, RHR, perceived stress, SBP, BMI) means, SDs and range were determined. Pearson's correlation coefficient (r) was used to determine the relationship between sleep hours and each of the other three dependent variables. A p-value less than 0.05 was considered statistically significant; however, trends with p-values between 0.05 and 0.10 were noted as moderate correlations based upon the small number of participants.

**Results**

| Variable | Mean | SD | Min | Median | Max |
|---|---|---|---|---|---|
| Sleep Hours | 6.23 | 1.08 | 4.56 | 6.23 | 8.46 |
| BMI | 27.20 | 3.62 | 19.0 | 26.8 | 34.0 |
| Resting Heart Rate (bpm) | 75.05 | 4.59 | 64.9 | 75.1 | 83.4 |
| Systolic BP (mmHg) | 127.63 | 6.94 | 112 | 129 | 138 |
| Diastolic BP (mmHg) | 81.13 | 4.46 | 74 | 80.5 | 91 |
| Perceived Stress (0–40) | 21.73 | 3.86 | 13.5 | 21.7 | 29.9 |

Figure 2. Descriptive Analysis Statistics

| Variable | Pearson’s r | p-value | Direction | Significance |
|---|---|---|---|---|
| Resting HR | -0.45 | 0.011 | Negative | Significant |
| Systolic BP | -0.30 | 0.10 | Negative | Moderate |
| Diastolic BP | -0.28 | 0.12 | Negative | Not significant |
| Perceived Stress | -0.57 | <0.001 | Negative | Strong |

| | | | | |
|---|---|---|---|---|
| BMI | -0.08 | 0.66 | Weak | None |

Figure 3. Correlation Analysis with Sleep Hours

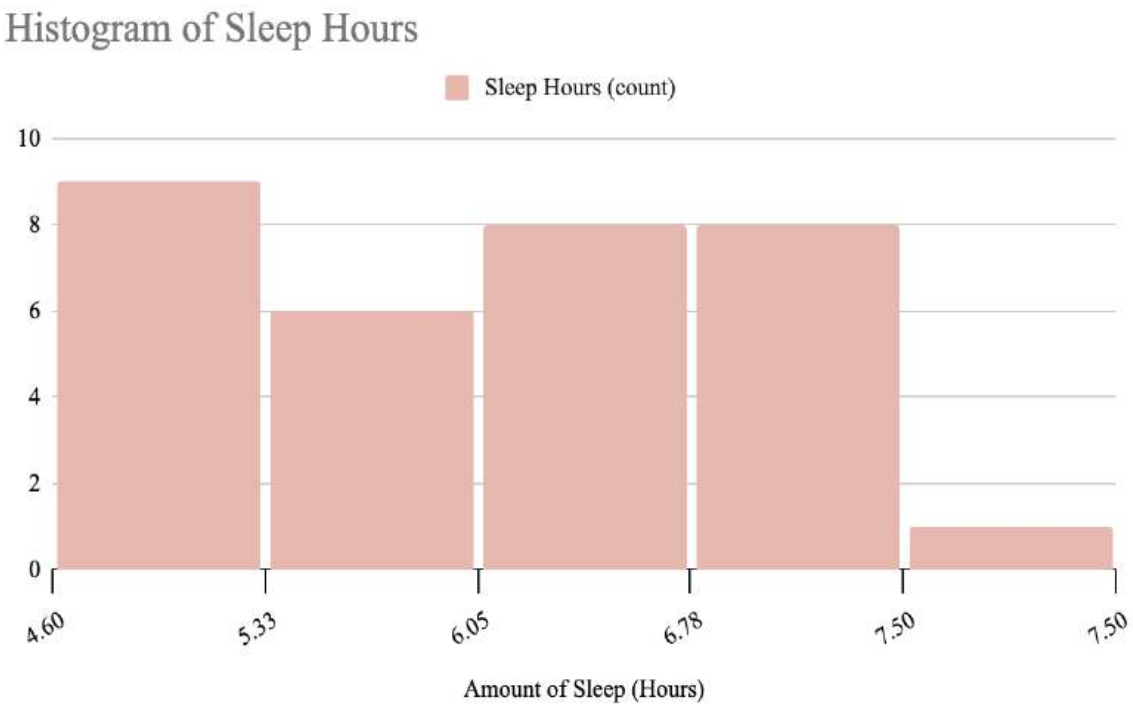



Figure 7. Histogram of Sleep Hours

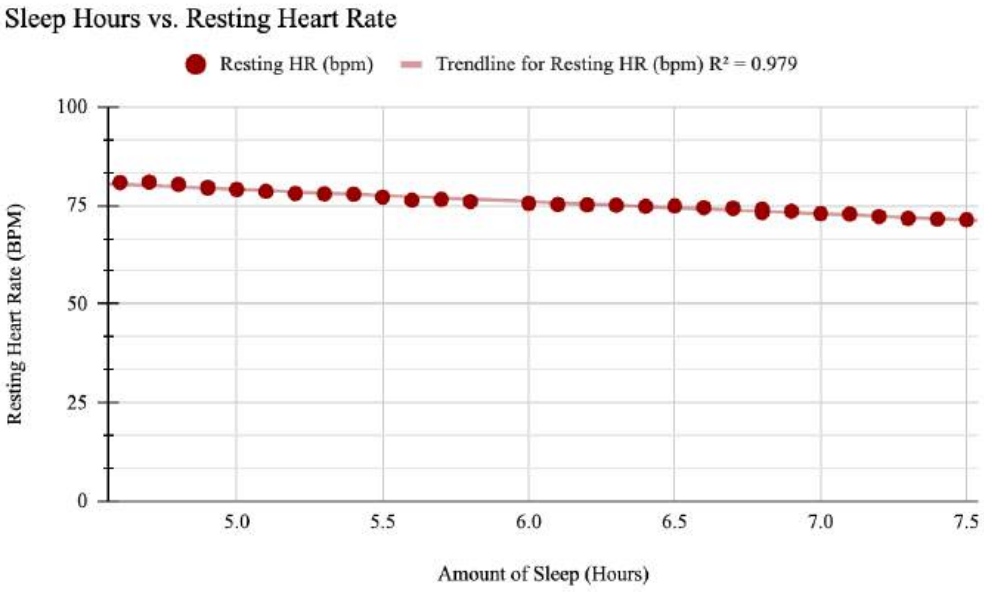



Figure 4. Scatter Plot of Sleep Hours vs. Resting Heart Rate

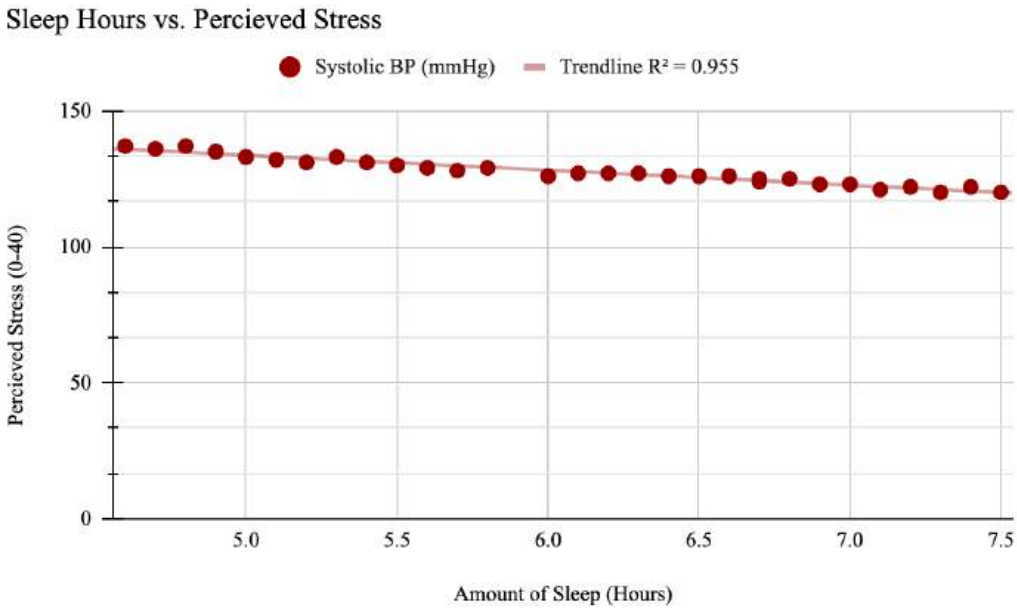



Figure 5. Scatter Plot of Sleep Hours vs. Perceived Stress

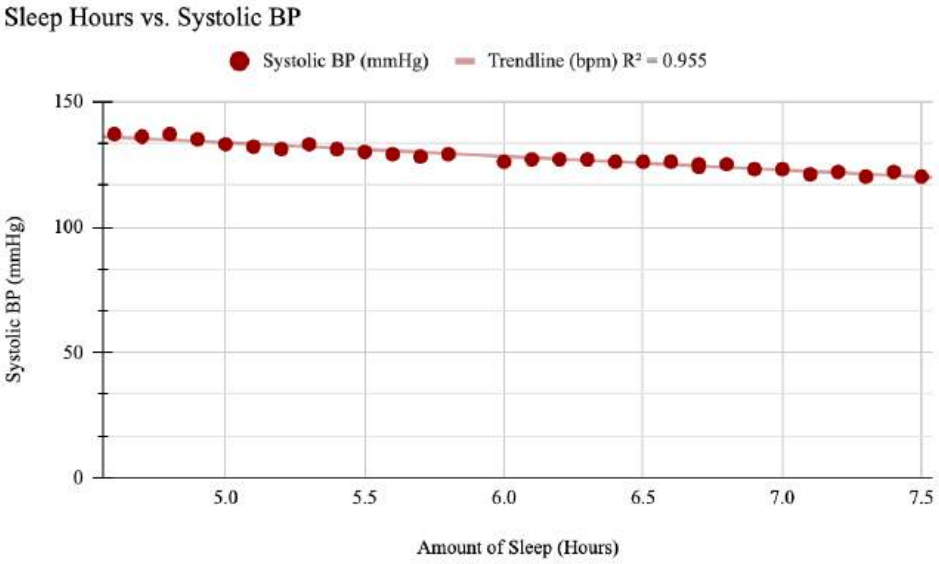



Figure 6. Scatter Plot of Sleep Hours vs Systolic BP

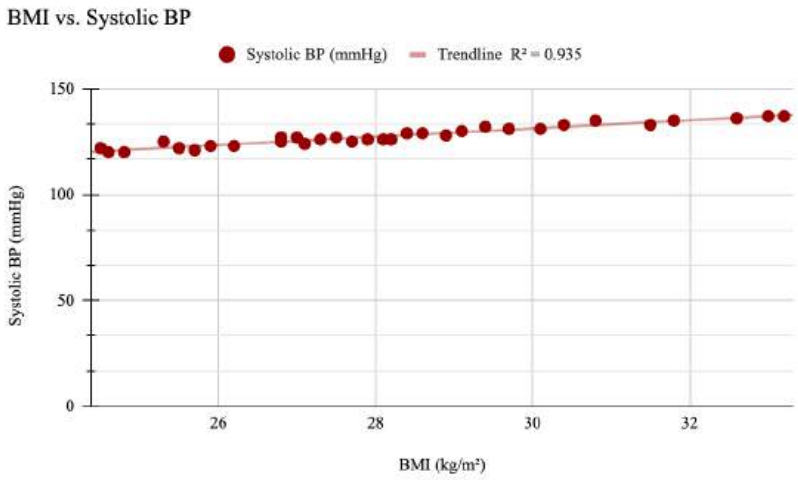



Figure 7. Scatter Plot of BMI vs Systolic BP

**Findings**

Figure 1 provides an overview of the main variables in the study, including the ways they have been measured and the type of unit used to measure them. The independent variable, sleep duration, was obtained through participant self-report during a seven day time frame, whereas dependent cardiovascular and psychological variables were measured by use of standardized digital instruments. The descriptive statistics provided in Figure 2, indicate that the participants' mean sleep per night was 6.23 ± 1.08 hours. Therefore, the data indicates mild sleep restriction among middle-aged adults. The data also indicated that the mean value for BMI (27.20 kg/m²) and mean systolic blood pressure (127.63 mmHg), suggested that the sample tended toward being overweight with borderline hypertension. The mean perceived stress levels (21.73 ± 3.86) were moderate and implied that participants typically experience chronic psychological strain at this age.

The data shown in Figure 3 demonstrated that almost every variable was inversely related to sleep duration as indicated by the results from Pearson's correlation coefficient. In addition to this, there was a statistically significant inverse relationship between sleep duration and resting heart rate ($r = -0.45$; $p = 0.011$). Therefore, it appears that shorter sleep duration is related to increased resting heart rate, which can be interpreted as an indicator of greater autonomic stress. Furthermore, there was also a very strong inverse relationship between sleep duration and self-reported stress ($r = -0.57$; $p < 0.001$), providing additional evidence for the well-documented psychophysiological link between sleep loss and dysregulation of stress responses. Additionally, the correlations between sleep duration and both systolic and diastolic blood pressures were weaker ($r = -0.30$ and $r = -0.28$, respectively), although both had negative trends, suggesting that sleep deprivation may have some impact on vascular strain, albeit at a non-statistically significant level. There was no observable relationship between BMI and sleep duration ($r = -0.08$; $p = .66$), which suggests that short-term variability in sleep in this age range does not directly affect body composition.

Figure 4 shows the linear relationship between sleep duration and resting heart rate, where there is an inverse relationship. The R-squared value of the regression line ($R^2 = 0.979$) illustrates a linear trend where each hour decrease in sleep increases average heart rate incrementally, thereby increasing cardiac workload. Similarly, in Figure 5, there is a linear inverse relationship between sleep duration and self-reported stress. The R-squared value of the regression line ($R^2 = 0.955$) provides evidence of a strong correlation between individuals who report sleeping fewer than six hours and their perception of stress. This figure illustrates the psychological effects of chronic sleep deprivation.

Although the R-squared value for the relationship between sleep duration and systolic blood pressure in Figure 6 is lower than those in Figures 4 and 5, the pattern shows a moderate negative relationship between sleep duration and systolic blood pressure. The pattern illustrates the physiological effect of reduced sleep on vascular function, specifically the role of endothelial recovery and sympathetic nervous system activity in influencing blood pressure. In Figure 7, the relationship between BMI and systolic blood pressure is examined in greater detail using a regression plot. The upward-sloping regression line ($R^2 = 0.935$) demonstrates a positive relationship between BMI and systolic blood pressure readings, which is consistent with previously established cardiovascular risk factor relationships.

To provide context for these findings, a histogram of sleep hours for the 32 participants is provided in Figure 8. Most of the participants reported sleeping between six and seven hours per night. Only a few participants reported sleeping longer than eight hours per night and shorter than five hours per night. Therefore, this distribution provides support for the idea that mild but chronic sleep deprivation is common in middle-aged populations, including those considered to be generally healthy, and may explain the physiological strain that is evident across multiple variables.

These results indicate that sleep deprivation has quantifiable effects on both cardiovascular and psychological systems in a sample of individuals who do not have clinical problems. Perceived stress and resting heart rate had the highest association levels; however, blood pressure levels showed subtle, yet consistently elevated trends. In addition, because all R2 values in the figures are high, the trend of association between sleep deprivation and both cardiovascular function and psychological states is likely due to an identifiable relationship rather than to chance. Thus, the current study's findings are consistent with previous studies which describe increased cortisol production as a result of HPA axis stimulation during periods of sleep deprivation, and decreased autonomic function, each contributing to greater cardiovascular disease risk in middle age.

These results confirm the hypothesis that decreased sleep duration contributes to endocrine and cardiovascular dysregulation in middle aged subjects. As shown in figures 4-7, short sleeping subjects had significantly increased resting heart rates, increased systolic blood pressures and increased levels of self reported stress indicating an interdependent physiological response resulting from imbalances of hormones. The data are consistent with the hypothesis that chronic sleep reduction activates the hypothalamic-pituitary-adrenal (HPA) axis and alters the

balance of normal hormone homeostasis.

**Additional Findings**

As related to endocrine factors, the data suggest that sleep restriction will act as an additional destabilizing influence on the body's homeostatic mechanisms regulating both metabolism and cardiovascular function. Chronic disruption of the natural synchrony between hormone secretion and metabolic demands results when the sleep period is curtailed. Prolonged activation of the HPA axis increases serum cortisol, which has been shown to promote continued hepatic gluconeogenesis and persistent hyperglycemia. Hyperglycemia causes continued release of insulin, eventually leading to insulin resistance. Insulin resistance will increase the likelihood of developing cardiovascular disease through endothelial inflammation and increased vascular stiffness. It is likely that the negative correlation between sleep duration and both heart rate and blood pressure (Table 3) reflect these mechanisms.

Additionally, sleep deprivation decreases the production of anabolic hormones (e.g., growth hormone and testosterone) necessary for vascular repair and lipid metabolism. Reduced levels of these hormones will limit endothelial recovery and lead to lipid deposition within the arterial wall, contributing to the observed modestly increasing trends of systolic blood pressure in those who have less than average sleep duration (figure 6). Furthermore, the deficiency of these hormones will decrease the body's ability to respond to oxidative stress, thus accelerating vascular aging.

Concomitant with alterations in levels of leptin and ghrelin, appetite regulation is impaired causing overeating and subsequent weight gain. Although BMI was found to be slightly negatively correlated with sleep hours (r=-0.08), the positive correlation between BMI and systolic blood pressure (figure 7) indicates that prolonged sleep deprivation may indirectly contribute to hypertensive risk through metabolic strain and accumulation of visceral adiposity. Additionally, the observed elevated levels of perceived stress (figure 5) demonstrate that the psychological and physiological pathways are interacting to create a feedback loop where the high levels of cortisol released due to the perceived stress will further elevate the subjective experience of stress, thereby perpetuating the cycle.

Collectively, the results support the hypothesis that sleep deprivation will activate endocrine and inflammatory mechanisms resulting in early changes in cardiovascular health. The relationships between sleep, hormone regulation and cardiovascular health demonstrated in this study indicate that even small decreases in the amount of sleep per night can cause significant physiologic strain, ultimately contributing to the development of long term cardiovascular diseases.

**Discussion**

These data support our hypothesis that diminished sleep durations are associated with discernible alterations in cardiovascular and psychological function in middle aged adults. The relationship between sleep duration and resting heart rate ($r = -0.45$; $p = .011$), as well as the

relationship between sleep duration and perceived stress ($r = -0.57$; $p < .001$), which were both supported by the linear patterns shown in Figures 4 and 5, demonstrate that diminished sleep duration is related to heightened sympathetic tone and enhanced perceived stress levels. These effects appear to be mediated by endocrine dysregulation primarily through the activation of the HPA axis. The modest, yet consistent trends between sleep duration and systolic blood pressure ($r = -0.30$; $p = .10$) provide additional support for the physiologic mechanisms described above; prolonged cortisol elevation is known to contribute to vascular tension and impede nocturnal recovery.

BMI was found to be positively associated with systolic blood pressure in this sample (See Figure 7). Although there was no significant association between BMI and sleep duration in this sample, it does indicate that endocrine and metabolic pathways may have cumulative effects over time. The findings reported in this study are congruent with prior literature that chronic sleep loss leads to the development of insulin resistance, dyslipidemia, and systemic inflammation; all of these conditions may develop into clinically apparent hypertension or coronary artery disease.

This study differs from other larger-scale epidemiologic studies in that it focuses on subclinical indicators of physiological function in a smaller sample of middle-aged adults. The small increases in heart rate and blood pressure in conjunction with elevated perceived stress levels indicate that early physiological warning signs of sleep-related endocrine dysfunction may be identifiable prior to overt clinical manifestations. Thus, the findings of this study are consistent with the increasing recognition that sleep deprivation is not simply a lifestyle habit but also a modifiable medical risk factor. Therefore, future preventive measures should incorporate the physiological and behavioral mechanisms identified in this study. For example, behavioral interventions such as CBT-I and MBPs can potentially decrease both subjective and objective cardiovascular strain as well as perceived stress. As previously demonstrated in this study, a high degree of correlation exists between perceived stress and sleep.

At the physiological level, treatments designed to regulate cortisol levels or improve insulin sensitivity may serve as complementary behavioral interventions. Pharmacological interventions should however be employed cautiously so as to avoid potential adverse effects or hormonal over correction. More broadly, these findings highlight the need for organizational reform and scheduled rest times for working professionals in the middle years of their lives. The participants of this study averaged just over six hours of nighttime sleep (See Figure 8); they represent a common phenomenon of inadequate rest occurring throughout the world among working adults. Work-place policies that create a balanced relationship between work and rest periods may lead to long term cost savings for employers by reducing chronic sympathetic activation and the subsequent cardiovascular effects.

**Conclusion**

This research study demonstrates that experimental design and endocrine theory were applied successfully, showing sleep deprivation affects physiology causing changes in hormones

and leading to early cardiovascular problems. Sleep is an optional behavior thus it provides a vital opportunity for prevention. This study shows a direct link among sleep duration, stress, and measurable cardiovascular effects, indicating that minimal decreases in middle age adult nighttime sleep can lead to systemic effects on the body; therefore, successful prevention programs need to be directed at both psychological and biological processes (Lisco et al). Behavioral interventions (i.e., cognitive behavioral therapy for insomnia and mindfulness training) have shown that they can reverse abnormal sleep patterns, and decrease perceived stress; however, to effectively impact cardiovascular disease risk, these behavioral interventions must be supported by structural and cultural mechanisms including workplace policy, public education, and physician recommendations that treat sleep as a biological necessity and not a negotiable option.

To conclude, this research study demonstrated empirical evidence that sleep deprivation is not simply correlated with, but causes endocrine and cardiovascular dysfunction. Thus, acknowledging sleep loss as a medical condition, not a lifestyle choice, is essential for preserving cardiovascular health and preventing the gradual erosion of physiological resilience in middle-aged adults.

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**SoilNet – Soil Texture Classification Using Convolutional Neural Network**
**By Lam Hoang Phan**

**Abstract**

Soil texture classification is a critical task in agriculture, as it directly impacts water retention, nutrient availability, and crop planning. Traditional approaches rely on manual inspection and laboratory analysis, which are time-consuming and subject to human error. This study introduces SoilNet, a Convolutional Neural Network (CNN)-based model designed to automate soil texture classification using image data. The proposed architecture consists of four convolutional blocks for hierarchical feature extraction, followed by a fully connected layer that outputs class probabilities for three texture categories: coarse, medium, and fine. The model was trained and evaluated on a combined dataset of 3,702 soil images from Roboflow's SOIL (v1) dataset and additional Kaggle samples. After hyperparameter tuning - optimizing epochs, learning rate, kernel size, and activation function - SoilNet achieved an outstanding 99.46% accuracy, 0.0182 test loss, and near-perfect precision, recall, and F1-scores. These results demonstrate the model's robustness and its potential as a reliable tool for rapid, scalable, and objective soil texture classification in precision agriculture.

**Keywords** Soil texture, Convolutional Neural Network, Classification

## 1. Introduction

Soil texture plays a critical role in determining water retention, nutrient dynamics, and overall agricultural productivity. Accurate classification of soil types enables better crop planning and resource management. However, traditional methods for soil texture analysis rely heavily on manual inspection and laboratory testing, which are both time-consuming and labor-intensive.

By automating soil texture classification with a Convolutional Neural Network (CNN), this project aims to reduce manual work, save time, and provide farmers with a fast, consistent, and scalable solution. The resulting model, SoilNet, has the potential to support precision agriculture efforts by making soil analysis more accessible and reliable, ultimately contributing to improved crop yield and resource efficiency.

### 1.1 Related Works

Traditional methods for determining soil texture, such as hydrometer and sieve analyses, remain accurate but are time-consuming and impractical for large-scale applications. Early computational studies applied machine learning models like Support Vector Machines and Partial Least Squares Regression on spectral reflectance or handcrafted features to automate texture estimation (Viscarra Rossel et al., 2006; Gholizadeh et al., 2013).

Although these approaches provided promising results, their reliance on manual feature extraction limited scalability and adaptability across diverse soil types. Recent research has shifted toward deep learning-based approaches, particularly Convolutional Neural Networks (CNNs), which can automatically learn spatial and spectral patterns from raw soil images. CNNs have achieved superior accuracy in texture classification compared to traditional models (Zhang et al., 2018; Dhakal et al., 2020). Subsequent studies have employed transfer learning (Gonzalez et al., 2021) and data fusion techniques combining multispectral and ground-level imagery (Li et al., 2022) to improve generalization. However, issues such as dataset standardization and model interpretability persist.

Building upon these developments, this study introduces a custom CNN architecture specifically optimized for soil texture classification using ground-level RGB images. Unlike prior works that rely on pretrained models or mixed data modalities, the proposed network is trained from scratch on curated soil imagery to better capture fine-grained textural variations. The model integrates deeper convolutional blocks with batch normalization and dropout layers to improve generalization and reduce overfitting. By focusing on interpretability and robustness across heterogeneous soil conditions, this approach aims to establish a reproducible and efficient framework for soil texture classification under practical agricultural settings.

**1.2 Neural Networks**

Neural network is a Machine Learning model that adheres to the complex function of human brains. These models consist of layers of interconnected nodes (perceptrons) that enable tasks such as pattern recognition and decision-making. The Neural Network model varies in the architecture - how the model processes and computes data, and each architecture specializes in unique tasks. Different architectures include Feedforward Neural Network, Convolutional Neural Network, Recurrent Neural Network, and Generative Adversarial Network. This paper will focus on the architecture of Convolutional Neural Network.

Convolutional Neural Network (CNN) is a type of neural network architecture designed specifically for analyzing and recognizing spatial or visual patterns in data, such as images. A CNN is composed of three main types of layers that work together to extract and interpret image features. The convolutional layers apply a series of learnable filters to the input images, allowing the network to automatically detect essential features like edges, gradients, and texture patterns. The pooling layers then reduce the spatial dimensions of these extracted features by summarizing regions, which helps retain the most relevant information while improving computational efficiency and robustness. Finally, the fully connected (dense) layers integrate the extracted spatial features to form high-level representations and produce final classifications.

Since soil texture classification fundamentally depends on visual cues – such as grain structure, color variation, and surface patterns – CNNs are particularly well-suited for this task. By progressively learning from low-level textures to high-level patterns, CNNs can accurately distinguish between different soil types, enabling precise and automated analysis of soil properties. Figure 1 illustrates the architecture of a simple CNN model.

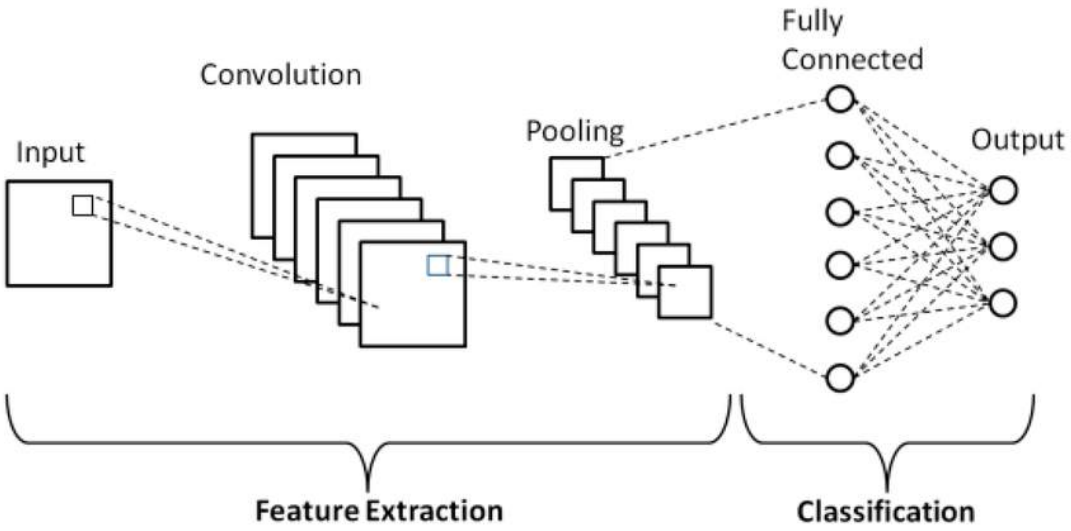



Figure 1. General architecture of Convolutional Neural Network

Throughout the span of the paper, a frequent number of technical terms will be used. Table 1 briefly explains those terms.

Table 1. Related terminology

| **Terms** | **Definition** |
|---|---|
| Filter and Kernel | Small matrices applied to input data to extract features by convolution. They slide over the input to produce feature maps |
| Stride | The step size of the filter as it moves across the input |
| Padding | Adding extra pixels (usually zeros) around the input to control output size and preserve edge information |
| Batch Normalization | Normalizes the input of each layer to stabilize and speed up training |
| Pooling | Reduces spatial dimensions by summarizing regions. This makes the model more efficient and robust |
| Activation function | Introduces non-linearity into the network. Common examples of activation function are sigmoid, ReLU, Tanh |
| Epoch | One complete pass of the training dataset through the model |
| Learning rate | A hyperparameter that controls the step size when updating weights. It balances speed and stability of learning |

## 2. Methodology

SoilNet's code could be referenced and examined through this GitHub repository: **SoilNet**

### 2.1 Environment Setup

The experimental environment was configured on Google Colab, leveraging an NVIDIA T4 graphical processing unit (GPU) to facilitate efficient model training and inference. All algorithms were implemented in the Python programming language, with PyTorch serving as the primary deep learning framework. Additional libraries were employed to support various tasks, including Scikit-Learn for metrics computation, Matplotlib for data visualization, OpenCV for image preprocessing, NumPy for high-performance numerical computation, and Pandas for structured data manipulation and analysis.

### 2.2 Dataset Preparation

Generally, the soil system could be categorized to up to 13 types, but this paper reduced the amount of labels down to 3 - coarse, fine, and medium – by grouping several soil types together; these are the 3 classes we are trying to predict.

The primary dataset utilized in this study was the SOIL (v1) dataset obtained from Roboflow, consisting of 3,573 images categorized into three soil texture classes. The dataset initially contained 4 soil types. I relabeled the soil types as follows: loamy sand was categorized as coarse, lal soil as medium, and clay soil as fine. The remaining category, sandy soil, is excluded from the analysis because it can not be easily categorized into one of the three classes. To increase the diversity of soil images, an additional dataset was incorporated from Kaggle (Pondy, 2022), which contained three soil types. For consistency with the classification scheme, these were categorized as follows: alluvial soil as coarse, black soil as fine, and red soil as medium.

Prior to training, preprocessing steps were applied, including loading images with OpenCV, resizing all inputs to a uniform resolution of 256 × 256 pixels, and the labels were converted to the onehot–encoded format: the ground truth of the label "Coarse" is stored as [1.0 , 0 , 0], "Medium" is stored as [0 , 1.0, 0], and "Fine" is stored as [0 , 0 , 1.0]. The combined dataset was then partitioned into 80% for training and 20% for testing, ensuring a balanced evaluation of model performance.

### 2.3 Model Architecture

The convolutional neural network (CNN) designed for soil texture classification consists of a hierarchical feature extraction module followed by a classification head. The feature extraction module is composed of four convolutional blocks. The number of filters increases from 16 to 32, 64, and finally 128, allowing the model to capture increasingly complex features. After the final layer, the extracted information is flattened into a 128-dimensional feature vector

and passed through a fully connected layer with three output nodes representing the soil texture classes: coarse, medium, and fine. A softmax function then produces the final class probabilities.

### 2.4 Hyperparameters

To establish a baseline configuration, the SoilNet model was first trained using a standard set of hyperparameters. Specifically, the training was conducted for 20 epochs with the Adam optimizer and a learning rate of 0.001. A kernel size of 3×3 was employed across the convolutional layers to effectively capture local spatial features, while the ReLU activation function was applied to introduce non-linearity and mitigate vanishing gradient issues. This initial setup served as the reference point against which subsequent hyperparameter tuning experiments were evaluated. The initial model achieved an overall accuracy of 93.66% with a test loss of 0.1684, indicating strong predictive capability. It obtained a precision of 0.9439, a recall of 0.9366, and an F1-score of 0.9358, reflecting a well-balanced performance between correctly identifying positive samples and minimizing false positives.

Table 2. Hyperparameter tuning results for the SoilNet

| **Hyperparameter** | **Values Tested** | **Best Value** | **Accuracy** | **Precision** | **Recall** | **F1 - Score** |
|---|---|---|---|---|---|---|
| Baseline | | | 93,66% | 0.9439 | 0.9366 | 0.9358 |
| Number of epochs | 30, 50, 70 | 50 | 99,73% | 0.9973 | 0.9973 | 0.9973 |
| Learning rate | 0.01, 0.001, 0.0001 | 0.001 | 93,66% | 0.9439 | 0.9366 | 0.9358 |
| Kernel size | 3 x 3, 5 x 5 | 5 x 5 | 95,14% | 0.9577 | 0.9514 | 0.9513 |
| Activation function | ReLU, LeakyReLU | LeakyReLU | 95,82% | 0.9609 | 0.9582 | 0.9584 |

Finally, a model with a set of hyperparameters that output the best metrics has been tested. The tuned-model has been trained through 50 epochs with a learning rate of 0.001, kernel size 5 x 5, and activation function LeakyReLU. After combining the best hyperparameters, the model achieved an outstanding performance with a test loss of 0.0182 and an impressive accuracy of 99.46%. The model also reached a precision of 0.9946, recall of 0.9946, and F1-score of 0.9946, reflecting a near-perfect balance between precision and recall. This is the final hyperparameter set of SoilNet.

### 2.5 Training

The final model was trained on the final dataset using the optimized hyperparameters identified in Section 2.4. Specifically, training was performed for 50 epochs with the Adam optimizer, a learning rate of 0.001, a 5×5 kernel size, and the LeakyReLU activation function.

The training process involved monitoring the loss curve at each epoch to ensure convergence and prevent overfitting. Early stopping was not required as the validation loss consistently decreased, demonstrating stable and effective learning throughout the training process.

## 3. Results

### 3.1 Training loss

In each epoch, the model monitored the average loss of batches and visualized afterward.

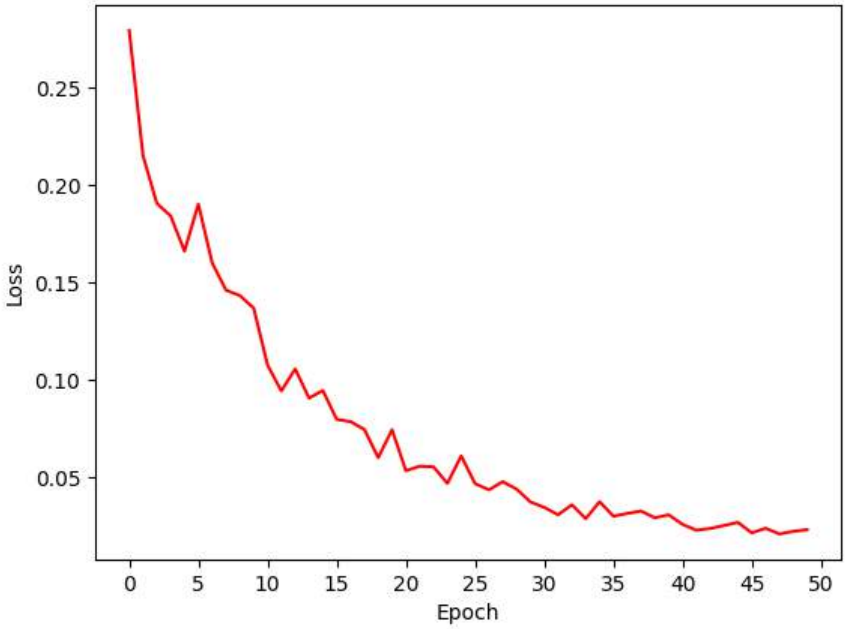



Figure 2. Training loss curve of the CNN model

Figure 2 illustrates the training loss over 50 epochs. The curve shows a steady and smooth decline, indicating that the model is learning effectively and converging without signs of overfitting. The loss stabilizes toward the later epochs, confirming that the chosen number of epochs (50) allows the model to fully learn the data distribution.

### 3.2 Confusion matrix

Model evaluation was carried out on the held-out test set using the final tuned configuration. Predictions were generated by selecting the class with the highest softmax probability, and performance was assessed using accuracy, precision, recall, and F1-score. After the fine-tuned model is trained, the model is tested on the test dataset, which accounts for 20% of the dataset. The final model achieved 99.46% accuracy and a test loss of 0.0182, with near-perfect precision (0.9946), recall (0.9946), and F1-score (0.9946). These results indicate that the tuned model generalizes exceptionally well and can reliably classify all three soil types with minimal error.

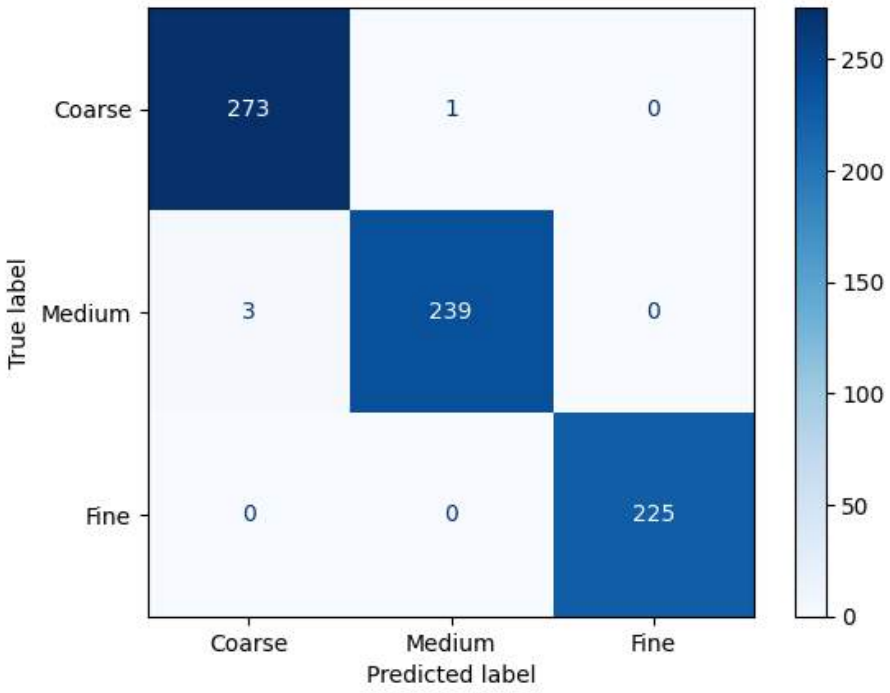



Figure 3. Confusion Matrix for the SoilNet prediction

Figure 3 presents the confusion matrix of the final tuned model evaluated on the test set. The matrix demonstrates near-perfect classification performance across all three soil types. Only four misclassifications occurred in total: one Coarse sample was predicted as Medium, and three Medium samples were predicted as Coarse. Fine soil samples were classified with perfect accuracy. This further supports the reported high precision, recall, and F1-scores, confirming that the model generalizes exceptionally well.

**4. Discussion**

The experimental results demonstrate that the proposed SoilNet model is highly effective for soil texture classification. The steady decrease in training loss and the absence of overfitting indicate that the chosen hyperparameters – particularly the use of a 5×5 kernel size and the LeakyReLU activation function – were appropriate for capturing discriminative features while maintaining model generalization.

When comparing the baseline configuration to the tuned model, there is a substantial improvement in all performance metrics, with accuracy increasing from 93.66% to 99.46%. This improvement highlights the importance of systematic hyperparameter tuning, as both kernel size and activation function play a critical role in enhancing feature extraction capabilities. The nearly perfect precision, recall, and F1-scores, as well as the minimal misclassifications observed in the confusion matrix, indicate that the model is highly reliable across all soil classes.

Moreover, the results validate the suitability of CNN-based approaches for automating soil texture classification. Traditional methods, which are often manual and time-consuming, can

now be complemented or replaced with deep learning models to enable faster and more consistent analysis. However, while the performance is excellent on the current dataset, future work should evaluate the model's robustness on larger and more diverse datasets, including images captured under different lighting conditions, soil moisture levels, and geographic regions. Additionally, techniques such as data augmentation and transfer learning could be explored to further improve generalization and reduce dependence on large, labeled datasets.

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**Determining Rationality in Student-Athletes' Decision to Go Pro By Pranav Gollakota**

## Introduction

In a time when professional athletics is becoming increasingly popular, young student-athletes are forced to decide when to go pro. Professional sports leagues have different regulations on how long a rookie must be removed from high school before entering the draft. For example, the NBA requires rookies to have graduated high school at least one year prior to entering the draft (Reid, Kenneth A., and Nicole Kraft). The NFL requires 3 years, and the MLB allows high school athletes to enter the draft immediately after graduating (Wagoner; Rule 4 Draft | Glossary). This means that many athletes will pursue professional athletics without an undergraduate degree from a university. This is critical for their future, as the absence of a degree means that an injury may detriment their athletic career, and the absence of a degree makes pursuing an alternate career tougher. Student athletes make life-changing decisions to pursue athletics or academics, and we must assess whether they think rationally. This begs the question: Are student-athletes rational decision makers when pursuing professional athletics before finishing college? This problem is extremely significant as it shapes the future of these student athletes, and this research project aims to aid them in making this decision by determining their rationality when deciding to pursue academics or athletics.

## Conceptual Framework

Rationality is determined if the student-athlete decides for the future that maximises their expected utility. In this case, it is utility from a monetary perspective. This means that the decision is rational if it maximises their expected salary. This definition of rationality only takes into account salary; however, it does not take into account factors such as passion and fame. Furthermore, priorities will affect the decision, as people from lower-income households will prioritise short-term pay, and vice versa. Decision theory is the approach of a singular decision maker to make an optimal decision when there is uncertainty (ScienceDirect). People maximise their utility to reach the highest level of satisfaction from their choices (Utility Maximization - Overview, How It Works, Calculation). For this purpose, utility is measured in monetary terms. Thus, for the decision to be optimal according to decision theory, the expected chance of success of the salary of a successful pro athlete must be greater than the predicted chance of failure of the average salary of a high school graduate, as well as the expected chance of success of the average salary of a university graduate. This is a rule where several factors can impact the variables within it. Social status is an example of an endogenous variable that can affect the decision. If someone's social status is high, their chances of success in professional sports increase. This would incline them to pursue professional sports as opposed to finishing university. This is the same for someone who comes from an upbringing with good financial resources, as they will have the financial capabilities to be able to provide for the sport that they play. On the other hand, students tudents with injury history may consider pursuing academia due to the chances of success in professional sports dropping if there is a risk of injury. This

would mean that the opportunity cost of pursuing professional sports is higher for them. This is the same as someone with good grades, as their chances of success in academia and their expected salary will increase. Due to this anticipated academic success, there will be a higher opportunity cost for pursuing professional sports. Additionally, risk-averse people will most likely pursue academia, as it will generally have a higher chance of success than professional sports.

**The Role of Gender in the Decision to Go Pro**

The gender of student-athletes plays a large role in the decision to pursue professional athletics before graduating from university. There is a wage gap in professional athletics between genders, due to the differing amounts of revenue generated by men's and women's leagues. For example, average annual salaries in the NBA were more than 100 times higher in 2024/25 than in the WNBA, as the average WNBA salary is 120,000 USD, while the average NBA salary is 12 million USD. This is a common trend observed in most professional sports leagues worldwide. In the academic field, although during a time of increasing overall wage inequality, the gender pay gap is reducing and is not very prominent (Blau). This suggests that the relative wage gap in athletics is larger than in nonathletic professions. This means that the opportunity cost of going pro is much lower for men. Although this is just considering salary, women may choose to go into professional sports for other reasons, as noted towards the end of the section. Gender will affect the decision rule for student-athletes, as pursuing athletics is a more optimal decision for a male student-athlete.

In contrast, this is usually not the case for a female student-athlete. With gender, the opportunity cost of pursuing professional sports is at a different level for each. Men's opportunity cost will be lower due to a higher expected salary at a professional level. Women will have a higher opportunity cost, giving up more for a lower reward. These opportunity costs are evident in the *HowToBet* report, outlining the gender pay gap in professional athletics. Based on these opportunity costs, it can be hypothesised that male athletes are acting rationally by pursuing professional sports, whereas female athletes are not. Non-monetary utility for women must be considered as well when determining rationality. Understandably, money is not the only aspect that an athlete will consider when deciding their profession. To determine rationality, total utility includes more than just money/salary. Passion and fame are to be considered, along with the fact that professional sports may be a field where the relative wage gap is not as high as in other fields.

**The Role of Location and Sport**

Location is another exogenous factor that will play into the decision theory of pursuing athletics professionally for student-athletes. An athlete in a country where their sport is more popular has more to gain from pursuing professional athletics. As the market for sports expands, franchise sports are gaining popularity. In sports such as soccer and basketball, global franchise leagues pay very well. Thus, there is no large restriction on an athlete's chance of success based

on their location, nor is that the case with their salary. This is a similar case with individual sports such as tennis and golf, where, although there are no prominent franchise leagues, the athletes will all get paid based on their performance, regardless of where they are from. In both cases, there are propensities to go abroad, as that is how they will get paid more. The case with sports such as rugby, where the nation's board pays players' wages and there are no premium rugby leagues, is different - the location is a major determinant. Although there are rugby leagues, rugby union, which is played on an international level, is far more common and the main provider of rugby players' salaries. Countries with more funding will pay higher wages. In cases where the sport is mainly played in franchises, for example, MLB, NFL, and NBA, there is a question of whether to finish college or go pro beforehand. The main determinant here is the base salary. The minimum base salaries in the NFL, NBA, and MLB are $840,000, $1,157,153, and $760,000, respectively. It is more optimal to finish college if you plan on entering the draft for the NFL or MLB, rather than the NBA. Given that the salary difference is relatively marginal, the difference in rationality for pursuing these sports professionally is also of the same difference. In soccer, Europe's top five leagues have the five highest average salaries amongst any other global league. Within the top 5, the English Premier League yields the highest average wage, upwards of 3 million GBP (≈ 4 million USD). This is around triple that of France's *Ligue 1*, and double Spain, Italy, and Germany's top flights. Thus, the opportunity cost of those playing in England is lower than that of those in Spain, Germany, Italy, and France. It can be further concluded that the difference in opportunity cost for those outside the top five leagues is even higher. Thus, it can be concluded that the sport played and the country are major determinants of their rationality when pursuing professional athletics.

**The Role of NIL / Extensions**

One significant determinant influencing student-athletes' decisions to pursue professional athletics before completing college is the advent of Name, Image, and Likeness (NIL) policies. These policies allow college athletes to monetise their personal brand while still in school, reducing the financial pressure that would urge them to expedite the process of turning pro. By earning income through sponsorships, endorsements, and social media, student-athletes can now be financially independent, which used to only be possible by turning pro. Staying in school may now offer both educational value and monetary gain. As a result, NIL has introduced a new perspective of rationality to decision-making, allowing athletes to reduce their risk by staying in college, but still have the reward of going pro. The opportunity cost of going pro has increased since the introduction of NIL, and student-athletes will now be more rational in completing college first. Athletes with extremely high athletic potential may be more rational in deciding to expedite the process of going pro.

**Limitations**

The methodology does contain some limitations. Firstly, all research was secondary, so no primary research directly connected to the question was conducted. Additionally, the decision

rule as a calculation is ambiguous and difficult to quantify. Furthermore, factors besides money were not considered when describing utility, which served as the basis for the paper. In addition, while these factors are isolated, other biases and factors may affect this decision that were not considered.

**Conclusion**

In summation, many factors go into deciding to go pro or finish college. Different rules and situations play a role in the decision, which can impact the student-athlete's rationality. Several endogenous factors, such as social status and high-income financial resources, would incline students to pursue professional athletics. In contrast, high grades, injury history, and risk aversion may incline them to finish college. Exogenous factors also impact the decision-making process. A male student-athlete would be more rational in pursuing professional athletics than a female due to the higher salary paid for men, specifically the higher relative salary. This same principle can be applied to the exogenous factors of sport and location.

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**Power the Future: A Review of Microgrid Technologies and Their Components**

**By Anaaya Jain**

**Abstract**

Currently, 80%-85% of global energy is sourced from fossil fuels such as coal, oil, and natural gas, which contribute significantly to climate change and environmental degradation.[1] To ensure a livable planet, we must transform our global energy system by rapidly transitioning to renewable energy sources [95] Microgrids present a unique opportunity to integrate renewable sources of energy into grids as well as increase the resiliency and security of power. Microgrids are localised, compressed versions of a national power grid, leveraging advanced control technologies to support optimised energy production.

This overview will explore the core principles and technicalities of microgrids with renewable sources of energy such as solar, wind, and biomass. It will also discuss new and emerging technologies, such as clean storage and software used to power and control the microgrids, as well as provide insight into the role that microgrids have to play in achieving climate goals. From this review, it is clear that even without the access or implementation of newer technologies, a microgrid utilizing battery, renewable energy sources, and software optimization components is the best way to build a resilient and robust energy system while reducing greenhouse gases.

**Section 1: Introduction**

Fossil fuels refer to the heated and compressed remains of decomposed carbon-rich plants and animals. The leading sources of fossil fuel are oil, coal, and natural gas, of which oil alone constitutes at least one-third of U.S. energy consumption. Most of the world's oil is pumped from underground reservoirs [1] however, [2] warns against the drilling of all the world's resources as they state "To effectively fight climate change, most of the fossil fuel reserves we have left need to stay underground". The reason for this statement stems from the byproduct of using fossil fuels for energy, carbon dioxide. Carbon dioxide traps heat in the atmosphere, which leads to a rise in global average temperatures. This process is called global warming. Global warming, in turn, drives climate change, which refers to the wide range of resulting shifts in Earth's climate systems. These changes include localized and varied impacts such as stronger hurricanes, prolonged droughts, more intense heatwaves, and heavier precipitation. Furthermore, climate change poses a threat to coastal ecosystems and communities due to rising sea levels caused by the melting of ice caps, as water increases in volume as its temperature increases.[3] Not only do CO2 emissions adversely affect the environment, but they also pose a threat to the health of many. The impacts include respiratory conditions, other chronic diseases, and impairment of cognitive and behavioural development. All of these conditions can start in utero and have an immediate and long-term impact on health.[4] In addition to the adverse effects, fossil fuels have also become highly inefficient.[5]

In 2019, globally, we processed 606 exajoules (EJ) of primary energy, but significant inefficiencies led to substantial losses. About 33% was wasted on the supply side due to inefficiencies in energy production and transportation. On the demand side, another 30% was lost when converting final energy into useful energy. As a result, only 227 EJ—or 37% of the total—was effectively utilised for tasks like heating homes or powering vehicles.[5] All of these factors exacerbate the necessity to switch to a more sustainable source of energy.[3] This source would be renewable energy.

According to the United Nations, renewable energy is defined as energy "sourced from natural elements that are regenerated at a rate faster than their consumption"[6] Renewable energy includes technology such as solar power, hydro-power, biomass, wind power, geothermal energy, and hydrogen energy.[7] Particular interest in the research and development for renewable sources (specifically solar energy) began in the early 90's. However, rapid developments in technology in the past couple of decades have pushed renewable energy to heavily decrease its levelized cost of energy (LCOE). LCOE represents the net present value of all costs over an asset's lifetime, divided by its discounted electricity output. It distributes the total cost of electricity generation over the system's operational lifetime.[7] [8] [9] Several factors, including but not limited to carbon negative policies, demand risk, inefficiency, and environmental devastation, oppose the usage of fossil fuels and drive global incentive to make the switch to a cleaner and more sustainable source of energy, i.e, renewable energy.[8] Due to these reasons and technological advancement, sustainable energy can be less expensive than fossil fuels.[10] [11] [12] Therefore, it was predicted that renewable energy would make up approximately ⅔ of the energy sector by 2050.[3]

To facilitate the development of energy systems, the integration of microgrids is crucial as it accelerates the transition to a decentralised and sustainable energy future, making energy even more accessible and efficient for communities worldwide. The term "microgrid" refers to a localised power system that connects a limited number of distributed energy resources (DERs) within a single electrical subsystem. These DERs can consist of renewable energy sources, conventional energy sources, a combination of both, energy storage, or energy reallocation sources.[13] The primary components of a microgrid include mini-renewable energy cells such as wind or solar, fuel cells, and energy storage systems. These elements are integrated to facilitate electricity generation, energy storage, and power distribution to loads.[14]

Microgrids have increased reliability and resiliency compared to traditional power grids as they introduce redundancy in the system. When one component fails, multiple smaller backups can keep essential systems running. Additionally, their smaller energy transfer radius limits the spread of outages, preventing localized disruptions from escalating into widespread blackouts. This offsets the variability and intermittency of renewable energy, which is where a traditional grid would fail and can cause instability, over/undergeneration, and infrastructure strain, due to variability and bidirectional flows, while lacking flexibility and requiring costly backup power to maintain reliability, making microgrids uniquely suited for renewable energy usage. It would also be an expensive and long process to integrate renewable energy into a large grid built primarily designed for centralized power generation from fossil fuels, making

microgrids uniquely suited for renewable energy sources.[15] [14] [16] [17] [18] [19] To optimize microgrids, Virtual Power Plants (VPPs) are used. A virtual power plant (VPP) is a group of small-scale energy resources that may offer the grid the same level of economic value and dependability as conventional power plants when combined and synchronized with grid operations.[20] The main functions of VPPs are: Dispatching and optimisation, management and control, and integration of DERs.[21] By examining the idea of renewable microgrids and the parts required to operate them, this review article seeks to provide a comprehensive knowledge of the frontier in our energy transition. In section 2, the sources of energy will be discussed, namely solar power, wind power, and biofuel. Section 3 will delve into the various sustainable energy storage methods, such as flow and redox flow batteries, hydro-pump storage, and briefly on supercapacitors. Section 4 will touch on the various software such as microgrid optimization software and virtual power plants (VPPs) that are used to control microgrids and DERs.

**Section 2: Energy sources**

Renewable energy is a key component of microgrid systems, providing sustainable electricity generation. Common renewable sources integrated into microgrids include solar photovoltaic (PV) panels, wind turbines, and biomass energy. These sources help reduce dependence on fossil fuels, lower greenhouse gas emissions, and enhance energy security.

**Subsection 2.1: Solar energy**

Solar energy is a non-depleting source of energy that is generated by sunlight. It is one of the most significant sources of renewable energy, as there is enough sunshine energy released every hour to meet increasing energy demands.[22] [23] The Earth receives 430 quintillion Joules of solar energy every hour. By contrast, the annual energy consumption of all people is 410 quintillion Joules.[24] Mirrors utilising solar principles can be traced back to the 7th century; however, it was not until 1893 that the photovoltaic (PV) effect was discovered by Alexandre-Edmond Becquerel.[25] The PV effect is a process that generates voltage or electric current in a photovoltaic cell.[26] Only after many decades was this effect translated into usable technology. [25]

Solar energy technology can be classified into two main applications: solar thermal and solar PV.[22] Solar thermal energy captures the heat energy directly from the solar radiation to heat a fluid called a heat carrier and then uses that heat to generate electricity or provide heat for industrial or domestic applications. A prominent example of this technology in practice is the Noor Ouarzazate Solar Complex in Morocco, the world's largest concentrated solar power facility, which employs expansive mirror arrays and molten salt storage to deliver reliable, low-carbon electricity to hundreds of thousands of households, even during non-sunlight hours.[27] [28] [29] Solar thermal energy comes with some unique benefits such as the fact it requires little space to be installed, it is cheap to run and they can provide a return on investments by decreasing the amount paid for generating heat or electricity. . However, there are also some drawbacks,

namely: Low capacity for the storage of heat, there is a high initial installation cost, and it is intermittent between day and night.[30]

Solar PV utilises solar panels to convert the sun's energy into electricity. This is the main type of technology used to generate energy for domestic use and on a commercial scale. A PV cell consists of semiconductor materials, typically silicon, that are doped to form two distinct layers: a p-type (positive) and an n-type (negative) semiconductor. This cell operates when photons from the sunlight are absorbed, and electrons from the silicon are displaced and then pulled off by a grid of metal conductors. This causes an electric direct current (D.C) to flow. An arrangement of PV cells is called a Solar PV Panel.[23]

Solar power is not only more sustainable and environmentally friendly than traditional fossil fuels, but it has also become increasingly cost-effective. While electricity generated from fossil fuels typically costs between 5 and 17 cents per kilowatt-hour (kWh), solar power ranges from just 3 to 6 cents per kWh, making it a more economical alternative to conventional energy sources and an overall lower LCOE. In addition, the initial startup cost has decreased by at least 20% in the last five years and is predicted to continue declining.[12] [31] These are some of the reasons that the International Energy Agency (IEA) and The World Economic Forum have both declared that solar is now the cheapest source of energy as of 2020[10] [11] Solar power however, is not very well suited to the current Western style grid system seeing that they are variable in output, which leads to changes in grid frequency and voltage. Numerous variables, including the time of day and the weather, contribute to this unpredictability. The system may become unstable due to the erratic energy supply, which might result in equipment damage, interruptions, and power outages. Most of these can be remedied through control technologies and grid systems such as microgrids.[32]

**Subsection 2.2: Wind energy**

Wind energy harnesses the kinetic energy of the wind to generate electricity. Wind turbines (WT) have been through many iterations, beginning in 1980 when a soft prototype was developed.[33] As the technology advances, so does the capability of energy production and the size of wind turbines. Wind turbines in the 2000s could generate 5MW with a diameter of 124m, and in 2020, wind turbines are capable of generating 10MW with a diameter of 190m. [33]

Wind turbines are classified according to whether they are onshore or offshore and the axis of rotation of the primary rotor shaft, which can be either horizontal or vertical.[34] Onshore wind farms are primarily built on land, including both urban and rural areas, whereas offshore wind farms are situated in water bodies such as oceans, seas, rivers, lakes, dams, and waterfalls.

Offshore wind turbines tend to be more efficient than their onshore counterparts due to the more consistent and reliable wind speed and direction over water. As a result, fewer turbines are needed to produce the same amount of electricity as onshore systems. Additionally, offshore wind resources are abundant, particularly in areas close to major coastal population centers, making them a valuable source of renewable energy.[35]

Due to the development from basic designs to intricate generation units, control systems must be implemented. These control systems dictate the power and speed of the wind turbine system (WTS). The main aim of these systems is grid stability reduction of stressors and maximisation of power output and continuous power delivery. Many people believe that wind energy is among the cleanest energy sources. Additionally, it is the first renewable energy source to become "affordable," meaning it can now provide power at rates that are comparable to those of traditional energy sources (with or without subsidies). It is also flexible, accommodating both large-scale and domestic use. [36] This allows for wind energy to be an easily deployable source of energy. [37] For instance, offshore wind farms such as the Hornsea Project in the UK can generate enough electricity to power millions of homes, while small onshore turbines can supply electricity to individual households, farms, or microgrids in remote areas.[38] These advancements have led to a dramatic increase in WT installations. The Global Wind Energy Council (GWEC) expects 680 GW of wind capacity to be added globally between 2023 and 2027.[39]

Wind turbines generate electricity by harnessing wind energy through large rotating blades, which drive a generator connected to a gearbox located at the top of the tower behind the blades. This technology is among the fastest-growing renewable energy solutions on a utility scale.

The primary components in a standard WTS to convert wind energy to electric power are: the turbine bearing rotor, an electric generator, a power electronic converter, a transformer, and potentially a gearbox, as seen in the figure below.[33]

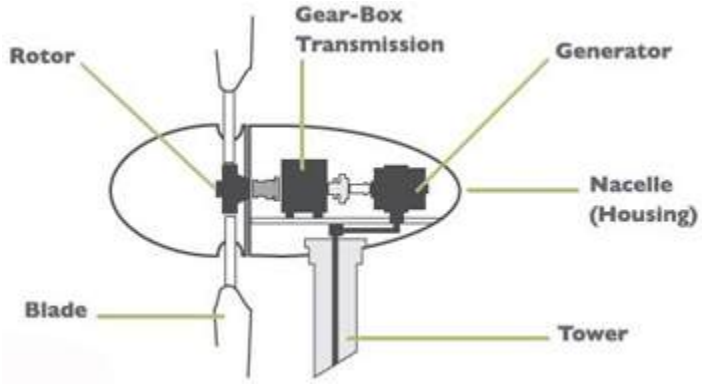



*Figure1: The diagram above shows the different parts of a wind turbine, namely the rotor, gearbox transmission, generator, housing, blade and tower. It is adapted from Engineer Live, "AM Opportunities in the Wind Turbine Industry," [Louise Davis], [January 31, 2019], URL.*

A wind turbine uses the aerodynamic force from its rotor blades, which function similarly to an airplane wing or a helicopter rotor blade, to convert wind energy into electrical power. One side of the blade experiences a drop in air pressure when wind blows over it. Both lift and drag are produced by the air pressure differential between the blade's two sides. The rotor spins because the lift force is greater than the drag force. In order to speed up rotation and enable a

physically smaller generator, the rotor can be connected to the generator directly (if the turbine is a direct drive turbine) or via a shaft and a set of gears (a gearbox). Electricity is produced by converting aerodynamic force into a generator's rotation. [40]

The implementation of wind energy can benefit countries by helping to diversify their energy mix.[41] Approximately 75% of the total cost of energy for a wind turbine is related to upfront expenses such as the turbine itself, foundation, and electrical equipment. This makes wind energy highly capital-intensive compared to conventional fossil fuel–fired technologies, since fluctuating fuel costs have no impact on wind power generation. It is also important to note that installation costs for large-scale wind farms are significantly higher than those for solar PV systems. However, despite these high initial expenses, wind energy remains economically competitive, environmentally friendly, and sustainable in the long term.[42]For example, utility-scale onshore wind power plants that were recently put into service saw a significant 68% drop in their levelized cost of electricity (LCOE) between 2010 and 2021. Similarly, solar PV saw an 88% decrease in LCOE during the same period, while offshore wind projects saw a significant 60% decrease, prices even reaching as low as 2 cents per kilowatt hour in 2019.[43] [44]

Therefore, wind power is a clean, affordable, and sustainable energy source that plays a crucial role in decarbonizing the energy sector, supporting global climate goals.[45] Similar to solar, the benefits of WTS are best optimized in a microgrid setting due to its variability.

**Subsection 2.3: Biofuel Energy**

Bioenergy is a form of renewable energy generated from biomass.[46] Biomass solid fuels (BSFs), like briquettes and pellets, are made by compressing biomass materials such as agricultural residues, gardening waste, food waste, manure, sawdust, and forest waste. This process, which may or may not involve a binder, which is an additive used primarily to improve the durability of briquettes and pellets, applies high pressure to create a denser, higher-energy product than the original raw material. Similar in size and shape to coal briquettes and traditional charcoal, these solid fuels are suitable for cooking, heating, and various other energy uses.[47] [48]

Thermochemical conversion techniques are widely used for transforming biomass into solid, liquid, and gaseous biofuels. These processes utilize heat and chemical reactions to break down organic biomass into renewable fuels and green chemicals. Due to their cost-effectiveness, fast reaction rates, and ability to produce high-quality outputs, thermochemical methods have become a leading approach for biomass energy production. The primary thermochemical techniques include: torrefaction, pyrolysis, gasification, and hydrothermal liquefaction.

1. Torrefaction is a process that enhances biomass by heating it to 200–300°C in an oxygen-free environment, improving its energy density, hydrophobic ability, and grindability. It primarily produces biochar, along with volatile gases and liquids, making it suitable for combustion, co-firing, and gasification. The process lowers transportation costs, improves storage stability, and enables biomass use in coal infrastructure.
2. Pyrolysis breaks down biomass in an oxygen-limited setting to create pyrolysis gas, charcoal, and bio-oil. It is divided into three categories: flash, quick, and slow pyrolysis.

The quality and yield of the final product are influenced by the operating circumstances. Bio-oil is used for chemical, electricity, and heating purposes. Technological developments such as co-pyrolysis and microwave-assisted methods are increasing productivity and broadening industrial uses.

3. Using high-temperature, high-pressure water, hydrothermal liquefaction (HTL) turns wet biomass into bio-oil, obviating the requirement for drying and cutting expenses. Although HTL bio-oil is a higher-quality fuel than pyrolytic oil, catalysts are needed to increase its lower yield and heating value. In order to increase efficiency and lower costs, research is being done on the co-liquefaction of different biomasses and bio-oil upgrading processes. To maximize the quality and commercial viability of bio-oil, more research is required.

4. Gasification is a high-temperature process that converts biomass into syngas (CO, $H_2$, $CO_2$, $CH_4$) using controlled oxidizing agents, producing ash and char as by-products. The syngas can be used for biofuels, hydrogen, power generation, and chemical production via Fischer-Tropsch synthesis. Fischer-Tropsch synthesis is a chemical method that uses a sequence of catalytic processes to transform synthesis gas (a mixture of hydrogen and carbon monoxide) into liquid hydrocarbons, like synthetic fuels. Syngas yield and quality are influenced by variables such as temperature, biomass composition, and gasifying agents. Tar formation, process instability, and low efficiency are obstacles that call for purifying methods and catalysts. [49]

Hydrogen derived from biomass has gained attention as a renewable energy source due to its high heating value, which is at least three times that of gasoline and four times greater than other hydrocarbon fuels. Higher heating value is advantageous for fuels, as it reflects a larger energy content, resulting in more efficient heat generation.[50] Syngas, a hydrogen-containing gas mixture, is produced during the gasification process by heating biomass with oxygen and steam. The syngas is then purified to generate hydrogen.[51] Hydrogen can be utilised across various industries, including ammonia and methanol production, catalytic hydrocracking in petroleum refining, soap manufacturing, hydrogenation of unsaturated oils in the food industry, and as a processing agent in silicon production. Notably, hydrogen is also used in fuel cells, vehicle power generation, and energy production application.[52]

In some microgrid applications, specifically, biomass briquettes are fed to an anaerobic digester, which converts the biomass to biogas, which is used to power the microgrid. Anaerobic treatment is the use of biological processes, in the absence of oxygen, for the breakdown of organic matter and the stabilization of these materials, by conversion to methane and carbon dioxide gases and a nearly stable residue.[53]

The BSFs have a lower carbon footprint when compared to fossil fuels and can lower the usage of fossil fuels. However, the European Union (EU) classifies biomass as a carbon-neutral resource, based on the principle that plant matter fixes atmospheric $CO_2$, which is the source of carbon in biogas. Biogas occupies a specific niche in microgrids by serving as a

reliable and renewable fuel source for on-site electricity generation, especially in off-grid and rural areas. Often it doesn't increase total emission, with the condition that the material used is produced sustainability.[46]

**Subsection 2.4: Hydrogen Fuel**

Hydrogen is one energy carrier that enables the efficient transfer of energy between locations. Among the advantages of hydrogen are its non-polluting, storable, adaptable, and renewable nature. It is a clean fuel that, when consumed in a fuel cell, produces only water. On Earth, hydrogen can naturally be found around the globe. It readily combines with other elements, and when that occurs, it can be found as gaseous, liquid, and solid compounds. It can be mixed with carbon to create various compounds, such as the hydrocarbons found in coal, petroleum, and natural gas, or it can be mixed with oxygen to create water. For hydrogen to be consumed on its own, it must be separated from the other elements. Producing and purifying hydrogen into usable energy requires more energy than it yields and can be produced from a variety of domestic resources, such as natural gas, nuclear power, biomass, and renewable power like solar and wind. These qualities make it an attractive fuel option for transportation and energy storage applications. It can be used in cars, in houses, for portable power, and in many more applications.

Depending on the initial hydrogen source (such as water, natural gas, coal, or petroleum), there are various manufacturing techniques available. Some production techniques are still being studied. The most widely used production techniques are electrolysis and steam methane reforming (SMR). Electrolysis is where electricity is used to break down the chemical bonds in Hydrogen compounds, and makes up less than 4% of global hydrogen production. On the other hand, SMR produces the majority of hydrogen used in commerce. Hydrogen is a colorless gas, but there are around nine colors for identifying hydrogen. These colors refer to the process used to produce the hydrogen, the assessment of the production method, the resources consumed to obtain the required energy, and the amount of polluting emissions generated. The colours include: green, blue, aqua, white, grey, brown or black, yellow, turquoise, purple, or pink. From those, blue, green and pink are considered low-carbon. [54] [55]

Green hydrogen, also known as clean hydrogen, renewable hydrogen, or low-carbon hydrogen, is produced through water electrolysis powered by renewable energy sources. It is made when water ($H_2O$) is split into hydrogen ($H_2$) and oxygen ($O_2$). The production of hydrogen through water electrolysis relies on two essential half-reactions: the anodic oxygen evolution reaction (OER) and the cathodic hydrogen evolution reaction (HER). These reactions occur within different electrolysis technologies, namely, anion-exchange membrane (AEM) electrolysis, solid oxide electrolysis cells (SOEC), proton-exchange membrane (PEM) electrolysis, and alkaline water electrolysis (AWE). This process generates no $CO_2$ emissions, making it a key component of the transition to a more sustainable energy, storage, and transportation system. Currently, green hydrogen accounts for only a small fraction of total

hydrogen production due to its high costs. However, as the cleanest form of hydrogen, it holds great potential for supporting net-zero carbon goals.

Pink, purple, and red hydrogen are all produced using nuclear energy, though the exact processes differ slightly. Pink hydrogen is generated through electrolysis powered directly by nuclear electricity, purple hydrogen combines nuclear power and heat through both electrolysis and thermochemical water splitting, and red hydrogen relies on high-temperature catalytic water splitting driven by nuclear thermal energy. Despite these variations, they are often grouped together and considered green, since nuclear power does not produce $CO_2$ emissions during energy generation. While the European Union's hydrogen strategies do not strongly promote nuclear electricity for hydrogen production, it remains a viable alternative in regions such as Russia and China.[54] [55] [56]

Blue hydrogen is produced mainly from natural gas, which is methane, using a process called steam methane reforming (SMR). SMR is a process where methane reacts with steam at high temperatures using a nickel catalyst to produce hydrogen and CO. The CO is then converted to $CO_2$ through the water-gas shift reaction, generating more hydrogen. Finally, impurities (including $CO_2$) are removed to purify the hydrogen. The definition of blue hydrogen includes the use of carbon capture and storage (CCS) to trap and store this carbon. Blue hydrogen is sometimes considered 'low-carbon hydrogen' and 'carbon neutral', as the steam reforming process does not actually inhibit the creation of greenhouse gases.[57] [55] [54] [56]

This technology is relatively new and is lacking in many ways, including scalability and high expenses for startup and maintenance. However, hydrogen fuel may prove to be a crucial instrument for decarbonizing hard-to-electrify industries like steel production and storing and transporting renewable energy when supplies are limited. The ability to store and transport energy is particularly significant for maintaining microgrid stability, as hydrogen can serve as a flexible buffer that balances supply and demand during periods of variability.[58]

**Section 3: Energy Storage**

Energy storage systems (ESS) play a crucial role in energy systems, especially in the context of renewable energy microgrids. Due to the intermittent and variable nature of most renewable sources of energy, ESS are necessary to enhance the resilience of the microgrid. By storing excess energy during peak generation and discharging it when needed, ESS helps stabilize the power supply, ensuring continuous and reliable electricity even during fluctuations or outages. They enhance power quality by regulating voltage and frequency, support quick system recovery after complete shutdowns, and reduce reliance on fossil fuel-based backup generators. Economically, ESS enables peak shaving and load leveling, reducing operational costs and alleviating infrastructure strain. Additionally, they facilitate energy arbitrage, allowing microgrids to store energy when prices are low and use or sell it when prices are high. These advantages make ESS an essential component of renewable microgrid systems.[59]

To maximize the carbon reduction of microgrids, this paper focuses on efficient and renewable energy storage systems.

**Subsection 3.1: Lithium-Ion Batteries**

Lithium-ion batteries have become the power storage method of choice for electronics due to their high specific energy, high efficiency, and long life. The lithium-ion battery has undergone several iterations beginning in 1973 when Adam Heller proposed the non-rechargeable Lithium thionyl chloride battery. The next milestone for the batteries came in 1980 when John Goodenough & Koichi Mizushima demonstrated a rechargeable Li-ion battery with Lithium Cobalt Oxide ($LiCoO_2$), and Rachid Yazami, who

Demonstrated the process of reversible electrochemical intercalation of lithium in graphite. The lithium-ion batteries were finally developed by Sony and were made available for commercial use in 1991.

Modern lithium-ion batteries have four basic components: a positive electrode (cathode), usually made of lithium cobalt oxide, lithium iron phosphate, or lithium manganese oxide; a negative electrode (anode), typically made of graphite; an electrolyte, generally a mixture of lithium salts in ethylene; and a separator, which is a fine porous polymer film such as polypropylene or polyethylene. However, cobalt-free lithium-ion battery alternatives, particularly lithium iron phosphate (LFP) and nickel-manganese-aluminum (NMA) cathode materials, offer solutions to compensate for chain vulnerabilities associated with cobalt's geographically concentrated production. These cobalt-free systems demonstrate advantages in cost reduction and improved thermal stability compared to conventional cobalt-containing lithium-ion batteries, though with some compromise in energy density. The development of such cobalt-free cathode materials provides a pathway toward more sustainable energy storage technologies by reducing dependence on geopolitically sensitive resources.[60]

The electrodes allow lithium ions to move in and out of their structures in a process called intercalation or deintercalation. During this, lithium ions move from the negative electrode to the positive electrode through the electrolyte. This allows electrons to flow through the external circuit in the same direction. It can be noted that when the battery discharges, the terminals and flow are switched.[56]

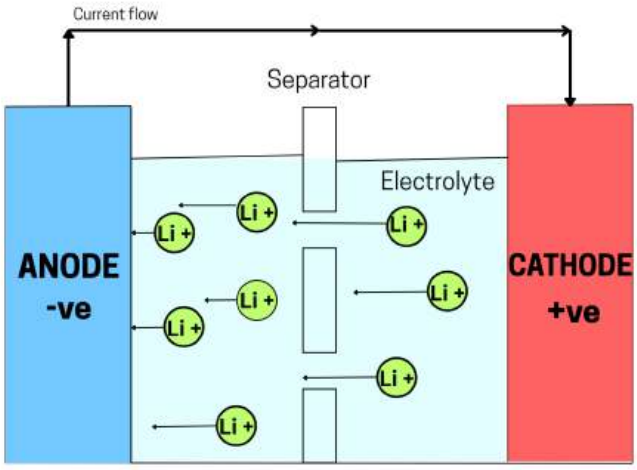



*Figure 2: The diagram above displays the mechanics of a basic Lithium-ion battery, showing the main components, the cathode, anode, separator, and electrolyte.*

However, their high cost per kWh, limited 10–15 year service life, and complex electric/thermal management make them unsuitable for the ultra-low-cost, decades-long, large-scale storage needed to support a 100% renewable grid. Additionally, exposing lithium-ion batteries to high voltages can harm them and lead to overheating.[61] [62] While these batteries are usually rather expensive, the high energy density and high specific energy, relative to other battery designs, make up for it. Lithium-ion batteries also have the advantage of being lightweight and typically leakproof. This and their fast charge and discharge rate make lithium-ion batteries the top choice for devices such as laptops and power tools, and when scaled up, can be used in electric vehicles and microgrids.[63]

**Subsection 3.2: Hydro-Pump Storage**

Pumped Hydro-Storage (PHS) Systems are a proven and mature technology that have recently garnered significant interest. A PHS system is essentially a large-scale reversible energy storage technology that heavily utilises the potential energy of water to store and release electricity. This technology has been used as early as 1880 in a region between Switzerland and Italy. However, it wasn't until 1939 that this technology was developed for commercial use.

To be viable, a PHS system requires specific site conditions such as suitable topography (high and low regions– such as hills), and availability of water. Pumped hydro storage (PHS) works by using electricity to pump water from a lower reservoir to an upper reservoir during periods of low demand and high energy generation. When electricity demand is high, water is released back down through turbines, generating electricity. This process stores energy as gravitational potential energy in the upper reservoir, allowing the system to produce power when needed.

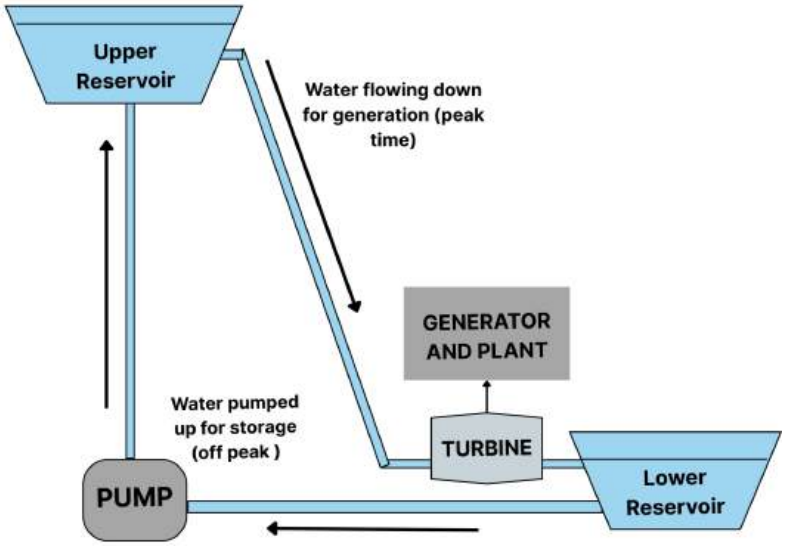



*Figure 3: The diagram above displays the mechanics of a hydro-pump storage system.*

Hydropower and Hydropump storage stand out among zero-emission renewable energy sources due to their unique operational flexibility. The water stored in reservoirs acts as a readily available energy reserve, enabling hydropower plants to function as reliable providers of operating reserves.[64] A PHS system is well-suited for the bulk storage of surplus variable renewable energy sources with power capacities ranging from 10 to 4000 MW.[65] In microgrid applications, specifically, pumped-hydro systems' power ratings can range from 7.2 MWh to 15 MWh. discharge at full load.[65] This storage capacity allows for precise control over electricity generation, where operators can rapidly increase output during peak demand or reduce it when less power is needed, which aids in grid stability and load balancing.

The ability to quickly adjust water flow through turbines gives hydropower plants exceptional grid responsiveness, making them particularly valuable for maintaining system stability and reliability compared to more intermittent renewable sources.[64] The fact that pumped storage hydropower accounts This technology utilizes stored water reserves that can be rapidly deployed to meet electricity demand continuously for 8 to 12 hours or longer. The system's large-scale storage capacity and extended discharge duration make it uniquely capable of providing sustained grid support and good long-term storage capabilities compared to other storage technologies. The ability for bulk storage makes PHS uniquely suited for the storage of highly variable renewable sources of energy present in an environmentally friendly microgrid.[58]

The biggest flaw in this system, however, is the limited availability of suitable locations. The PHS system allows for reduced greenhouse emissions and offers very little chemical waste when compared to regular batteries. Pumped hydro storage (PHS) is highly cost-competitive due to its low levelized storage cost (€0.05–€0.15/kWh), which is cheaper than batteries

(€0.30–€1.00/kWh) and has exceptional longevity, with operational costs of just €0.01–€0.03/kWh over a 50+ year lifespan. Its scalable design reduces capital costs to €500–€1,500/kW for large projects, while geographic optimization can cut expenses by 20–30%. Unlike batteries, PHS requires little to no replacements, making it the most economical choice for long-duration energy storage.[66]

Despite high initial costs of USD 1,000–4,000 per kW for equipment and construction, and USD 500–1,000 per kW (adjusted to 2021), the system provides long-term and reliable efficiency with low operational costs, allowing it to be economical, especially when used in conjunction with intermittent renewable energy sources. [65]

**Subsection 3.3: Redox flow Batteries**

Redox flow batteries, commonly known as flow batteries, are rechargeable cells that can convert energy through electrochemical processes and store it in external tanks.[67]

The flow battery technology, especially the zinc-bromine version, can be traced back to the late 1800s. However, it wasn't accepted until the late 1980s when Rychick Sum and Skyllas-Kazacos demonstrated the advantages of an all-vanadium redox flow battery (RFB).[68] Now there are different variances with a range of active species such as iron–chromium, hydrogen–bromine, zinc–bromine, and all–vanadium.

The three main components of an RFB include:

1. The **Membrane** separates the positive and negative electrolytes, preventing short circuits and cross-contamination. It also allows for the channel of supporting electrolyte ions, which maintains the balance in the system. Therefore, these membranes must have specific characteristics such as extended lifespan, low solvent diffusion coefficient, high ionic conductivity, high electronic resistivity, high selective permeability for particular ions, low swellability, and affordability. Such properties can be observed in dense ion exchange membranes (IEMs), which are usually polymer electrolytes such as Nafion.
2. The **Electrolyte** serves as the medium for storing and converting chemical energy, containing dissolved active species that undergo redox reactions to either release or absorb electrons during charging and discharging processes. There are generally two types of RFBs, categorised by the type of electrolyte being used: aqueous and non-aqueous. Aqueous flow batteries utilize aqueous electrolytes and have been extensively studied due to their ease of preparation, non-flammability, non-explosiveness, and cost-effectiveness.

   Organic solvents and ionic liquids are the primary non-aqueous solvents employed in RFBs. Non-aqueous RFBs have limitations, including low current density, energy efficiency, and cycle life. These limitations often stem from high solvent viscosity or poor cycling stability. However, they are primarily used for instances where a high voltage is required, mainly because they possess a much wider electrochemical stability window, which allows the battery's electrolyte to remain stable without decomposing at higher voltages.[69]
3. The **Electrode** is where the reduction and oxidation processes occur. Electrodes usually have porous surfaces to maximize the number of active sites and electrolyte access.

The materials used for electrodes are limited due to the corrosive nature of RFBs. Carbon-based materials, especially graphite felt, are commonly used as electrode materials in the RFBs.

Separate tanks store two chemical solutions, the anolyte and catholyte. These solutions are pumped into a battery stack where the solutions are separated by a membrane. An oxidation then occurs when the anolyte flows through a porous electrode. This generates electrons in the external circuit, which are then transported to the cathode side, where a reduction reaction occurs. Pumps continuously circulate the anolyte and catholyte solutions from the storage tanks. A permeable separator separates the anode and cathode, allowing charge carrier ions to flow through while blocking redox species from crossing over.

Due to their extended cycle life, high energy densities, and scalability in comparison to traditional batteries, RFBs have been investigated as a possible technology for large-scale energy storage. RFBs perform well in large-scale applications because of their affordable scalability, even though they have a lower power and energy density than other energy storage systems. The environmental benefits of redox flow batteries (RFBs) include their ability to support renewable energy integration by storing excess energy for later use, which reduces greenhouse gas emissions. RFBs also use recyclable materials, have a long lifespan, and produce minimal waste, making them a cleaner alternative to conventional batteries. [67]

## Section 4: Software - Microgrid and Virtual Power Plant (VPP) Optimization

### Section 4.1: Software - Microgrid and Virtual Power Plant (VPP) Optimization- Introduction

According to Ahmad Faiz Minai et al., "A Virtual Power Plant (VPP) is defined as the coordination of several dispersed power plants under the oversight of a single command system, with two-way communication across each facility to maximise efficiency."[70] In a Virtual Power Plant (VPP), energy is distributed across distributed energy resources (DERs)such as microgrids, buildings, and plug-in electric vehicles (PEVs). Virtual coordination is achieved through cyber-physical integration between flexible energy sources and optimized control systems, supported by participants in the electricity market.[71] It should be noted that VPPs and microgrids are two distinct forms of reliable supply of electricity in a power system.

Some key differences are:

- Microgrids depend primarily on hardware components, whereas VPPs heavily depend on information technology and software.
- Microgrids usually need some sort of storage mechanism, while it is possible for VPPs to operate in the presence or absence of storage systems
- While VPPs can match a wide range of resources in huge geographic areas, microgrids only comprise a fixed set of resources inside a constrained geographic area.

The aggregation and optimization of variable renewable sources through VPP software is essential, as it is the only way a renewable microgrid can reliably provide stable and continuous energy to meet demand.[72]

Between 2020 and 2027, the global VPP market is projected to expand at a compound annual growth rate (CAGR) of 21.3%, rising from a valuation of $1.3 billion in 2019 to an estimated $5.1 billion by 2027. An Example of a large VPP is the VPP in Europe, which is headquartered in Germany and is operated by the Norwegian corporation Statkraft. This VPP produces an output of more than 10,000 MW. This shows the expansive role that VPPs can and will further contribute to aiding the transition to renewable energy.[70]

**Section 4.2: Software - Microgrid and (VPP) Optimization- Operation of a VPP**

In a Virtual power plant system, a microgrid can be utilized as a DER, allowing the VPP to connect several microgrids to each other or to other DERs.[72] Secondary functions like load, market pricing, and renewable generation predictions are also included in a virtual power plant. [73] In wholesale markets, VPPs can engage in load market pricing by adjusting demand or supply bids based on real-time price signals (e.g., Locational Marginal Pricing - LMP). They may shift flexible loads to low-price periods or sell excess generation during peak-price intervals, optimizing revenue while supporting grid stability.[74] Additionally, for VPPs, renewable generation predictions refer to the forecasts of energy output from renewable sources like wind and solar power. These predictions are crucial for the effective scheduling and operation of Virtual Power Plants (VPPs), as they help in managing the inherent variability and uncertainty associated with renewable energy sources.[75]

A VPP is similar in structure to a microgrid, consisting of energy generation units and storage units; however, a key component that differentiates the two is the flexible loads. Flexible loads, also known as responsive loads, are energy consumers that can adjust their consumption patterns based on electricity prices or specific incentives, playing a critical role in maintaining grid stability and optimizing energy use. These loads consist of two key components: a communication structure that exchanges information with a central control system and a control mechanism that regulates their utilization levels.[76] The collected data is then used for AI-based optimization, control, and real-time monitoring of power electronics.[71]

This connection is facilitated through the advancement of the Internet of Things (IoT), which allows the assets to communicate with the central controller and with each other. The Internet of Things (IoT) is an interconnected system of physical devices—such as appliances, vehicles, and machinery—equipped with sensors, software, and internet connectivity to gather and exchange data. These IoT-enabled devices, often called 'smart objects,' vary from basic consumer products like smart thermostats and fitness trackers to advanced industrial equipment and logistics systems.[77] For instance, smart thermostats connected to AC systems can optimize home temperatures and regulate energy consumption. During summer heatwaves, these devices can pre-cool houses before peak demand periods—when cooling usage spikes. By staggering cooling cycles, they help avoid sudden electricity surges that could strain the power grid and lead

to blackouts.[78] Adjustments can be made through authorized control commands from a central operator or dynamic pricing methods, where real-time electricity prices incentivize shifts in consumption.

Another component is the central controller, which facilitates the compilation and analysis of all data coming from the DERs and energy markets and combines them within the constraints of the system. The central controller is also where artificial intelligence and software are used for algorithmic trading. Algorithmic trading is the process by which a sophisticated algorithm collects market data, evaluates it, identifies opportunities, evaluates risks, and, without human assistance, makes bids more quickly and accurately than human traders. It encompasses three main categories of automated systems: execution algorithms, profit-driven algorithms, and high-frequency trading (HFT) strategies. Although these often overlap in practice, they all represent computerized methods for conducting financial transactions and making market decisions. These systems utilize factors like price movements, timing, trade volume, and predefined rules to solve complex trading challenges and tasks that traditionally required teams of financial experts to perform manually.[79]

However, VPPs can also operate in a decentralized manner by distributing control across interconnected energy resources rather than relying on a single central authority. This approach enables solar panels, battery storage systems, and electric vehicles to autonomously adjust their power generation or consumption based on real-time signals like electricity prices or grid demand. Through peer-to-peer (P2P) energy trading, these distributed assets can directly negotiate transactions with one another using blockchain or smart contracts, which eliminates the need for intermediaries. At the local level, AI-driven controllers embedded in smart inverters, thermostats, or EV chargers make rapid, independent decisions while still contributing to broader grid stability.[80] [81] The ability of VPPs to access wholesale power markets makes it easier for them to sell electricity on behalf of DER (which can be a connected microgrid) holders, increasing their profit.[70] This is how a VPP can carry out one of its main aims of economic optimization for consumers.[72]

**Section 4.3: Software - Microgrid and (VPP) Optimization- Advantages of a VPP**

VPPs have significant benefits over traditional power plants in terms of highly regulative control structures, variable physical properties, and efficient transmission infrastructure.[82]

The major benefits include:

1. Reliability. Through the distribution of energy generation across several decentralized resources, VPPs greatly increase grid resilience. This distribution improves overall grid stability and lessens the effects of power interruptions. VPPs also provide reliability-related benefits such as rapid deployment, which can allow for easy reconfiguration. Furthermore, VPPs can have modular growth. Modular growth in VPPs refers to the gradual expansion of these systems by integrating additional DERs. This approach enables VPPs to scale flexibly in response to changing energy demands, market conditions, and policy landscapes without requiring large upfront investments. It enhances

adaptability, as systems can be reconfigured in real time to optimize performance based on live grid data and market signals. Economically, it lowers entry barriers and improves cost-effectiveness by spreading out investments and leveraging economies of scale over time.[83] [84] [85]

2. Revenue Income. VPPs take part in energy markets and give participants access to revenue streams. They also directly compensate participating households and businesses through bill savings, cash payments, or rewards programs. Examples include: OhmConnect's California VPP, which includes 40% of their consumers qualifying as low income, saving customers on average $250–$300 per year.[16] Also, in South Australia, customers save $200 per year by participating in the state's VPP.

Virtual power plants (VPPs) outperform traditional power plants in efficiency by reducing energy transfer losses. Conventional power plants are typically situated far from the communities they serve, requiring electricity to travel long distances, a process that leads to significant energy loss, primarily due to heat dissipation in transmission lines. The farther electricity must travel, the more inefficient the transfer becomes. In contrast, VPPs operate on a decentralized model, sourcing power from distributed energy resources (DERs) located closer to where electricity is consumed. By minimizing transmission distances, VPPs drastically cut down on energy losses.[86]Additionally, VPPs create new revenue streams for the flexibility provided by electric devices, incentivizing consumers to adopt electric solutions over non-electric alternatives, thereby supporting broader electrification efforts. This would in turn, make a VPP cheaper for communities in the long run.

3. Transition to Renewable Energy. Virtual Power Plants (VPPs) play a significant role in reducing emissions and supporting the transition to a carbon-free energy system. By shifting demand away from times when the grid relies on highly polluting coal- and gas-fired power plants and toward periods when carbon-free resources are available, VPPs directly decrease near-term emissions. Moreover, this shifting demand allows VPPs to help avoid bottlenecks in transmission, distribution, and generation capacity that could otherwise limit the potential for electrification.[76] [79] Additionally, VPPs enhance the value of renewable energy sources like solar and wind by reducing curtailment, therefore indirectly driving the expansion of carbon-free power supply and decreasing the need for new fossil fuel-fired power plants while accelerating the closure of existing ones.

VPPs benefit four key groups: power suppliers, aggregators, the grid, and participating households or businesses. Suppliers gain incentives such as reduced bills or battery discounts, while aggregators earn revenue by managing a decentralized, cloud-based system without the costs of traditional plants. The grid gains improved stability, especially during peak demand or outages, as VPPs act as backup energy sources. Finally, households and businesses benefit from reduced blackout risks, lower energy costs, and access to cleaner energy, as VPPs reduce the need for fossil fuel-based generation.

In recent years, utilities, aggregators, and technology companies have increasingly adopted VPPs due to significant advancements in the longevity and flexibility of electrical systems, particularly in managing high-demand responses.[86]

**Section 4.4: Software - issues and challenges**

Due to the fact that VPPs are a relatively new technology, there are some setbacks. Some include: Technical challenges, customer awareness, policy and regulation and market participation.

While VPPs mitigate intermittency and voltage issues, they introduce notable cybersecurity risks due to the sensitive data they manage. Breaches or unauthorized access can enable manipulation of energy dispatch and exploitation of connected devices, creating grid instability. Additionally, the inclusion of third-party devices and software increases supply chain vulnerabilities, as weaknesses in any component can be exploited.[87] Additionally, managing bidirectional power flows between DERs and the grid requires advanced communication technologies and real-time coordination to maintain system balance. These technologies rely on continuous data exchange, making data security and privacy critical. Since VPPs depend on real-time data from a wide range of DERs, which need to be connected to the internet, maintaining cybersecurity through strong encryption and secure data handling is essential, yet increasingly difficult due to the complexity and scale of the system. [84] [88]

To protect VPPs from cyber threats, key measures include segmenting networks to limit attack spread, using encryption and multi-factor authentication for secure access, and continuous monitoring for suspicious activity. Regular software updates and employee cybersecurity training further strengthen system resilience and reduce vulnerability.[89]

Secondly, Customer awareness and understanding of VPPs remain a significant barrier to their broader adoption and effectiveness. Many consumers are unaware that VPPs exist or lack a clear understanding of how they function, how participation affects their devices, or how they will be compensated. Since a VPP relies on consumers enrolling their devices and agreeing to participation terms, this lack of awareness can greatly limit customer engagement and, in turn, hinder VPP deployment in certain regions. Educating consumers about the benefits of VPPs and their role in the energy transition is essential to increasing participation and unlocking the full potential of these systems.[84] [90]

The successful implementation of a VPP is also heavily dependent on supportive and adaptive policy frameworks. However, current regulations are largely designed for traditional, centralized power systems and fail to accommodate the unique characteristics of VPPs, such as decentralized control, peer-to-peer energy trading, and participation in grid services. This regulatory mismatch, combined with a lack of clear policies and standardized market rules, creates uncertainty and discourages broader adoption. There is an urgent need for long-term, fruitful governmental policies that support small-scale participants in liberalized energy markets. Furthermore, complex market structures and unclear pricing mechanisms make it difficult for

DER owners to engage, highlighting the importance of developing simplified market accessibility mechanisms to ensure VPPs can thrive in future energy systems.

Finally, VPPs must effectively participate in energy markets to maximize revenue, yet this goal is often challenged by complex pricing systems, regulatory restrictions, and market structures that can limit profitability and fair compensation for participants. Ensuring equitable remuneration is essential to maintaining stakeholder engagement and financial viability. At the same time, achieving this requires strong alignment between the commercial (CVPP) and technical (TVPP) components of a VPP. Conflicting objectives, such as profit maximization versus grid stability, can hinder overall performance. [84] [88]

It is necessary to overcome logistical, financial, and technical obstacles in order to move VPPs from pilot projects to large-scale deployment. Infrastructure, funding, and stakeholder cooperation are all essential.[84]

**Section 5: The Future Outlook of Microgrids**

There is extensive research and development underway to improve the performance of microgrids. This includes advancements in a wide range of technologies such as hydrogen fuel cells, AI-driven grid optimization, thermal energy storage, vehicle-to-grid systems, and next-generation photovoltaics.[91] [92] However, for the purpose of this paper, five particularly promising new technologies will be focused on. This includes: perovskite solar cells, vertical-axis wind turbines (VAWTs), supercapacitors, lithium metal batteries, and solid-state batteries. These technologies were selected based on their potential impact, proximity to implementation, and technological uniqueness. Perovskite solar cells offer high efficiency and low-cost manufacturing[93]; VAWTs provide compact, urban-friendly wind solutions[94]; supercapacitors enable rapid energy balancing[95]; lithium metal batteries promise exceptional energy density[96]; and solid-state batteries enhance safety and long-term performance.[97] Together, these innovations represent transformative long-term possibilities for microgrid development.

**Section 5.1:Energy Production**

The low-cost production and superior photoelectric quality of a solar perovskite cell (PSC) are garnering much attention and research efforts. The quality of the perovskite film, which is made up of hybrid organic-inorganic materials with the general formula $ABX_3$, is crucial to the efficiency of PSCs, which have achieved a power conversion rate of 25.7%.[93] In perovskite materials with the formula $ABX_3$, A is a large monovalent cation ($CH_3NH_3^+$, $CH(NH_2)_2^+$, or $Cs^+$), B is a smaller divalent metal cation ($Pb^{2+}$ or $Sn^{2+}$), and X is a halide anion ($Cl^-$, $Br^-$, or $I^-$) forming the crystal structure.[98] There is a lot of interest in using these materials for solar applications because of their high photovoltaic activity, magnetism, ferroelectricity, and even superconductivity.[93]These physical properties of perovskites contribute to their superior light absorption, charge transport, and energy conversion efficiency, making them highly promising materials for next-generation solar cells.[99] [100] The perovskite layer in PSCs absorbs light and produces electron-hole pairs, or excitons, between electrodes and charge transport

layers (electron and hole transport layers). At the perovskite/CTL interfaces, these excitons split apart, producing a photocurrent and an open-circuit voltage (Voc).

Although PSCs provide benefits including increased fault tolerance, a longer diffusion length, lower recombination rates, and superior absorption coefficients, challenges remain, particularly in terms of scalability and toxicity. Despite current challenges, the long-term outlook for perovskite solar cells remains strong, with research aimed at improving durability and performance. Their high photovoltaic efficiency and adaptable form factors support integration into windows, facades, rooftops, and other built environments. By enabling reliable, distributed generation near load centers, they strengthen microgrid decarbonization.[93]

Vertical-axis wind turbines (VAWTs) are emerging as effective forms of energy production for microgrids in low-wind urban environments. Unlike horizontal-axis turbines, VAWTs feature blades that rotate around a vertical shaft and can operate efficiently regardless of wind direction, making them ideal for cities where wind patterns shift frequently. There are four main types of VAWTs currently in use: Darrieus, Gorlov, Giro Mill, and Savonius. Recent advancements have focused on developing innovative small-scale variable-pitch VAWTs with streamlined blade-pitching mechanisms. By kinematically coupling the blade-pitching mechanism with turbine rotation, the energy required for blade adjustments is significantly reduced, improving overall efficiency.[94]

These turbines integrate seamlessly into urban infrastructure, offering a sustainable energy source while optimizing performance through advanced control strategies in variable wind conditions. Economic analyses highlight their potential for commercialization, contributing to a 4% increase in the wind energy market.VAWTs are well-suited for urban areas because their design captures wind from any direction, performing effectively in turbulent, variable city winds. However, they are less efficient in steady, high-speed winds found in rural or open areas because their design creates higher drag and aerodynamic losses, limiting energy conversion compared to Horizontal Axis Wind Turbines.[94] [102]The more compact design also allows for scalability and domestic usage, making VAWTs suitable for industrial microgrid applications.

**Section 5.2: Energy Storage**

Supercapacitors (SCs) are gaining prominence for their high specific capacitance, rapid energy storage, and long lifespans of up to 1 million cycles. Capable of delivering high power (up to 10,000 W/kg) over short durations, they can operate independently or complement batteries to enhance efficiency across various applications. Unlike conventional batteries, SCs store charges physically on electrode surfaces without irreversible chemical reactions, making them recyclable and highly durable. However, their energy storage capacity currently remains lower than that of traditional batteries.

SCs are composed of porous electrodes, an electrolyte, and a separator. During charging, ions in the electrolyte form an electric double layer (EDL) or undergo surface-level redox reactions, which reverse during discharge. These processes enable quick charge-discharge cycles, making SCs ideal for applications requiring rapid energy delivery.

Ongoing research attempts to improve their energy density and overall performance is being conducted, to bring them closer to the storage capacity of other batteries while maintaining their benefits of efficiency, durability, and recyclability [103] [95] In microgrids, SCs can balance short-term fluctuations in renewable generation, providing frequency regulation and voltage stabilization. When combined with higher-energy-density storage, they help optimize both reliability in renewable-powered microgrids.

Lithium metal batteries (LMB), unlike Lithium-ion batteries, use solid lithium instead of silicon or graphite for the anode of the battery. These batteries are a part of a new generation of storage devices due to their exceptionally high energy densities. This is contributed in part due to solid Li metal electrodes having negligible electrode porosity and being devoid of inactive substances like conductive carbon or binders, which are frequently found in graphite or silicon anodes and adversely affect their specific energies.[96]

Recently, to combat the issues the LMB faces, such as complex thermal management and shorter life span, researchers at the Korea Advanced Institute of Science and Technology have found a way to increase the lifespan of these batteries by 750%. The researchers employed eco-friendly nanofibers as protective layers. This protective layer was created using an eco-friendly electrospinning method that used water as the only solvent and guar gum, which was taken from plants as the main ingredient. The interface between the electrolyte and the lithium metal surface was stabilized by the hollow spaces inside the fibers, which prevented the irrational buildup of lithium ions on the metal surface, therefore increasing the lifespan of the LMB.

The increasing demand for batteries has raised concerns about the environmental impact of their production and disposal. Using water-based manufacturing methods with biodegradable materials can reduce these environmental burdens, supporting the development of next-generation eco-friendly batteries. Incorporating such sustainable batteries into microgrids not only enhances their energy storage capacity but also improves overall system sustainability. [104]

In light of growing concerns about the environmental impact of conventional batteries, solid-state batteries (SSBs) have emerged as a promising alternative, with one of their key differences being the type of electrolyte used, solid compared to the traditional liquid [105] Solid-state electrolytes are generally classified into two main categories: organic and inorganic. Electrolytes composed of ceramic, polymer, glass, or sulfide materials are the foundation of SSBs because they enable lithium ions to transit between the anode and cathode without the dangers of liquid electrolytes, like instability and combustibility. The solid electrolyte in traditional batteries performs similarly to its liquid counterpart, but it is composed of nonflammable elements that promote ionic conduction and guard against short-circuiting. In addition to improving safety, this solid medium makes it possible to use lithium metal as an anode, which has a larger theoretical capacity and a stable interface that inhibits lithium dendritic development, which could cause a reduction in battery lifespan and major safety hazards due to the risk of internal shorts and catastrophic failure.[97] Furthermore, the lifetime of these batteries is

potentially longer while being lighter and smaller than conventional batteries.[105] However, there are still some challenges that these batteries face, such as costs, manufacturing complexity, scalability, and limited understanding of solid electrolyte behavior. [97] More research on these batteries can help overcome these struggles to realize the potential solid-state batteries have to be developed to the point where they can replace the liquid electrolyte batteries currently found in small everyday gadgets and present a significant possibility for the electric car sector in the future.[105]

Recent fires at lithium battery sites, such as Tesla's Giga Berlin battery pack production building in Germany and the Moss Landing Power Plant in California, highlight the safety risks of conventional lithium-ion batteries. Solid-state batteries, which replace flammable liquid electrolytes with safer solid components, offer greatly improved thermal stability and reduced fire risk. When integrated into microgrids, where energy storage is distributed in smaller, localized arrays with advanced monitoring and management, solid-state batteries can significantly enhance system safety and public acceptance. [106] [107]

**Section 6: Conclusion**

As the transition to renewable energy becomes increasingly urgent, microgrids present a promising solution to accelerate the shift away from fossil fuels. By combining energy production, storage, and, in the case of VPPs, energy distribution, microgrids can optimize energy generation and enhance grid resiliency. Renewable sources such as solar, wind, biofuels, and hybrid systems are key to powering these microgrids. Solar power, due to its lower cost and widespread availability, is the most established option, while wind turbines offer significant potential for large-scale energy production. To improve efficiency and productivity, advanced technologies like solar perovskite cells and vertical-axis wind turbines are being developed and implemented, both offering higher energy conversion rates and spatial optimization. Energy storage methods such as lithium-ion batteries, pumped hydro-storage, and redox flow batteries are commonly used and environmentally friendly, with lithium-ion being the most widely adopted. Emerging technologies in energy storage, including supercapacitors, solid-state batteries, and lithium metal batteries, hold promise for even greater efficiency. Additionally, integrating microgrids into the larger grid through VPPs can further enhance their potential, offering benefits such as decarbonization, electrification, improved reliability, and cost-effectiveness. However, challenges such as data security, public awareness, market participation, and regulatory concerns must be addressed for optimal implementation.

To support the development of microgrid and VPP technologies, further research should focus on refining policy and regulation, as well as enhancing data privacy protections. Additionally, exploring unique microgrid layouts tailored to specific environments, such as urban, rural, or remote areas, will optimize their effectiveness and scalability. This suggestion stems from the varying spatial constraints, such as where hilly terrain in rural areas often makes hydro-pump storage an ideal solution, while spatial limitations in urban areas call for VAWTs, which are compact and operate in turbulent conditions. These efforts are essential for ensuring

that microgrids and VPPs can be successfully implemented across various settings. These examples illustrate the importance of matching technology to its environment.

Conclusively, microgrids–through their integration of localised energy generation, smart control systems and energy storage– form the foundational architecture for an efficient, resilient and adaptive energy system. When interconnected, these decentralised networks enhance grid flexibility and reliability as well as accelerate the transition to a more sustainable and scalable energy system. Therefore, policymakers and industry leaders must act now to accelerate the deployment of microgrids and VPPs, ensuring these technologies are implemented efficiently and sustainably across diverse environments.

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**How Can India Accelerate Development? (in Four Key Areas: Sustainability, Digital Currency, and Education) By Keyaa Vishal Patel**

**Keywords**

India; Developed; GDP Per Capita; Sustainability; Digital Currency; Employment; Education

**Abstract**

Although India has experienced rapid economic growth and is now considered one of the world's largest economies by GDP, it remains significantly behind developed nations in key indicators such as GDP per capita, employment quality, and sectoral productivity. This paper explores India's potential to achieve developed country status by 2047 by examining three pivotal areas: sustainability, digital currency, and education. Each of these sectors directly impacts crucial macroeconomic goals such as economic growth, employment generation, and income equality. The analysis highlights the structural challenges that hinder progress, including overdependence on agriculture, underutilization of human capital, and limitations in technological and financial infrastructure. India's current policy initiatives in each area are assessed to determine their effectiveness in meeting development goals. The study also draws comparisons with both developed and emerging economies to identify successful strategies and policy approaches. It concludes that while India has laid foundational efforts toward achieving developed status, sustained progress will require comprehensive reforms, improved implementation mechanisms, and greater alignment between environmental, economic, and social policy objectives.

**Section 1:Introduction**

Multiple papers including those by C. P. Chandrasekhar (2024) and Paul and Mondal (2019) establish that India is far away from being considered a developed country.Despite its rapid growth—becoming the world's fifth-largest economy with a nominal GDP of $4.19 trillion in 2025—the country continues to face fundamental development challenges. These include low GDP per capita, widespread underemployment, and structural inefficiencies across sectors. As of 2025, India's GDP per capita is only around 4.5% of the G7 average, revealing a significant gap in living standards, industrial capacity, and human capital productivity (IMF DataMapper, 2025). Achieving developed-country status therefore demands not just economic expansion but comprehensive progress across sustainability, financial modernization, and education—three pillars that together determine long-term growth, equity, and resilience. This topic holds immense importance as India's developmental trajectory will not only affect its 1.4 billion citizens but also reshape global economic and environmental dynamics.

Current researchers have established how a country would be classified as "developed". For example, existing research on India's development highlights both its potential and constraints. C. P. Chandrasekhar (2024) and Paul and Mondal (2019) emphasize that while

India's macroeconomic indicators appear promising, deeper structural issues—such as overdependence on agriculture and weak industrial productivity—continue to hinder inclusive development. Studies by Paprotny (2020) and Farias (2023) outline international benchmarks used by the IMF and other organizations to classify nations as "developed," identifying economic diversification, environmental responsibility, and human capital as decisive indicators. Furthermore, scholars like Singh and Kaur (2022) and Zahid (2024) show how sustainability can serve as both a constraint and a catalyst for growth, while Koparan (2025) and Zhang (2023) demonstrate how digital currencies can modernize financial systems in emerging economies. Similarly, Chandra Pal (2023) and Kuwar (2021) establish that education remains the foundation for innovation and social mobility. Collectively, this literature reveals that India's advancement toward developed-nation status depends not solely on the pace of economic expansion but on the depth of structural transformation that enhances inclusivity, sustainability, and human capital productivity.

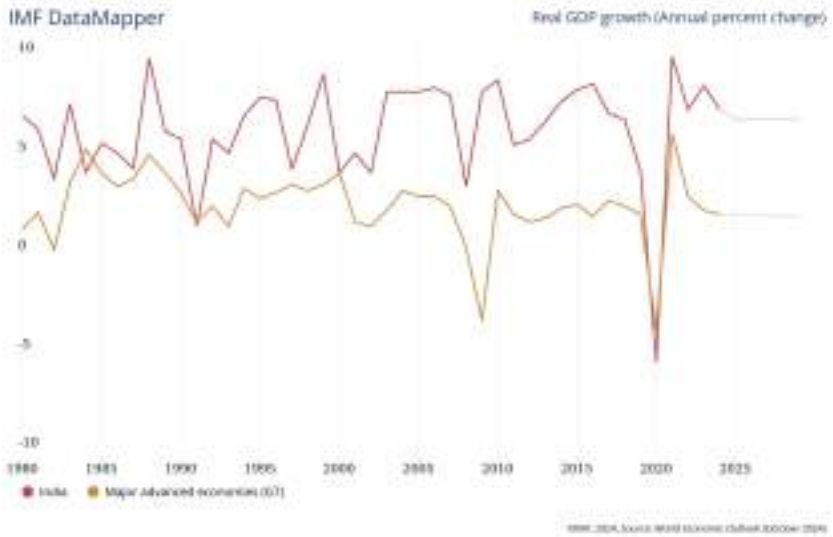
This paper builds on the existing literature by conducting a focused analysis of three interlinked areas, sustainability, digital currency, and education, and their respective roles in accelerating India's development. Using comparative data from emerging and developed economies, it evaluates India's current policy measures and institutional frameworks to determine their effectiveness in achieving long-term macroeconomic objectives such as employment creation, higher productivity, and equitable income distribution. The study synthesizes evidence from both domestic and international sources to identify structural reforms and implementation strategies that could enable India to meet the criteria of a developed nation by 2047.

The rest of the paper is structured as follows. Section 2 provides the contextual background and comparative quantitative economic analysis of India with developed economies and developing economies. Section 3 reviews existing literature on development benchmarks and key thematic areas. Section 4 presents the analysis of India's progress in sustainability, digital currency, and education. Section 5 concludes with key findings, policy implications, and recommendations for accelerating India's path toward developed-nation status.

**Section 2: Context**

Before analysing how India could become a developed nation by 2047 it's vital to first highlight how India's current progress in some important metrics compared to that of other developed economies.For graphs 1 and 2 the G7 or advanced economies include Canada, France, Germany, Italy, Japan, the United Kingdom, and the United States. The International Monetary Fund (IMF) classifies countries as "advanced economies" or "emerging market and developing economies". Developed economies have been characterized by high per capita income, significant industrialization, diversified export base, and integration into the global financial system. While there isn't a strict numerical definition, these factors are key indicators used by the IMF.

Graph 1: Real GDP growth of India




The above graph shows a comparison between the year on year real GDP growth between India and the G7 economies (IMF DataMapper, 2025).

Graph 1 shows that India is growing at a faster rate with an annual change of 6.5% in 2025 while other advanced economies have an annual 1.7% change in real GDP .India's growth has exceeded that of other advanced economies relatively consistently from 1980 to 2025: Canada, France, Germany, Italy, Japan, the United Kingdom, and the United States. There's a prominent dip in real GDP growth for India and Major advanced economies 2020 (start of covid-19 pandemic) however India's dip is greater at 5.78%. This disparity can be attributed to India's more stringent lockdown measures, which affected consumption, investment, and employment leading to a more pronounced negative impact on economic activity (Business Standard, “India witnessing V-shaped recovery; lockdown led to drop in economy: FinMin, 2020). Private consumption expenditure, accounting for over half of GDP, plummeted sharply as household consumption saw an estimated daily loss of around $2.42 billion, with roughly 28 % due to wage losses and 72 % from lost earnings between March 25 and May 31, 2020. This equated to nearly $74.6 billion overall, or 2.75 % of overall GDP (India’s economy was hit by the coronavirus lockdown. These charts show how, 2020).

Graph 2: GDP per capita in India

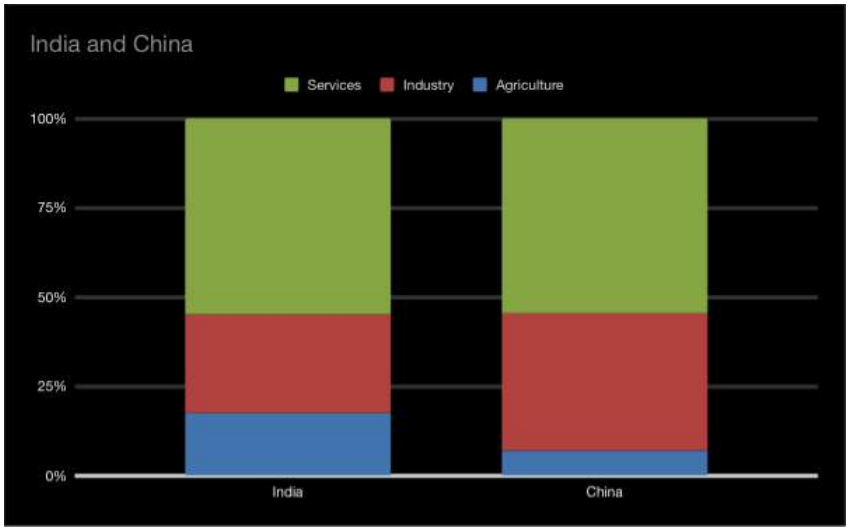



The above graph shows a comparison between the year on year GDP per capita growth between India and the G7 economies (IMF DataMapper, 2025).

However, as much as the GDP in India has grown rapidly throughout the years, it still has a very low GDP per capita compared to advanced economies. As seen in Graph 2, compared to the G7 average, India's GDP per capita is consistently much lower. As of 2025 India's GDP per capita is only 2.94 thousand dollars while the average GDP per capita of the G7 economies is 65.78 thousand dollars. Despite the GDP per capita being so low in absolute terms India's average yearly growth in GDP per capita is 6.1% while average yearly growth in GDP per capita for the G7 economies is only 4.1%. Furthermore India's average year on year growth in GDP is 7.7% while the average year on year growth in GDP is only 4.6%.India has also been declared the fastest growing economy, a clear sign of a developing economy but coupled with the growing population GDP per capita still remains very low relative to developed economies.

India and China are the two fastest growing economies while also being the most populous countries in the world, yet China's GDP is higher at 1.953 trillion dollars while India's lags behind at 4.27 trillion dollars. Furthermore China's GDP per capita is also higher at 13.87 thousand while India's is only 2.94 thousand. A major reason for India's lag is a lack of industrialisation and urbanisation, hence its essential to break down the sectoral differences between the countries to analyse which sectors India is behind in and which sectors are being given too much importance.

Graph 3: Value added to GDP by each sector



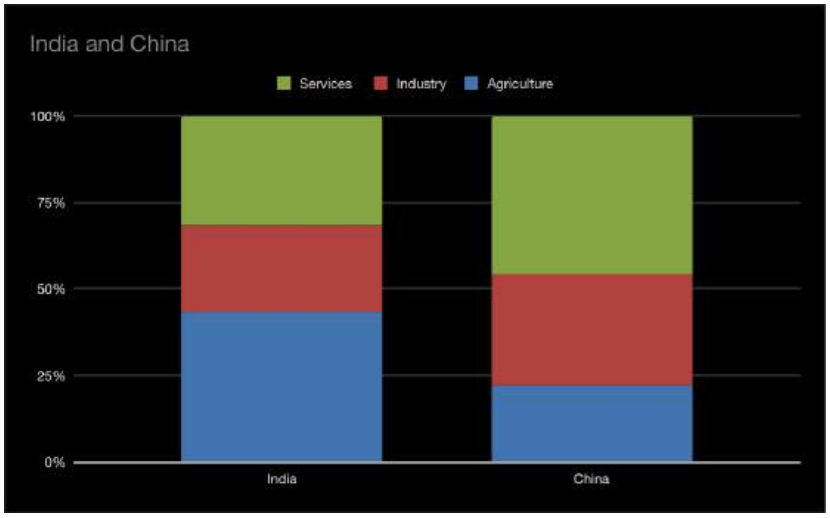

Graph 3 helps show a comparison between the contribution of each sector to the total GDP of India and China.

The graph illustrates the fact that services add the most value to the GDP of both India and China, however industry contributes a smaller proportion to GDP in India relative to that of China, showing a lack of growth in India's industrial sector compared to that of China in terms of output produced. The percentage of GDP accounted for by agriculture in India is double that of China, showing prominent dependence on the agricultural sector for its contributions to India's total GDP. As of 2024 India's economy, with a nominal GDP of approximately US $3.94 trillion, was significantly smaller than China's, which stands at around US $18.8 trillion. Agriculture accounts for about 16% of India's GDP, translating to roughly US $630 billion, whereas in China, agriculture contributes only 6.8%, or about US $1.28 trillion (India GDP sector-wise, 2025; Distribution of Gross Domestic Product (GDP) across economic sectors in China from 2014 to 2024, 2025) . In contrast, industry constitutes 27.6% of India's GDP (about US $1.09 trillion) compared to 36.5% in China, which amounts to a much larger US $6.9 trillion, underlining China's stronger industrial base. The services sector forms the largest share in both economies 54.7% in India and 54.6% in China but in absolute terms, China's services sector (around US $10.3 trillion) is nearly five times larger than India's (US $2.16 trillion).

While GDP by sector is a great metric to highlight the breakdown of how different sectors contribute to the overall economy and how much each sector actually contributes to India's real GDP, this might not translate directly to employment due to productivity differences. For instance, the agricultural sector in India employs a disproportionately large share of the workforce despite contributing a smaller portion of GDP, largely because it relies on less mechanization and lower productivity compared to industry and services. Many agricultural workers have limited access to technical training and advanced skills, which constrains productivity growth. Nevertheless, India remains the world's largest exporter of several key

agricultural products, the biggest being Basmati rice which generated approximately US $9 billion in 2023–2024, underscoring the sector's vital role.As such, we turn to employment by sector to analyse not only the productivity of each sector but also understand India's relatively low GDP per capita.

Graph 4: Employment in each sector as a % of total employment




Graph 4 shows a comparison between India and China's employment in each sector as a % of total employment.

As of December 2024, the employment-to-population ratio (the share of the working-age population employed) was about 47.2% in India and significantly higher at 62.4% in China (India Unemployment Rate, 2025). The graph clearly shows that while almost half of China's labour force is employed in the service sector almost half of India's labour force is employed in the agricultural sector. Furthermore India's percentage employment in agriculture is nearly double that of China while it seems to be lagging significantly behind in services, followed closely by percentage employment in Industry. Developing countries like China are closer to becoming developed countries compared to India, a large reason being due to China having most of its human resources concentrated in industry and services rather than agriculture.

Combining Graphs 3 and 4, we can see that despite almost half of India's population being employed in agriculture it contributes to a mere 20% of India's GDP. This is due to multiple reasons including underemployment, lack of technological development, low productivity and fluctuating prices and incomes. Underemployment is a significant challenge in India, but far less prevalent in China, primarily due to differences in economic structure, industrialization, and labor market development. In India, a large portion of the workforce is engaged in informal, low-productivity jobs–especially in agriculture. India's slower pace of industrialization and limited growth in formal manufacturing and service sectors have failed to absorb surplus labor from agriculture, resulting in a lack of high-quality job opportunities. In contrast, China underwent a rapid industrial transformation, with strong government-led

investment in manufacturing, infrastructure, and urbanization. This enabled millions of rural workers to shift into higher-productivity industrial and service jobs, reducing underemployment. The biggest disadvantage of this is that it leads to economic inefficiency as workers are not optimally allocated and other sectors (like manufacturing or services) that offer higher returns and need skilled workers are deprived of potential workers. This high-effort manual work generates low GDP and income, straying India away from potential development.

**Section 3: Literature Review**

This paper focuses on 4 different aspects of economics, especially in regards to the growth of developing versus developed nations: 1) how countries are classified as developed nations, 2) how sustainability could challenge and support economic growth, 3) impact of digital currency on financial systems 4) importance of education for employment and economic growth.

Paprotny (2020) identifies 21 benchmark countries that are considered developed and then identifies five main criteria for this compartmentalisation: economic indicators, health indicators, education indicators, environment indicators and employment outside agriculture. Each of these criteria is carefully analysed by international organisations like the IMF before they decide the "benchmark criteria" to label a country as developed or developing, making this a fair method of classifying countries. This aligns with the technocratic criteria established by Farias (2023), who also identified 3 other contexts for classifying countries: Elective, Northern Gaze and Southern Solidarity.

In development studies, *elective affinity* refers to the natural alignment between certain institutional values, governance models, or policy ideologies across societies. Applied to developing nations, it suggests that specific development models are not merely imposed externally but are often adopted because they resonate with a nation's internal political and cultural logic. Chemouni (2019) provides a pertinent example through post-genocide Rwanda, where President Paul Kagame's government pursued centralized, technocratic development inspired by Singapore's state-led model. Despite donor influence, Rwanda's preference for disciplined governance, minimal corruption, and long-term planning reflected a voluntary alignment rather than external compulsion—illustrating elective affinity in practice.
By contrast, Hogan and Patrick (2024) describe the *Northern Gaze* as a top-down, paternalistic perspective that frames development through Western standards, often resulting in policy frameworks detached from local realities or indigenous knowledge systems. In opposition to this, *Southern Solidarity* emphasizes cooperation and mutual support among countries in the Global South, representing a collective effort to challenge Northern dominance in development discourse and to formulate more context-sensitive, equitable strategies for progress.

Having outlined these global frameworks and theoretical lenses for defining development, this paper now situates India within this broader context. The goal is to examine the extent to which India aligns with international "benchmark criteria" and to identify the areas

in which it continues to lag behind. Paprotny's (2020) time-lag method demonstrates that many South Asian countries, including India, have shown greater progress in education and health outcomes than in economic indicators such as GDP per capita or industrial diversification. This underscores the need for targeted policy interventions that address not just the pace but the quality and inclusivity of India's development.

**Sustainability: Balancing Growth and Environmental Responsibility**

Sustainability, as defined by Singh and Kaur (2022), refers to ensuring that natural resources are used wisely and preserved for future generations, preventing them from being depleted or overexploited. This principle emphasizes that economic development should not come at the expense of ecological health, and aligns with the Brundtland Report's call for "meeting present needs without compromising the ability of future generations to meet their own needs."

India's pursuit of rapid GDP growth, however, has brought with it significant environmental challenges. Dhankhar (2016) points to the pressures created by India's vast population and limited resource base, which strain ecosystems and lead to overexploitation of land, water, and energy. Air and water pollution, deforestation, and rising greenhouse gas emissions illustrate how unchecked economic expansion has often come at a severe ecological cost. Compared to developed nations, India faces weaker regulatory enforcement and lower societal pressure for environmental accountability (Kvasnickova Stanislavska & Pilar, 2023). As a result, corporate sustainability reports in India often prioritize social issues such as labor rights and community welfare, while placing less emphasis on climate change mitigation or emissions reduction, highlighting a divergence in priorities between developed and developing nations.

Yet, India's challenges also open up the possibility of forging a more sustainable growth pathway. Adopting green economic practices not only mitigates environmental risks but also offers new opportunities for job creation and economic diversification. Zahid (2024) argues that transitioning toward renewable energy, sustainable agriculture, and conservation industries could generate significant employment, particularly in developing countries. For India, this is crucial since such industries could absorb surplus labor and reduce dependence on traditional, resource-intensive sectors. Moreover, aligning with global sustainability norms could enhance India's competitiveness in international trade, where eco-compliance is increasingly becoming a benchmark for market access.

In this way, sustainability should not be seen as a trade-off against economic growth but as a driver of long-term resilience. If India can strike this balance, addressing its ecological vulnerabilities while leveraging green investments, it will not only strengthen its economic stability but also move closer to the benchmark criteria of developed nations.

**Digital Currency: Driving Financial Inclusion and Efficiency**

While sustainability addresses India's ecological future, financial modernization is crucial for creating an inclusive and efficient economy. Central Bank Digital Currencies (CBDCs) and

broader digital financial systems have emerged as transformative tools. Koparan (2025) notes that advanced economies are 332% more likely to adopt CBDCs due to robust technological infrastructure. However, digital currencies hold perhaps even greater potential for developing nations, where financial exclusion remains a barrier to growth.

Digital currencies could accelerate India's development by enhancing financial inclusion, reducing transaction costs, and improving transparency. Zhang (2023) emphasizes the decentralization of digital currencies, which minimizes reliance on intermediaries like banks and lowers transaction costs—critical in a country where millions remain unbanked. Martinčević et al. (2021) add that blockchain-based currencies improve accountability and reduce corruption risks, which aligns with India's ongoing struggles against financial opacity.

Moreover, digital currencies can stimulate entrepreneurship and small business growth by easing access to credit and reducing dependency on cash economies. Cesaratto and Febrero (2023) highlight how this democratization of finance enhances individual control over assets, while Nițu and Negruțiu (2021) argue that blockchain's immutability can reduce fraud and increase trust in financial systems. For India, where informal economies dominate, this shift could unlock new avenues for tax revenue, efficiency, and integration into the global digital economy. In effect, digital currency adoption supports multiple development benchmarks simultaneously: economic growth, employment diversification, and improved institutional transparency.

**Education: Building Human Capital for Inclusive Growth**

If sustainability secures long-term stability and digital currencies modernize the financial system, education remains the foundation of development by cultivating human capital. Education has been consistently linked with better employment opportunities, higher wages, and improved health outcomes. For instance, in 2020, individuals with a high school diploma earned $162 more weekly than those without (U.S. Bureau of Labor Statistics, 2020). While this data is Western, it illustrates the universal link between education and upward mobility.

Chandra Pal (2023) emphasizes education as an investment in human capital, yielding higher productivity and innovation. This resonates with Paprotny's (2020) classification benchmarks, since education simultaneously improves economic, employment, and health outcomes. Johnson (2024) further demonstrates that education correlates strongly with better healthcare systems, as seen in countries like Canada and the Netherlands. For India, expanding access to quality education can thus yield a "triple dividend": higher labor productivity, better health, and stronger innovation capacity.

Kuwar (2021) and Chandra Pal (2023) both link education to technological advancement, noting that educated individuals drive research, innovation, and patents. This is critical for India, which seeks to transition from a labor-intensive economy to one capable of competing in global knowledge industries. At the same time, education reduces inequality by providing the poor with tools to break cycles of poverty, participate in formal labor markets, and save for emergencies. Hence, education not only fulfills the social dimension of development but also strengthens economic resilience and competitiveness.

**Section 4: Analysis**

Building on the contextual and theoretical foundations established in the previous sections, this analysis examines how India can accelerate its progress toward developed-nation status by evaluating three interdependent factors: sustainability, digital currency, and education. Each subsection assesses India's existing policy measures, their effectiveness, and the potential reforms required, ultimately illustrating how a synchronized advancement in sustainability, financial modernization, and education can lay the foundation for a resilient, inclusive, and high-income economy by 2047.

**Section 4.1: Sustainability**

According to Dhankhar (2016), the Indian government acknowledges that economic growth cannot be sustained without strong social and environmental foundations. Several initiatives have been launched to promote sustainability. The Swachh Bharat Abhiyan (2014) has led to the construction of over 100 million toilets, improving sanitation and reducing open defecation. The National Clean Air Program (NCAP) aims to reduce air pollution in urban areas, while Phase II of the FAME India Scheme (2019) allocated INR 10,000 crores to promote electric vehicles, supporting subsidies for 7,090 electric buses, 500,000 electric three-wheelers, 55,000 electric four-wheelers, and 1,000,000 electric two-wheelers. By February 2022, 966,363 EVs were registered under this scheme. The Ministry of Finance (2023) also reports that renewable energy capacity reached 168.9 GW, including 67.82 GW of solar and 43.20 GW of wind power (Ministry Of Finance, Economic Survey 2024-25, 2026). Urban policies such as mechanized road sweeping and stricter dust control regulations at construction sites have been introduced to address road dust pollution.

These programs have yielded mixed results. While Swachh Bharat improved sanitation, maintenance of toilets remains poor. The NCAP has expanded monitoring networks, yet as of 2025, 28 of 130 cities still lack Continuous Ambient Air Quality Monitoring Stations (CAAQMS), and data remains inconsistent (Manojkumar & Muruganandam, 2025). Mechanized road sweeping is often ineffective due to limited coverage, irregular maintenance, and personnel shortages (CSE Air Quality Report, 2024) (Ministry of Environment, Forest and Climate Change Government of India, OVERVIEW OF NCAP AND XV-FC MPCCF AND CONVERGENCE OF CENTRAL SCHEMES/PROGRAMMES FOR AIR QUALITY IMPROVEMENT IN IDENTIFIED CITIES, 2025). Despite efforts, India remains the 5th most polluted country globally, with 13 of the 20 most polluted cities (Mohan, 2025). FAME II has expanded EV adoption, but EVs accounted for only 4.7% of sales in 2023 (NITI Aayog) (Ministry Of Heavy Industries, Fame II, 2025). The main barriers are inadequate charging infrastructure, especially outside Tier-I cities, and high upfront costs. Renewable energy growth has reduced reliance on fossil fuels, but challenges remain: dependence on imported solar PV cells and turbine components, particularly from China, raises costs due to tariffs, transport, and currency fluctuations (Chaudhury & Agarwal, 2023; Khezri Mahmoudi & Aki, 2022). Additionally grid infrastructure, designed for centralized fossil fuel systems, struggles with renewable variability,

causing instability.

India must strengthen enforcement of environmental regulations, including emission standards for industries, waste management, and penalties for non-compliance. Investing in domestic R&D for renewable technologies, energy storage, and grid modernization is essential to reduce foreign dependence. Introducing fiscal measures like a carbon tax, similar to Singapore, could encourage emission reduction and fund green initiatives. Adoption of Green GDP metrics would internalize environmental costs into growth assessments. Public awareness and behavioral nudges, such as tiered electricity pricing, recycling mandates, and littering fines, should be implemented to change consumer behavior.

Integrating sustainability into growth models avoids the "pollute now, clean later" trajectory that hampers development. By expanding green industries such as renewable energy, sustainable agriculture, and eco-tourism, India can create jobs, attract global investment, and enhance competitiveness in a low-carbon global economy. Drawing lessons from Singapore's resource efficiency and Denmark's renewable leadership, India can strike a balance between growth and sustainability, strengthening resilience and advancing toward developed-nation status.

**Section 4.2: Digital Currency**

In February 2022, India's Finance Minister announced the development of a Central Bank Digital Currency (CBDC), or digital rupee. Since then, pilot projects have been launched in major cities (Gupta et al. & Ozili, 2023). This initiative builds on India's digital finance ecosystem, which already includes Aadhaar-enabled services, Jan Dhan accounts, and UPI.

CBDC pilots have demonstrated potential for efficiency, but challenges are significant. India has 190 million unbanked adults (World Bank, 2021), the world's second-largest such population. While platforms like Paytm, Google Pay, and PhonePe have expanded access (Patnaik et al., 2023), rural areas remain cash-dependent, with 30% of bank accounts inactive. Distrust in digital systems, poor internet connectivity, and digital illiteracy hinder adoption (Dash et al., 2022; Srivastava, 2023). Data privacy concerns also remain unresolved, as India lacks strong data protection laws. Furthermore, cryptocurrencies are often associated with illegal activity, adding to skepticism (Swaminathan, 2024).

The government must strengthen digital infrastructure in semi-urban and rural areas, expand digital literacy programs, and pass robust data protection legislation to secure user trust. Regulatory frameworks should clarify the legal status of CBDCs versus cryptocurrencies while promoting cross-border interoperability to enable remittances and trade. Partnerships with fintech companies can enhance adoption and accessibility.

CBDCs can formalize the informal economy, enhance tax compliance, reduce corruption through transparent transactions, and lower cross-border transaction costs—benefiting remittances, which totaled $129.4 billion in 2024 (Nayak, 2025). This efficiency can support manufacturing by reducing operational costs and help IT exports by eliminating conversion charges. The Indian blockchain market, projected to grow at a CAGR of 47.3% from 2022–2027

(IMARC), could expand into agriculture, pharmaceuticals, and supply chain management. By promoting financial inclusion, CBDCs can give marginalized communities access to services, reduce inequality, and make India a leader in digital finance innovation.

**Section 4.3: Education**

India's literacy rate has risen from 18% in 1951 to 81.3% in 2023 (Desk, 2024). With over 62,000 institutions serving 42.5 million students, India has one of the world's largest higher education systems. The government has introduced the National Education Policy (NEP) 2020, which focuses on foundational literacy, multilingual education, vocational training, and digital integration. It also aims to establish flexible credit transfers and multidisciplinary higher education.

Despite progress, challenges persist. The Gross Enrollment Ratio (GER) in higher education is only 28%, below the global average of 37% and far behind developed nations at 40–60% (Raychaudhury, 2025). ASER (2024) shows that only 73% of Grade 3 children can do basic arithmetic, revealing low learning outcomes. The skill mismatch is evident: only 45% of graduates are considered employable (India Skills Report, 2023). Unemployment remains 3.2% in 2023–24 (Agrahari & Neelam, 2023), with significant underemployment. Brain drain persists, with skilled professionals emigrating due to limited infrastructure, low salaries, and weak research opportunities, causing economic losses in tax revenue and productivity (George & Baskar, 2024). Critical sectors like healthcare face doctor shortages, further reducing service access.

India must increase education spending from the current 2.9% of GDP toward the UNESCO benchmark of 6%. Investment should target teacher training, infrastructure, and equity in rural areas. Vocational education must be linked to high-growth industries such as renewable energy, biotechnology, and IT. Public-private partnerships can enhance research, innovation, and apprenticeships, while policies to retain skilled graduates can reduce brain drain.

Education strengthens human capital, which drives productivity, innovation, and global competitiveness. Higher earnings from education raise living standards, with college graduates earning 37% more by age 31 and a median lifetime income of $2.8 million compared to $1.6 million for high school graduates (Georgetown CEW, 2021). Leveraging its large youth population, India can replicate models from South Korea and Singapore, where education reform enabled rapid industrialization and technological leadership. By building a skilled workforce, India can sustain growth, attract investment, and transition to a knowledge-driven developed economy.

**Section 5: Conclusion**

This paper has explored India's potential for development in three broad categories-sustainability, digital currency and education. The merits of sustainability, digital currency and education have been highlighted along with how they can help India progress as a country by aiding social, environmental and financial improvement.

The analysis was grounded in the existing literature on development classifications (Paprotny, 2020; Farias, 2023) and comparative benchmarks of progress, emphasizing that achieving development is not merely about quantitative growth but about qualitative transformation across multiple sectors. These three domains were selected as they capture the economic, social, and technological pillars of modernization, aligning with global frameworks established by institutions such as the IMF and the World Bank. Together, they provide a multidimensional understanding of how India can transition from a developing to a developed economy through synergistic policy interventions.

When comparing the three dimensions, the analysis reveals that digital currency reform appears to be the most immediately achievable goal, given India's strong digital infrastructure, government backing, and widespread fintech adoption.Education reform, while requiring sustained investment, offers long-term benefits through enhanced labor productivity, innovation capacity, and social mobility. On the other hand sustainability seems like a more complex and resource intensive objective that's likely to take place over the long term due to its demand for industrial shifts, new energy systems, technological development and changes in consumer behaviour.

The findings of this paper carry significant policy implications. Banks and financial institutions must accelerate the integration of digital currencies and strengthen cybersecurity frameworks to build trust and financial inclusivity. Businesses should invest in digital upskilling and sustainable production models to ensure future employability and competitiveness in a green economy. Educational institutions must align curricula with future labor market demands, fostering innovation, critical thinking, and technological literacy. By studying successful models from benchmark nations, India can adopt hybrid policy strategies that are context-sensitive yet globally aligned, ensuring progress across all three dimensions.

Despite its comprehensive scope, this paper has certain limitations. It focuses primarily on India's domestic policy landscape and does not fully examine international interdependencies or the role of global financial institutions, trade partnerships, and geopolitical dynamics. Additionally the paper remains largely qualitative, suggesting that future research could incorporate empirical modeling or cross-country quantitative comparisons to reinforce these findings.

Ultimately, this paper contributes to the growing body of development economics by offering a multidimensional framework for understanding India's trajectory toward developed-nation status—one that underscores the interdependence of financial modernization, human capital formation, and environmental sustainability as the foundation of both short-term and long-term progress.

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**Retributive Versus Restorative Justice In Post-conflicts States**
**By Rehaan Waheed**


## Abstract

This paper enquires into depth, the contrast between the two most majorly prevalent models of justice (retributive and restorative), defining them and showing which framework is most suitable for post-conflict states. Further, this paper analyzes how the integration of a devised metric, with a scale of measure, could highly aid these states. It also takes into account the economic aspect of the situation. The objective of this paper is to put forward a viable model of justice for post conflict states after critical analysis of the current models adopted by many of them.


## Introduction

Post-conflict states are some of the most complex to manage. Their governments are often either completely destroyed, corrupt, or slowly recovering from the violence they have endured. The people frequently suffer from PTSD, and both GDP and HDI are low. At the same time, trust in the state's security has vanished, leading to vigilantism. The shortage of law enforcement personnel and courts makes the situation worse. For example, after the Rwandan Genocide in 1994, only 12 judges remained in the entire country, which made formal trials impossible. Immediate needs like food, water, and medical aid often take priority over justice issues. Therefore, it is crucial for these states to have a solid framework for justice. Inadequate restoration leads to a lack of accountability for terrible crimes and suggests the state will not take action to address these offenses. Conversely, excessive punishment will only frighten civilians who are already in a fragile state; this is harmful to the state itself. A model that explains to citizens why a particular form of justice is emphasized is necessary. This should be accompanied by further reforms that address humanitarian violations and highlight how international customary law can support those in need, all while respecting the state's sovereignty and the rights of individuals.

## Definitions

1. Retributive Justice - Whenever a state leans towards a punitive form of justice, which focuses on reparation on conviction, consequently leading to a stricter system of making criminals pay for crimes. Its core principle is "Wrongdoers deserve to suffer in proportion to the harm they have caused.

2. Restorative Justice - When a state, rather than emphasizing on the reparations paid by a criminal for their crime, focuses on betterment through dialogue, accountability, and reconciliation between victims, offenders, and the community, consequently leading to a system heavily relying on psychological factors, rather than physical. Its core principle is "Justice is achieved when harm is repaired and relationships are restored."

3. Conflicting States - Refers to a situation where opposing forces, laws, or principles are in opposition or contradiction with each other. In a legal context, it describes a conflict of laws, where different state or national laws apply to the same dispute and need to be reconciled. In a psychological context, it refers to internal emotional conflict between incompatible desires or drives

4. Post-Conflict State- A state which was a conflicting state in the recent or distant past, which has not gained back stability, and is transitioning back to normalcy.

5. Rome Statute- The Treaty which defined the ICC's Jurisdiction over genocide, crimes against humanity, war crimes and crimes of aggression.

6. International Customary Law- International customary law consists of rules derived from the consistent and general practice of states, accepted as legally binding. Unlike treaties, which are formal written agreements, customary law is unwritten but is a primary source of international law, alongside treaties and general principles of law. It applies to all states, even if they have not ratified a specific convention, as it arises from a shared belief that a practice is legally obligatory.

7. Capital Punishment- the state-sanctioned execution of a person as punishment for a crime after a legal conviction. It is a controversial issue with strong arguments both for and against it. While some countries have abolished it, others, like China and Iran, still use it, often for serious crimes such as murder, but sometimes also for non-violent offenses like drug trafficking

**A deeper understanding of the two main models**

Retributive justice is a legal and philosophical approach that addresses wrongdoing with proportionate punishment. It is based on the view that crime disrupts social order and moral balance. Justice is achieved only when offenders face penalties that match the harm they have caused. This concept is rooted in the ideas of Immanuel Kant, who believed punishment should come from moral obligation rather than social benefit, and G.W.F. Hegel, who saw punishment as restoring violated rights. Retributive justice focuses on the crime committed rather than on the offender's future reintegration.

Many states primarily use retributive systems. The United States, for example, widely employs life imprisonment without parole, mandatory minimum sentences, and the death penalty. China uses strict punitive measures and capital punishment according to its "strike hard" policy. Japan has strict sentencing laws and high conviction rates, along with capital punishment. In parts of the Middle East, including Saudi Arabia and Iran, harsh penalties under strict interpretations of Sharia law reflect a strong retributive philosophy. In these systems, the state

plays a main role in delivering justice, while victims often have limited involvement. This underscores the punitive and state-centered nature of the model.

During my time representing a delegation at an international Model UN simulation, I noticed that retributive justice often emerged as the favored approach for states valuing legal order, moral accountability, and deterrence. This was especially true in discussions about war crimes, genocide, and crimes against humanity. Many delegates contended that without firm punishment, post-conflict societies might appear to signal impunity, which would undermine international humanitarian law.

Restorative justice is a framework that focuses on accountability after conflict or crime. It aims to repair harm, help offenders reintegrate into society, and rebuild relationships, rather than just imposing punishment. It is based on dialogue, acknowledgment, truth-telling, and engagement between victims and offenders. Restorative justice is commonly used in transitional justice scenarios where long-term reconciliation is needed. Key examples include the South African Truth and Reconciliation Commission, Rwanda's Gacaca courts, New Zealand's Māori-informed youth justice system, Canada's Indigenous restorative practices, and Colombia's transitional justice framework from the 2016 peace accords. These models operate on the belief that punitive outcomes alone do not resolve the social wounds caused by conflict or mass violence. Sustainable peace is achievable when communities collectively take responsibility and rebuild trust. I felt a strong connection to this idea during my time at the Model UN. While representing a post-conflict state, I argued that "punishment alone may produce compliance, but restoration produces legitimacy." This perspective shaped our bloc's stance on long-term reconciliation strategies. Therefore, restorative justice is not just an alternative to retribution; it is a comprehensive approach that puts victims at the center. It promotes offender accountability through truth and participation instead of coercion and integrates justice into broader societal healing. This is especially relevant in conflicts marked by division, identity-based violence, or extended political repression, where rebuilding social trust is as important as addressing the original harm.

**The Great Question: Which Model should post-conflict countries follow?**

This question has been raised for many years. The answer can significantly shape a country's future. It can lead to prosperity or decline. For this reason, choosing the right model is crucial. The best path for a post-conflict state would be a model that combines the best aspects of both retributive and restorative justice, providing a balanced and effective approach. Why is this necessary? Post-conflict states are among the most fragile and complex places to navigate. People are often afraid for their safety and their families' well-being, uncertain whether their country will return to normal. Additionally, vigilantism can pose a major issue in these areas, making retribution necessary. However, excessive retribution can lead to chaos. People might start to fear their own government, viewing the courts as places of suffering rather than justice. On the other hand, too much focus on restoration could make victims' families feel that the justice system is being lenient on offenders. This could lead them to take matters into their own

hands or lose faith in the system altogether. Therefore, a balanced approach is essential. Merely suggesting balance can feel generic; that's why I will present a specific metric in the following sections of this paper.

**The Economic Aspect**

Post-conflict states are especially vulnerable because they come from periods marked by severe political disruption, economic collapse, and widespread human rights abuses. Neither purely retributive nor purely restorative justice can effectively address their challenges alone. The best internationally supported approach is a balanced hybrid model. In this model, retributive justice lays a foundation for accountability regarding serious crimes like genocide, war crimes, and crimes against humanity, according to the Rome Statute. At the same time, restorative justice works to mend the social fabric, help reintegrate offenders, and rebuild community trust, which is vital for long-term stability.

Retributive mechanisms such as international tribunals, hybrid courts, and special prosecutor's offices send a strong message that impunity cannot be tolerated. They deter future crimes and fulfill victims' rights to justice. However, these approaches can be costly, slow, and demand significant institutional resources. For these reasons, restorative methods like truth commissions, community hearings, victim-offender mediation, and programs for demobilization and reintegration are crucial for nations whose systems, budgets, and civil infrastructures have been devastated by conflict.

The economic angle reinforces this balanced model. Pure punishment exhausts financial resources through long-term incarceration, forensic investigations, and international legal processes. On the other hand, pure restoration can overlook systemic atrocities, which can diminish investor confidence and long-term political legitimacy. Hence, a balanced model lets states allocate their limited post-conflict resources wisely. It uses retributive justice for the most responsible offenders while applying restorative justice to reintegrate lower-level actors and reclaim human capital. This approach can be seen in Rwanda, Sierra Leone, and Colombia. During my time at the Model UN, I highlighted this connection by stating that post-conflict societies cannot afford either total forgiveness or complete punishment. Justice without stability collapses, and stability without justice weakens. This frame captures why hybrid models are now seen as best practice by international organizations like the UN, ICTJ, and the World Bank. They recognize that justice and rebuilding can work together when retributive and restorative elements operate in harmony, rather than in opposition.

**Arms vs. Justice**

In post-conflict environments, governments often spend too much on military rebuilding, including weapons, troop increases, and security operations, even after major fighting has stopped. While short-term stability needs some level of security, lasting peace depends on restoring justice systems that can address grievances, hold offenders accountable, and rebuild public trust. The financial logic is simple: each dollar, soldier-hour, or logistics effort spent on

military resources means a missed chance to support underfunded courts, understaffed truth commissions, or help victims. Investing in justice institutions, whether courts, tribunals, truth commissions, or community mediation, leads to benefits like reducing violence, preventing revenge cycles, and increasing trust in government. Historical and recent examples show that heavy military spending at the expense of justice has weakened efforts to transition from war to peace. After the Rwandan genocide, Rwanda initially directed its budget mainly toward military rebuilding, causing its judicial system to collapse under more than 120,000 genocide-related detainees. The lack of courtroom space created long delays and drew international criticism. Only when Rwanda invested resources in the Gacaca courts, which improved community-level restorative justice, did case processing speed up and reintegration began. Sierra Leone offers another clear example. In the early post-civil war period, spending prioritized security reforms and weapons purchases, but true stability came only after more funds went to the Special Court for Sierra Leone and the Truth and Reconciliation Commission, which helped establish accountability and support community reintegration. More recently, South Sudan's heavily militarized budget, with over 40% of government spending on arms, has stalled the Hybrid Court for South Sudan, leaving serious crimes unresolved and perpetuating cycles of impunity. In contrast, countries that balance security spending with early and strong investments in justice show far more lasting peace. After the Balkan conflicts, Bosnia and Herzegovina allocated significant resources to peacekeeping as well as the International Criminal Tribunal for the Former Yugoslavia (ICTY) and its War Crimes Chambers. This dual strategy of providing basic security alongside meaningful justice was essential in preventing renewed ethnic violence. Colombia's post-FARC efforts similarly show that shifting resources from military operations to the Jurisdicción Especial para la Paz (JEP), truth commissions, and land restitution initiatives has strengthened the government's legitimacy in former conflict zones and allowed for reduced military spending. Ultimately, reducing arms spending in post-conflict states is not just a political choice; it is a necessity for economic stability and peacebuilding. Excessive military spending after conflict often arises from political fear rather than sound planning. A focus on justice acknowledges that wars do not end when fighting stops; they end when institutions work to prevent future violence. Redirecting funds toward courts, investigators, reparations, and community reconciliation lays a strong foundation for recovery, reestablishes humanitarian protections, and ensures adherence to international legal standards. Therefore, a fair allocation of resources that prioritizes justice is crucial for transforming fragile ceasefires into lasting peace.

**The Devised Formula**

**Variables**

Variables (each scored 0–10):

C = Crime severity (scale: 0 = no mass crimes; 10 = systematic genocide/ongoing mass atrocities)

P = Perpetrator level (0 = mainly low-level offenders; 10 = concentrated command-level culpability)

V = Victim demand for accountability (0 = low/ambivalent; 10 = overwhelming, organized demand)

J = National judicial strength (0 = collapsed courts; 10 = functioning, independent judiciary)

E = Economic standing / fiscal capacity (0 = poor economy; 10 = strong fiscal capacity)

R = Reintegration importance (0 = low need to reintegrate ex-combatants; 10 = mass demobilization needed)

S = Social fragility (0 = socially cohesive; 10 = extreme fragmentation / revenge risk)

All variables are normalised 0–10.

**Formula**

$$JS = (0.25C + 0.20P + 0.18V + 0.15J + 0.12E) - (0.06R + 0.04S)$$

**Interpretation**

JS is measured on a comparable scale of about 0–10. A higher JS suggests that the justice system should focus on retributive elements, while a lower JS indicates that restorative elements should take precedence.

**Why These Weights?**

Crime severity (C, 0.25) has the highest weight because the type and seriousness of crimes determine the need for prosecution (e.g., genocide and war crimes require trials).

Perpetrator level (P, 0.20) is important since prosecuting command-level actors is a key goal of retributive justice.

Victim demand (V, 0.18) is crucial to legitimacy; strong victim demand supports formal accountability.

Judicial strength (J, 0.15) and economic standing (E, 0.12) indicate capacity: even if justice is necessary, weak courts or limited budgets push toward restorative options.

Reintegration (R, 0.06) and social fragility (S, 0.04) take away some weight because high reintegration needs and fragility support restorative approaches; their smaller weights indicate they influence the balance but do not completely override the importance of gravity and culpability.

**Thresholds & Policy Guidance**

$JS \geq 6.5$: Retributive-preferred. Focus on tribunals, hybrid courts, and prioritized prosecutions (command-level and most serious crimes). Restore rule of law investments to support trials. Restorative measures are acceptable as supplements (victim services, reparations) but not replacements for prosecution.

$3.5 < JS < 6.5$: Hybrid recommended. Combine targeted retributive prosecution (senior leaders, most serious crimes) with strong restorative programs (truth commissions, community reconciliation, reintegration for low-level combatants). Resource split guidance is below.

JS ≤ 3.5: Restorative-preferred. Emphasize truth-seeking, reparations, community reconciliation, DDR, and economic reintegration. Use prosecutions sparingly (e.g., where there is evidence and capacity for the worst offenders).

**Resource-ratio heuristic (how to translate JS into allocation ratios)**

For practical policy-making (not absolute rules), convert JS into an approximate retributive- restorative resource split:

Retributive % = clamp((JS / 10) × 100, 10%, 90%)

Restorative % = 100% - Retributive %

(The clamp ensures minimum attention to justice and avoids complete neglect.) For example, if JS = 7.0, then Retributive ≈ 70% resources (courts, investigations) and Restorative ≈ 30% (truth, reparations, DDR).

For the hybrid zone (3.5 -- 6.5), fine-tune: allocate at least 30% to restorative programs even if retributive is dominant to ensure social healing.

**Use of Formula**

This formula gives a number that can be evaluated using the mentioned thresholds. This way, a country can better allocate resources and also use it as an "Index" to rank countries to identify those needing the most external help. This can contribute to uplifting post-conflict nations and achieving global peace.

**Example Using a Real Life Case**

I will use Sierra Leone as an example, applying the formula based on the state of the country from 1991 to 2002.

**Variable Scores (0–10)**

This section presents the scores for each variable based on evidence from post-conflict Sierra Leone.

C — Crime Severity: 9

There were widespread war crimes, including mass rape, mutilations, forced conscription, and systematic atrocities. It was not genocide, but it was extremely severe.

P — Perpetrator Level: 7

Senior leaders of the RUF and AFRC orchestrated mass atrocities, but decentralized fighters and child soldiers reduced command control.

V — Victim Demand: 8

There were strong calls for accountability from civil society, survivor groups, and nationwide consultations.

J — Judicial Strength: 3

Domestic courts collapsed post-war, suffering from low capacity, political influence, and lack of prosecutorial resources.

E — Economic Standing: 2

Sierra Leone had one of the poorest economies in the world; post-war state revenue couldn't support major judicial processes independently.

R — Reintegration Importance: 9

Over 70,000 ex-combatants—including thousands of child soldiers—needed disarmament, demobilization, and reintegration (DDR).

S — Social Fragility: 8

High displacement, trauma, and community fragmentation raised the risk of revenge cycles.

**Calculation of JS**

Positive Block:

$0.25C = 0.25 \times 9 = 2.25$

$0.20P = 0.20 \times 7 = 1.40$

$0.18V = 0.18 \times 8 = 1.44$

$0.15J = 0.15 \times 3 = 0.45$

$0.12E = 0.12 \times 2 = 0.24$

Total Positive: 5.78

Negative Block:

$0.06R = 0.06 \times 9 = 0.54$

$0.04S = 0.04 \times 8 = 0.32$

Total Negative: 0.86

Final JS Score: 5.78 - 0.86 = 4.92

**Interpretation of Results**

According to the interpretation thresholds:

$JS \geq 6.5 \rightarrow$ Retributive justice preferred

$3.5 < JS < 6.5 \rightarrow$ Hybrid justice model

$JS \leq 3.5 \rightarrow$ Restorative justice preferred

JS = 4.92 (Hybrid Justice Model Recommended)

**Real Life Proof**

Sierra Leone's post-war justice system closely aligns with the hybrid model suggested by the JS score. Although the level of atrocities prompted strong international and domestic calls for accountability, the country's collapsed judiciary, severe economic weakness, and the pressing need to reintegrate tens of thousands of ex-combatants made a purely retributive approach impossible. Instead, Sierra Leone adopted a dual system: the Special Court for Sierra Leone pursued senior commanders who bore the most responsibility, while the Truth and Reconciliation

Commission focused on public testimony, healing, and reintegration. Community-led reconciliation ceremonies and DDR programs addressed deep social fragmentation that prosecutions alone could not resolve. This combination of targeted trials and broad restorative efforts reflects the structural constraints and societal needs at the time, confirming the JS prediction that Sierra Leone required a balanced, hybrid form of justice.

**Conclusion**

Global peace is urgently needed today, given the state of the world. I hope this paper can assist those aiming to create a better world by helping both conflict and post-conflict states assess which form of justice to implement and how to allocate resources, using the formula outlined above. Post-conflict justice has never been simply about choosing between punishment and forgiveness, but about understanding how societies heal while upholding the rule of law. Retributive and restorative justice are not opposites; they are interdependent tools that address different levels of harm, varying capacities, and different expectations from victims and communities. This paper shows that the success of any justice mechanism relies not on ideological preference, but on precise diagnosis, understanding the context, and making decisions with limited resources. By incorporating variables such as crime severity, perpetrator hierarchy, judicial strength, social fragility, reintegration needs, victim demands, and economic standing, the improved Justice Score Formula (JSF) gives post-conflict states a practical, evidence-based way to determine which model or combination of models is most likely to restore stability and prevent a return to violence. The analysis also highlights that justice is tied to economics: courts, truth commissions, reintegration programs, and reparations all compete for limited state resources alongside military and reconstruction needs. The PPC model and its allocations demonstrate how excessive military spending and insufficient investment in justice risk extending cycles of insecurity, while a balanced approach strengthens institutions, deters future crimes, and fosters long-term peacebuilding. Ultimately, post-conflict states should not overly rely on punitive trials or romanticize reconciliation; instead, they should adopt a strategic hybrid approach grounded in the realities of capacity, legitimacy, and societal needs. If the international community is serious about preventing renewed violence, justice must be concrete, planned, measured, funded, and adaptable. The JSF is not a rigid guideline but a flexible, UN-endorsed diagnostic tool that can transform political debates into organized assessments, guide donors and governments, and ensure that justice interventions are not just morally desirable but also practically feasible and socially effective. In post-conflict settings where every choice matters for survival, a balanced, evidence-based approach to justice is not just ideal; it is essential for building sustainable peace.

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# Modeling Economic Dynamics in the Bridgeport–Stamford–Norwalk, CT Metro Area Using a Bayesian Vector Autoregression; Analyzing Interdependence Between Regional Housing & Labor Markets By Adrian Montenegro


## Abstract

This paper examines the dynamic relationship between housing prices, employment, and unemployment in the Bridgeport–Stamford–Norwalk metropolitan area using quarterly data from 1977 to 2023. A Bayesian Vector Autoregression (BVAR) model with a Minnesota prior is employed to capture the interdependence between local housing market activity and labor market conditions. The analysis finds that positive shocks to housing price growth generate short-term increases in employment and corresponding declines in unemployment, suggesting that housing market expansions stimulate local economic activity in the near term. However, these effects dissipate after roughly four to six quarters, indicating that the influence of the housing market on the regional labor market is transitory rather than persistent. Compared to a standard VAR, the Bayesian approach produces smoother impulse response functions and narrower confidence intervals. The Bayesian approach is suitable for small-sample regional economic analysis. The findings in this paper highlight the importance of the housing sector as a short-run driver of local labor market conditions within Connecticut's largest metropolitan economy.


## 1. Introduction

The Bridgeport–Stamford–Norwalk metropolitan area represents one of the most economically diverse and dynamic regions in Connecticut. Characterized by a blend of financial services, suburban housing markets, and proximity to New York City, the area's economic performance reflects both local conditions and broader regional trends. Understanding how key sectors, particularly housing and labor, interact over time is essential for evaluating the resilience and growth potential of this metropolitan economy.

Housing markets often play a central role in local business cycles. Rising home prices can stimulate employment in construction, real estate, and related service industries, while falling prices may dampen consumer confidence and spending. Similarly, labor market outcomes such as employment growth and unemployment rates can reinforce or offset housing trends, creating feedback loops that shape the trajectory of regional economic activity. Despite the importance of these relationships, empirical research focusing specifically on smaller metropolitan areas such as Bridgeport–Stamford–Norwalk remains limited, with most studies emphasizing national or state-level data.

This paper seeks to address that gap by modeling the short-run dynamic interactions between housing prices, employment, and unemployment in the Bridgeport–Stamford–Norwalk metropolitan area. Using quarterly data from 1977 to 2023, a Bayesian Vector Autoregression (BVAR) model with a Minnesota prior is employed to estimate how shocks to one variable affect

others over time. The Bayesian framework is especially well suited to regional analysis, as it produces stable and interpretable estimates even with relatively small sample sizes.

The objective of this study is twofold: first, to determine how fluctuations in the housing market influence local labor market conditions; and second, to evaluate whether these effects are transitory or persistent. The findings indicate that positive shocks to housing price growth tend to increase employment and reduce unemployment in the short term, though these effects fade after several quarters. By capturing these localized relationships, this research contributes to a deeper understanding of how housing market dynamics influence regional economic performance within Connecticut's largest metropolitan area.

## 2. Data and Variables

This paper uses quarterly data from 1977Q1 through 2023Q1 for the Bridgeport–Stamford–Norwalk, Connecticut Metropolitan Statistical Area (MSA). The dataset combines measures of housing market performance and labor market activity to capture local economic dynamics over time. All data were obtained from publicly available federal sources to ensure transparency and replicability.

### Housing Prices (HPI)

The housing market is represented by the All-Transactions House Price Index for Bridgeport–Stamford–Norwalk, provided by the Federal Housing Finance Agency (FHFA). This index measures changes in single-family home prices based on repeat mortgage transactions, providing a reliable indicator of real estate market fluctuations. The series is originally quarterly, which aligns naturally with the model's frequency.

### Employment

Employment is measured using Total Nonfarm Employment from the Bureau of Labor Statistics (BLS) Current Employment Statistics (CES) program. This variable reflects the total number of payroll jobs within the MSA and serves as a proxy for regional economic activity. The monthly series was converted to quarterly averages to ensure consistency across all variables.

### Unemployment Rate

Unemployment data come from the BLS Local Area Unemployment Statistics (LAUS) program. The unemployment rate measures the share of the labor force actively seeking but not holding employment. Like the employment series, monthly data were averaged to a quarterly frequency.

### Transformations

To ensure stationarity and interpretability, several transformations were applied before modeling:

- The employment and house price series were transformed into natural logarithms and then differenced to obtain quarterly growth rates:
  $\Delta ln(Employment),\ \Delta ln(HPI)$
  These represent approximate percentage changes quarter to quarter.
- The unemployment rate was found to be non-stationary in levels; therefore, the first difference was taken:
  $\Delta(Unemployment\ Rate)$

The resulting dataset included three key variables: the growth rate of employment ( $\Delta ln(Employment)$), the growth rate of housing prices ($\Delta ln(HPI)$), and the change in unemployment rate ($\Delta Unem$).

Descriptive Statistics

Table 1 reports the descriptive statistics for each transformed series:

| Variable | Obs | Mean | Std. Dev. | Min | Max |
|---|---|---|---|---|---|
| Δln(Employment) | 47 | –0.0439 | 3.8773 | –18.1469 | 17.2597 |
| Δln(HPI) | 47 | 0.0122 | 0.0181 | –0.0204 | 0.0709 |
| Δ(Unemployment) | 47 | –0.2801 | 0.7055 | –3.0333 | 0.8333 |

Table 1 presents summary statistics for the transformed series used in the analysis. Average quarterly employment growth was slightly negative over the sample period, while housing prices grew by roughly 1.2 percent per quarter on average. The change in the unemployment rate fluctuated around zero, consistent with a stationary series. The extensive range of values for employment growth reflects periods of substantial expansion and contraction in the regional labor market, including recessions and recoveries.

Data Summary

After processing, the dataset contains approximately 180 quarterly observations (1977–2023). The transformations and quarterly aggregation help mitigate noise while preserving the cyclical patterns of the local economy. This will serve as the foundation for the subsequent VAR and BVAR analyses.

## 3. Methodology

This study employs a Vector Autoregression (VAR) framework to analyze the dynamic interactions between housing price growth, employment growth, and changes in unemployment in the Bridgeport–Stamford–Norwalk metropolitan area. The VAR model allows each variable to depend on its own past values and on the past values of the other variables, capturing interdependencies across local housing and labor markets.

The VAR Model

A basic κ-variable VAR(p) model can be written as:

$$y_t = A_1 y_{t-1} + A_2 y_{t-2} + \cdots + A_p y_{t-p} + c + \varepsilon_t$$

Where:

- $y_t$ is a κ x 1 vector of endogenous variables
  $$y_t = [\Delta \ln(\text{Employment}_t),\ \Delta \ln(\text{HPI}_t),\ \Delta(\text{Unemployment}_t)]'$$
- $A_i$ are κ x κ coefficient matrices for each lag *i*
- c is a vector of constants
- $\varepsilon_t$ is a vector of white-noise error terms

The model uses one lag (p = 1), selected based on the Akaike Information Criterion (AIC) and Hannan-Quinn Information Criterion (HQIC). All variables are stationary after differencing, satisfying the standard requirements for VAR estimation.

Bayesian VAR (BVAR) Estimation

Though classical VAR models are flexible, they can suffer from overparameterization (too many estimated coefficients relative to the available observations), especially in regional analyses with small datasets. To mitigate this, the paper uses a Bayesian Vector Autoregression (BVAR) that incorporates prior beliefs about coefficient stability via a Minnesota prior. This approach "shrinks" coefficients on lagged variables toward zero, stabilizing estimates and improving out-of-sample accuracy.

Formally, the BVAR estimation imposes priors on the elements of the coefficient matrices $A_i$ and on the variance-covariance matrix of the error terms. The Minnesota prior assumes that:

- Each variable follows a random walk as a reasonable benchmark,
- The coefficients on lagged own variables are centered near one,
- The coefficients on lagged other variables are centered near zero, and
- The overall tightness of the prior is controlled by a hyperparameter λ.

In STATA, the model is estimated using the *bayes: var* command with the conjugate Minnesota prior. The general specification is:

$$\text{bayes: var } y_t,\ \text{lags}(1)\ \text{minnconjprior}(\text{selftight}(0.3)\ \text{crosstight}(0.5)\ \text{lagdecay}(1))$$

where:

- selftight(0.3) controls the tightness on own-variable lags,
- crosstight(0.5) controls shrinkage on cross-variable lags, and
- lagdecay(1) determines how fast tightness decreases for longer lags.

This formulation provides a balanced regularization, ensuring stable, interpretable impulse responses even with limited observations.

Impulse Response Functions (IRFs)

After estimating both the VAR and BVAR models, Impulse Response Functions (IRFs) are computed to trace the effect of a one-standard-deviation shock to one variable on the others over 12 subsequent quarters. The IRFs are orthogonalized using a Cholesky decomposition of the covariance matrix, which assumes an ordering of:

$$[\Delta \ln(\text{HPI}),\ \Delta \ln(\text{Employment}),\ \Delta(\text{Unemployment})]$$

This ordering reflects the assumption that housing price shocks affect employment and unemployment contemporaneously, while labor market variables respond with a short lag.

The IRFs provide an intuitive way to visualize how a sudden change in the housing market influences the regional labor market dynamics over time.

Model Stability and Diagnostics

Model stability is verified using the *varstable* and *bayesvariable* diagnostics in STATA. Both the traditional VAR and Bayesian VAR models satisfy the stability condition that all roots lie within the unit circle, indicating that the estimated system is stationary.

**4. Results and Discussion**

This section presents the results from both the standard Vector Autoregression (VAR) and the Bayesian Vector Autoregression (BVAR) models. The primary tool for interpretation is the Impulse Response Function (IRF), which traces how each variable responds to a one-standard-deviation shock in another variable over twelve quarters.

Standard VAR Results

The conventional VAR(1) model provides a baseline view of the local housing–labor interaction. The estimated system is stable, as confirmed by the unit-root diagnostics (*varstable*), with no roots lying outside the unit circle.

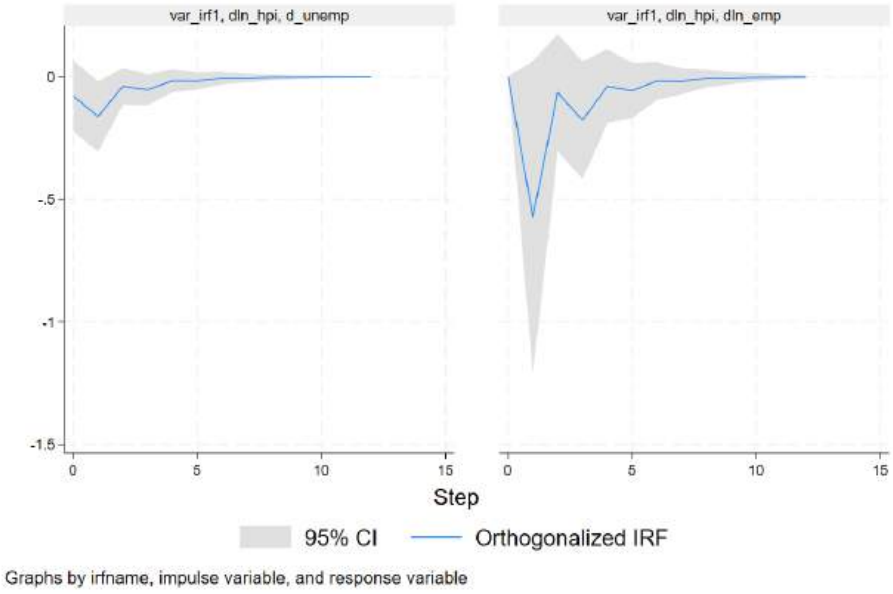



**Figure 1.** presents the orthogonalized impulse responses of employment growth and unemployment change to a housing price growth shock. A positive housing shock initially produces a decline in the unemployment rate and a modest, short-lived increase in employment growth. The negative unemployment response is economically intuitive: higher housing prices stimulate construction, household wealth, and local spending, which in turn boosts labor demand. The impact diminishes after roughly 4 to 6 quarters, suggesting that the housing market's effect on the regional labor market is primarily short-term.

The employment response shows a brief negative movement before rising, likely reflecting short adjustment lags between the housing and labor sectors. Although the point estimates exhibit volatility, the direction of the effects aligns with standard regional macroeconomic theory.

Bayesian VAR Results

The Bayesian VAR model, estimated with a Minnesota prior, refines these results by shrinking unstable coefficients toward zero and reducing estimation noise. The Bayesian impulse responses (Figure 2) exhibit smoother dynamics and narrower 95% confidence intervals than those of the standard VAR, emphasizing the stabilizing influence of the Bayesian framework.

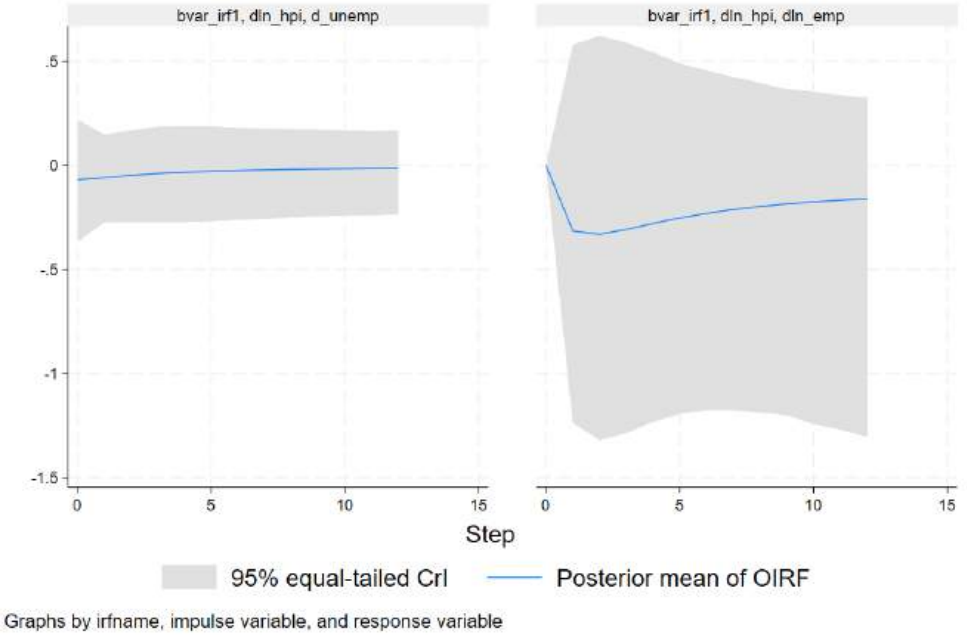



**Figure 2.** Consistent with the classical VAR, the unemployment rate decreases following a positive housing price shock, while employment growth increases modestly. However, the Bayesian responses show a smaller amplitude and more gradual adjustment, suggesting that the true underlying effects are likely moderate rather than extreme. The tightening of credible intervals around the mean responses indicates greater statistical confidence in these results.

These findings confirm that the BVAR framework is particularly effective for regional economic analysis, where data samples are limited and series are often noisy. The results demonstrate that Bayesian regularization helps filter out random fluctuations while preserving economically meaningful patterns.

Economic Interpretation

The results imply that fluctuations in the housing market play a leading role in short-run local economic conditions. When housing prices rise, construction activity typically expands, household wealth effects boost consumption, and local employment increases, contributing to temporary declines in unemployment. Conversely, housing market slowdowns or price declines can depress hiring and increase joblessness in the near term.

However, the fading of these effects after approximately one year indicates that the Bridgeport–Stamford–Norwalk labor market is resilient and adjusts relatively quickly to housing shocks. This resilience may stem from the region's diversified economy and strong commuter linkages to New York City's labor market.

In summary, the Bayesian VAR results highlight a short-term cyclical connection between housing and employment but little evidence of persistent long-term effects. These findings

reinforce the view that the housing market is an essential but transitory driver of local business cycles.

Figures

Each figure displays the estimated response (blue line) and its 95% confidence interval (gray band). The responses are orthogonalized using Cholesky decomposition with the ordering:

$$[\Delta \ln(\text{HPI}),\ \Delta \ln(\text{Employment}),\ \Delta(\text{Unemployment})].$$

**5. Conclusion**

This study examined the dynamic interrelationships among housing prices, employment, and unemployment within the Bridgeport–Stamford–Norwalk metropolitan area using both classical and Bayesian Vector Autoregression (VAR and BVAR) models. By leveraging regional data from the Federal Reserve Bank of St. Louis (FRED), the analysis sought to identify how local economic indicators respond to shocks in housing market activity, particularly housing price growth.

The traditional VAR suggests that a positive shock to housing prices initially exerts a modestly negative effect on unemployment and short-term employment declines, followed by gradual stabilization. These results align with the expectation that higher housing prices can signal localized economic overheating or reduced affordability, leading to temporary employment adjustments before returning to equilibrium.

The Bayesian VAR produced more conservative and smoother impulse responses, reflecting the model's ability to incorporate prior information and handle parameter uncertainty. The 95% credible intervals were wider, reinforcing the uncertainty inherent in smaller regional samples. Nonetheless, both models suggest that shocks to the housing sector have only short-lived effects on labor market outcomes and that the Bridgeport–Stamford–Norwalk economy demonstrates a relatively strong capacity for mean reversion following disturbances.

From a policy perspective, the results highlight the importance of monitoring housing market fluctuations as a leading indicator of local employment stability. Housing dynamics in the region appear closely tied to economic confidence, investment, and labor demand. Future work could expand the model to include additional macroeconomic variables, such as wages, construction permits, or consumer sentiment, to capture a broader picture of local business cycle dynamics.

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**The Unyielding Glass Ceiling: Analyzing Systemic Sexism and Inequality in the U.S.**
**By Kayla Weng**


## Abstract

This paper aims to analyze the rationale for the glass ceiling in the United States and its effects. The concept of the glass ceiling emerged from the intersection of historic systemic sexism, such as legal barriers and social norms, and the ideology of male superiority. This paper will examine how this concept has furthered the double standard for women and men and led to inequality in the workplace, such as wage gaps, underrepresentation in leadership positions, and experiences of microaggressions. The false notion of male superiority in the workplace has justified these inequalities. However, the differences in skills are not due to male superiority but because women receive fewer opportunities to obtain the skills needed in the workplace. Even with the necessary skills, the achievements of a woman are often overshadowed by those of a man. Women are held to stricter standards to prove their competence and gain the same recognition as men. When they don't meet these standards, they are often terminated, reinforcing stereotypes and hindering the advancement of future generations of women in the workplace. Despite the many laws that have been enacted to address this discrimination against women in the workplace, it remains a problem due to loopholes, such as the bona fide seniority system.


## Introduction

Throughout history, gender inequities, especially wage gaps, have been present in every aspect of life. These disparities can be attributed to several factors, such as differences in psychological and physical characteristics, a historical notion of male superiority, a lack of awareness, and inefficient policies. This became the basis of Marilyn Loden's introduction of the term "glass ceiling" in the 1970s. Loden hoped to outlive the glass ceiling, but her wish was unfilled, and she died at age seventy-six in 2022 with the glass ceiling persisting to affect women today.[1] As Judith Oakley stated, "The glass ceiling is not one ceiling or wall in one spot, but rather many varied and pervasive forms of gender bias that occur frequently in both overt and covert ways," this concept has had detrimental effects on women, including leadership prevention, increased financial insecurity, and a decline in female engagement in the workforce.[2]

Gender disparities in the US have persisted for centuries, but were not addressed until the 19th and 20th centuries. For example, in 1869, Myra Bradwell became the first woman to pass the bar exam in Illinois. Despite this, she was denied a license to practice law in an eight-to-one decision by Illinois' Supreme Court in 1872, even though she possessed the same qualifications as male candidates.[3] The court justified this decision by saying that the right of citizens to enjoy

[1] Rachel Treisman, "Remembering Marilyn Loden, Who Gave a Name to the Glass Ceiling," *National Public Radio,* September 5, 2022, https://www.npr.org/2022/09/05/1121132384/marilyn-loden-glass-ceiling.
[2] Judith Oakley, "Gender-Based Barriers to Senior Management Positions: Understanding the Scarcity of Female CEOs," *Journal of Business Ethics* 27, no. 4 (2000): 321–34, https://doi.org/10.2307/25074386, 321.
[3] "Myra Bradwell," *Supreme Court of the United States*, n.d, https://www.supremecourt.gov/visiting/exhibitions/LadyLawyers/section1.aspx.

privileges and immunities did not include the right to practice law in state courts since it was not explicitly stated as a right or privilege granted by citizenship in the 14th Amendment. Justice Joseph Bradley, one of the justices in this case, reasoned that women should not practice law and stay home to be housewives. He justified his belief by claiming that women needed protection from the "harms" of the workplace. He emphasized the importance of maintaining the "respective spheres of man and woman," which was the "law of the Creator." [4]

**Literature Review**

This research paper investigates how these factors slow the progression of women into high leadership positions in the workplace. Many previous studies have also examined these factors, but there is a research gap in connecting these separate factors and how they strengthen other factors. Research by Marianne Bertrand and Judith G. Oakley has indicated the existence of the invisible barrier of the glass ceiling.[5][6] Due to historic prejudice, gender biases have been embedded into society in many ways, such as through discriminatory hiring practices and gender roles at home. Cailin S. Stamarski and Leanne S. Son Hing's work highlights how the impacts of biased practices in the workplace have created an environment that hinders the advancement of women.[7] Through his studies on equal employment cases, Jason Rubinstein examines how several companies avoided punishment despite having discriminatory policies due to the ambiguity of legislation regarding equality in the workplace.[8] Arlie Russell Hochschild's book, *The Second Shift*, shows how gender roles have caused women to lack the motivation to work on their careers due to the additional disproportionate burden of housework and childcare at home.[9] Sheryl Sandberg's book, *Lean In*, also studies the factors that contribute to women's reluctance to pursue leadership positions, emphasizing the need for both societal and individual change.[10] The literature examines the multifaceted barriers to women's career advancement, focusing on the glass ceiling, gender biases in workplace practices, legal ambiguities in addressing discrimination, and the impact of domestic responsibilities.

**Research Methodology**

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[4] Kirsten Silwanowicz, "Women's Rights in the Workplace: The Struggle Is Still Real." *Social Science Research Network Electronic Journal*, 2019, https://doi.org/10.2139/ssrn.3569324, 103.
[5] Marianne Bertrand, "The Glass Ceiling," *Social Science Research Network Electronic Journal*, June 2018, https://doi.org/10.2139/ssrn.3191467.
[6] Oakley, "Gender-Based Barriers to Senior Management Positions: Understanding the Scarcity of Female CEOs."
[7] Cailin S. Stamarski and Leanne S. Son Hing, "Gender Inequalities in the Workplace: The Effects of Organizational Structures, Processes, Practices, and Decision Makers' Sexism," *Frontiers in Psychology*, September 16, 201, https://doi.org/10.3389/fpsyg.2015.01400,
[8] Jason Rubinstein, "Seniority Systems as a Potential Threat to Equal Employment Opportunity," *University of Pennsylvania Journal of Labor and Employment Law,* n.d, https://scholarship.law.upenn.edu/cgi/viewcontent.cgi?article=1237&context=jbl.
[9] Arlie Russell Hochschild, *The Second Shift: Working Parents and the Revolution at Home*, *Penguin Books*, 1989.
[10] Sheryl Sandberg, *Lean In: Women, Work, and the Will to Lead*, New York: Alfred A. Knopf, 2013.

This topic was selected because I'm passionate about empowering women and girls to chase their dreams and take on leadership roles without fear. Eliminating the glass ceiling is the first step to my goal. This paper analyzes the glass ceiling in the USA, its origin, and its multifaceted impacts, using a mixed method of both qualitative and quantitative data. The research relies on a literature review of academic journals, books, and articles, with the addition of analyses of interviews and statistics. The literature review is a systematic and comprehensive analysis of existing research on the impact of the glass ceiling, synthesizing findings to provide a cohesive understanding of the context. There are some limitations to this method, including a lack of control over data collection in the research used. However, using this methodology allows my research scale to be larger, which I believe is more important, as gathering primary data would not be enough to study the impact and trends of the glass ceiling across decades. The approach was to first assess the historical context that allowed the glass ceiling to emerge and progress, such as Myra Bradwell's case. Then, the paper delves into the legal complications engendering the lack of sufficient policies addressing gender discrimination in the workplace. Following this, the paper explores the influence of the glass ceiling in the workplace and at home, and how inequality in both can reinforce gender roles in the other. Finally, the paper considers possible solutions to the problems that allow the glass ceiling to persist.

**Factors Contributing to the Glass Ceiling**

The extent of discrimination against women is often underestimated, and its impact is downplayed as seen in the oppressive reality of the glass ceiling.[11] In Myra Bradwell's case, the Supreme Court of Illinois stated that disparities would only affect minorities and not women because they make up a majority of the population. In addition to court judges, many people also do not believe that this prejudice exists, and when proven wrong, they would justify it by saying that men worked more high-risk jobs for their families instead of personal fulfillment like women.[12]

A common misconception is that the glass ceiling originated due to male superiority and differences in skills between women and men. However, the creation of the glass ceiling is mostly due to ingrained stereotypes, a lack of awareness surrounding gender biases, and the significant impact of legal barriers. Although these factors have been highlighted through several public research papers and articles, many people refuse to accept them and believe in a false notion of male superiority.[13]

Differences in childhood education and culturally instilled values for women and men have influenced discrepancies in personality and mindsets. Most women are not as competitive in the workplace because they have been taught not to compete with men since their childhood,

[11] Caroline Criado Perez, Invisible Women: Exposing Data Bias in a World Designed for Men, London: Vintage, 2019, 33.
[12] Silwanowicz, "Women's Rights in the Workplace: The Struggle Is Still Real," 104.
[13] Jocelyn Frye and Robin Bleiweis, "Rhetoric vs. Reality: Making Real Progress on Equal Pay," *Center for American Progress*, March 26, 2019, https://www.americanprogress.org/article/rhetoric-vs-reality-making-real-progress-equal-pay/.

which negatively impacts their opportunities for higher positions.[14] Some blatant cultural messages have also been printed on onesies, such as "smart like daddy" for boys and "pretty like mommy" for girls. Girls are also labeled bossy when they try to lead, while boys are rarely called bossy since it is "normal" for them. These messages are ingrained and discourage girls from attempting to gain leadership roles in the long run.[15]

In 2011, before Christmas, a young girl, Riley, gained popularity on social media for pointing out that companies marketed pink stuff and princess toys to girls and superhero toys to boys. To this, Riley said, "Some girls like superheroes, some girls like princesses. Some boys like superheroes, and some boys like princesses. So why do all the girls have to buy pink stuff and the boys have to buy different colored stuff?"[16] Girls are also taught from a young age to play games that include emotion and inclusion, compared to games that include rules and fairness for boys. Boys are also taught to emphasize their knowledge and ability to challenge others and become the leader of their friend group and a leader in society.[17]

Similarly, due to these teachings, women avoid risk more than men, causing them to evade high-risk positions that often provide significantly more benefits.[18] Women also tend to have different leadership and linguistic styles. Female leaders prefer to collaborate with team members, prioritizing understanding and fostering strong relationships. Male leaders, on the other hand, prefer to act as the protector and decision-maker.[19] Many cultural teachings also advise girls to be obedient and listen to men. Ultimately, these slight differences can substantially hinder a woman's success in the workplace substantially.[20]

In addition to differences in personality traits, the development and reinforcement of the ideology of male superiority throughout history have significantly impacted society's views on the role of women. As well as a normal job, Women are expected to work a "second shift," taking care of housework and children. Many men justify this difference by claiming that a woman's job is for personal fulfillment, while a man's job is essential to the financial stability of the family and is more tiring.[21] This belief has increased the number of things women have to balance, affecting their flexibility at work. Many women have to trade off work opportunities because of the lack of flexibility they have due to childcare and housework. Although many new technologies, such as vacuum cleaners and washing machines, have been created to lower the time needed for housework, the observed increase in parenting time to educate children offsets the time saved.[22]

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[14] Bertrand, "The Glass Ceiling," 10.
[15] Sandberg, *Lean In: Women, Work, and the Will to Lead*, 17 and 19.
[16] Sandberg, *Lean In: Women, Work, and the Will to Lead*, 21.
[17] Oakley, "Gender-Based Barriers to Senior Management Positions: Understanding the Scarcity of Female CEOs," 325.
[18] Bertrand, "The Glass Ceiling," 9.
[19] Oakley, "Gender-Based Barriers to Senior Management Positions: Understanding the Scarcity of Female CEOs,"
[20] Hochschild, *The Second Shift: Working Parents and the Revolution at Home*, 327.
[21] Hochschild, *The Second Shift: Working Parents and the Revolution at Home*, 142.
[22] Bertrand, "The Glass Ceiling," 18.

As shown in many of sociology professor Arlie Russell Hochschild's case studies, men who have had negative relationships with their mothers in childhood have an unconscious fear of women with authority, which is a major reason for the male perception of women in the workplace. Most men also feel shame when they lose in a competition against women due to traditional beliefs that men are superior. This fear resulted in the creation of a social system that excludes women, known as the Old Boys Network. To protect their unreasonably high salaries and perks from possible "threats", many men in decision-making positions use corporate downsizing to lay off women, limit women's access to networking opportunities, and prevent women from joining men in the upper ranks of the workplace.[23] For example, in an EClinicalMedicine study, it was revealed that female colleagues were purposely not invited to golf games, where many male colleagues engaged in work-related discussions with a participant stating, "It did not feel like we were actively excluding the women, but I can tell you that if there was a woman resident, she would not have been invited to the golf games."[24] As Julia Boorstin stated, "Women at the highest ranks in business can exist in a paradox: even when they are insiders, they're often still outsiders…The systems they're working in most often were built by, and are being perpetuated by, a largely homogenous group of white men."[25]

Most men who agree that there is a wage gap believe that it is justified by the contrast in skills between them and their female counterparts, but this gap is largely because of discrimination. Most companies hire and retain men more than women, and when they do hire women, they are placed in support positions with no path to leadership positions, such as human resources (HR) or public relations (PR). These positions do not teach the necessary skills or experiences, such as marketing or operations, that are needed to rise to executive roles. In addition to support positions, women are also put in token positions that are subject to more pressure and criticism if a mistake is made, further discouraging them from attempting to seek high-ranking positions.[26]

> It's not that all of a sudden the boards wake up and say, 'Oh, there should be a female here.' They do that sometimes, because it's easier to hide behind, 'Well, of course. Of course that failed, because it was female. What could we have been thinking?'" There's also a "savior effect" that sometimes happens after a woman is brought on and pushed out as a CEO — she's replaced by a man, a mark of a return to the status quo.[27]

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[23] Oakley, "Gender-Based Barriers to Senior Management Positions: Understanding the Scarcity of Female CEOs," 328.

[24] Alpana Mohta, "The Old Boys' Club: Female Physicians Are Often Excluded from Networking Opportunities," *MDLinx*, June 1, 2023, https://www.mdlinx.com/article/the-old-boys-club-female-physicians-are-often-excluded-from-networking-opportunities/SF7sXHsuqc1z1x7FsPhA5.

[25] Julia Boorstin, *When Women Lead*, Hachette UK, 2022, 13 and 14.

[26] Oakley, "Gender-Based Barriers to Senior Management Positions: Understanding the Scarcity of Female CEOs," 329.

[27] Emily Stewart, "The Glass Cliff and Why Struggling Companies Promote Women, Explained," *Vox*, October 31, 2018, https://www.vox.com/2018/10/31/17960156/what-is-the-glass-cliff-women-ceos.

A Harvard Business Review study further supported this, discovering that when participants were asked whether a woman or a man should be given the CEO position, 62 percent chose a man when given a thriving company and 69 percent chose a woman when given a declining company. Another example, Anne Mulcahy was promoted to CEO when the company she was working at, Xerox, was nearing bankruptcy because none of her male colleagues wanted to take on a risky position.[28] Many women also do not receive as much feedback as men in the same position and company, hindering their ability to improve and secure promotions.[29] Still, although mostly women work in HR, the leadership and decision-making positions are held by men. These men use personal bias and biased HR policies when hiring and evaluating current employees for promotions, an example of the Old Boys Network. Face time, physically working in the office, is a major part of performance evaluation, which is unfair to mothers because they have less face time due to their need for flexible work hours to take care of their children. These decision-makers also often have to make judgments and reports without fully understanding and evaluating employees, resulting in the use of stereotypes to fill in missing information.[30]

In 2003, researchers at Columbia Business School gave business students a case study on the professional achievements of a successful venture capitalist (VC). Half of the students were given the version with a female VC, Heidi, and the other half was given the version with a male VC, Howard. Although both groups thought they had the same competence level, their personalities were perceived differently. Howard was seen as likable, and his assertiveness and networking skills were viewed positively. Heidi, on the other hand, was often perceived as aggressive, bossy, selfish, and less likable. Her assertiveness, the very same traits that contributed to her success, were viewed negatively. With these results, the researchers concluded that unconscious biases and gender stereotypes can influence people's perception of others. While men are often rewarded for being assertive and ambitious, women who exhibit the same traits may be criticized. As Sandberg said, "Female achievements come at a cost," and "Success and likeability are positively correlated for men and negatively for women. When a man is successful, he is liked by both men and women. When a woman is successful, people of both genders like her less."[31][32]

Women in leadership positions receive fewer benefits than men in the same position, such as fewer shares, a lower severance payment, and a lower wage, discouraging women from seeking these positions.[33] For example, Kate Rotondo, a software engineer at a tech giant, made

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Stewart, "The Glass Cliff and Why Struggling Companies Promote Women, Explained."

[28] Stewart, "The Glass Cliff and Why Struggling Companies Promote Women, Explained."

[29] Oakley, "Gender-Based Barriers to Senior Management Positions: Understanding the Scarcity of Female CEOs," 323.

[30] Stamarski and Hing, "Gender Inequalities in the Workplace: The Effects of Organizational Structures, Processes, Practices, and Decision Makers' Sexism, " 4.

[31] Sandberg, *Lean In: Women, Work, and the Will to Lead*, 17.

[32] Sandberg, *Lean In: Women, Work, and the Will to Lead*, 39 and 40.

[33] Oakley, "Gender-Based Barriers to Senior Management Positions: Understanding the Scarcity of Female CEOs," 324.

$20,000 less than her colleagues in restricted stock units (RSUs), which is a form of employee compensation.[34] This pattern of disadvantage extends beyond unequal compensation at the top, also manifesting in hiring practices in general. Significantly more women are hired for positions in companies that are already experiencing a decline. This decline is then blamed on the fact that the management position is occupied by a woman, which strengthens the stereotypes that associate "feminine" traits with incompetence and "masculine" traits with competence.[3536] For example, when a woman is hired for the superintendency role, they are placed in a district with kids who have more needs and lower academic achievements. These positions are precarious, and women are blamed for any failures.[37]

It has also been proven that employment and wage differences between men and women are not due to skills or qualifications but to gender. Women occupy most positions in education, nursing, and social work. Therefore, they have the most experience in these sectors and are more qualified than men. However, in the education sector, men are hired as superintendents more than women. In fact, some women have more experience and skills, but men are still chosen.[38] Many people also think that the wage gap is due to differences in work choices, but research shows that this is not true. The Bureau of Labor Statistics proved that the wage gap is not due to work choices because, in a study with over 125 occupations, a wage gap was seen in all but 12 occupations. A significant factor in the wage disparity is actually discrimination, despite the number of laws banning discrimination in the workplace.[39]

**Legal Challenges and the Limitations of Legislation**

In the 20th century, the Civil Rights movement was on the rise and brought the injustices many minorities faced due to discrimination to national attention, generating widespread public awareness and moral outrage. After WWI, women became accustomed to working at factories and wanted to keep their jobs. However, most husbands and men did not approve of this due to their traditional views that the primary roles of women should be confined to the domestic sphere, with responsibilities as wives, mothers, and homemakers. This led to the rise of women's suffrage.[40]

The Fair Labor Standards Act of 1938 (FLSA) was one of the first laws that addressed fair work and pay. It ensured that employees were paid fairly and set a minimum wage that all

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[34] Sydney Pereira, "4 Women Who Went Public with Pay Gap Stories," *The Muse*, June 21, 2022, https://www.themuse.com/advice/going-public-with-pay-gaps-stories.
[35] Timmer and Woo, "Precarious Positions: Glass Ceilings, Glass Escalators, and Glass Cliffs in the Superintendency," 3.
[36] Oakley, "Gender-Based Barriers to Senior Management Positions: Understanding the Scarcity of Female CEOs," 326.
[37] Timmer and Woo, "Precarious Positions: Glass Ceilings, Glass Escalators, and Glass Cliffs in the Superintendency," 2.
[38] Jennifer D. Timmer and David S. Woo, "Precarious Positions: Glass Ceilings, Glass Escalators, and Glass Cliffs in the Superintendency," *Frontiers in Education*, November 6, 2023, https://doi.org/10.3389/feduc.2023.1199756, 2.
[39] Frye and Bleiweis, "Rhetoric vs. Reality: Making Real Progress on Equal Pay."
[40] Silwanowicz, "Women's Rights in the Workplace: The Struggle Is Still Real," 104.

employees would receive. It also set standards for overtime pay and required employers to pay a higher rate for every hour an employee worked over 40 hours a week. With the rise of women's suffrage, many women believed that legislation explicitly targeting equal pay for women should also be established, since the FLSA was not specifically for women. After the creation of the FLSA, women demanded further regulations to ensure equal pay, leading to the establishment of the Equal Pay Act (EPA).[41] The EPA stated that men and women would receive equal pay for equal work. The Equal Employment Opportunity Commission (EEOC) was also created to help enforce these regulations and later those of Title VII, too.[42]

Title VII enhanced data collection to better identify and address pay disparities, making it easier to pursue class action lawsuits regarding pay discrimination. The act limited the "factors other than sex defense" to be based on a bona fide system, job position, or necessity for business operations. It also allowed employees to challenge an employer's defense by proving that a similar job does not have a wage gap, which would be especially helpful for women affected by the glass ceiling.[43] However, the act's protections for bona fide systems became a loophole that many companies exploited to continue paying women unequal wages.[44]

Many companies also discriminate against pregnant women, preventing them from finding a stable job. Until 1974, California's Disability Fund under Section 2626 of California's Unemployment Insurance Code denied pregnancy as a reason for benefits from the disability fund. However, the court in *Geduldig v. Aiello* ruled that discrimination based on pregnancy was not necessarily discrimination based on sex. General Electric's disability policies did not include pregnancy. Despite the controversy, the Court followed the precedent in *Geduldig v. Aiello*. At the time, 85% of working women became pregnant while employed and were not given proper protections to maintain financial stability and health insurance, emphasizing the importance and need for this act.[45] These two rulings, in addition to the large number of working pregnant women, led to public outrage, pressuring Congress to pass the Pregnancy Discrimination Act (PDA) in 1978, which amended Title VII and included discrimination due to pregnancy as discrimination based on sex.[46]

In the 21st century, due to the ineffectiveness and inconsistent enforcement of the FLSA, EPA, and Title VII, resulting from the EEOC and the Department of Labor's lack of resources, several new legislations were created. In 2020, Kate Rotondo found out that she was paid substantially less than her male colleagues and did not receive a raise even after complaining to HR. Therefore, she turned to the EEOC, expecting them to help her. However, the EEOC was not

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[41] Silwanowicz, "Women's Rights in the Workplace: The Struggle Is Still Real," 105.
[42] "The Paycheck Fairness Act: Closing the 'Factor Other than Sex' Loophole to Strengthen Protections against Pay Discrimination," *National Women's Law Center*, March 2019, https://nwlc.org/wp-content/uploads/2019/03/PFA-Closing-the-Loophole-v2.pdf.
[43] "The Paycheck Fairness Act: Closing the 'Factor Other than Sex' Loophole to Strengthen Protections against Pay Discrimination."
[44] Rubinstein, "Seniority Systems as a Potential Threat to Equal Employment Opportunity," 258.
[45] Silwanowicz, "Women's Rights in the Workplace: The Struggle Is Still Real," 117.
[46] Silwanowicz, "Women's Rights in the Workplace: The Struggle Is Still Real," 109.

able to help her and instead treated her with disdain.[47] *Corning Glass Works v. Brennan* also reaffirmed the ineffectiveness of these acts. Corning Glass Works created day shift and night shift positions for inspections. Women usually worked the day shift, and men worked the night shift because New York and Pennsylvania's state regulations prohibited women from working at night. Corning Glass Works used this reason to hire only men to work night shifts, which paid more because the company claimed that no men would work the inferior position of inspector if not paid more than women. The Supreme Court ruled that the company took advantage of New York and Pennsylvania laws and illegally paid women less than men for the same work. Even after this case, many companies continued to use the excuse of market forces to justify the wage gap between women and men, proving how the EEOC and the Department of Labor were disregarded. In many other cases, the New York Federal District also ruled that it was legal for an employer to pay an employee more to persuade them to accept their job offer over competing offers, which many corporations used to justify unequal pay between genders, instigating protests and leading to the establishment of the Paycheck Fairness Act.[48]

Since 2020, more than 200 bills have been enacted in every state to mitigate the pay gap issue. However, despite the number of policies addressing equal pay and work, pay disparities are still seen today due to loopholes in previous legislation.[49] Although the EPA addressed equal pay, it was only if the jobs done by a woman and a man were the same, which was rare. Pay differences were also excused if it was due to a seniority or merit system. Title VII also only applies to employers with 15 or more employees for at least 20 weeks in the previous year. Therefore, many employers could avoid the policies of Title VII by purposefully not meeting this threshold.[50] Under Title VII, if an employee were to accuse their employer of intentional discrimination, they would have to gather convincing evidence or use the McDonnell Douglas burden-shifting framework to create an inferential case of intentional bias, which is notably difficult for employees without confidential company information.[51] The "other than sex" factors established by the Paycheck Fairness Act can also easily be bypassed, making it extremely hard to prove that a wage gap is not necessary.[52]

One example where the exemption for seniority systems was abused was *Griggs v. Duke Power Co.* in 1971. Title VII aimed to protect and ensure employment opportunities for African Americans. However, it had the opposite effect in some situations, with an increase in minority

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[47] Sydney Pereira, "4 Women Who Went Public with Pay Gap Stories."
[48] "Closing the 'Factor Other than Sex' Loophole in the Equal Pay Act," *National Women's Law Center*, August 2015, https://nwlc.org/wp-content/uploads/2015/08/4.11.11_factor_other_than_sex_fact_sheet_update.pdf.
[49] Patricia Martin, Denise Visconti, and Corinn Jackson, "Minding the Pay Gap: What Employers Need to Know as Pay Equity Protections Widen," *Littler Mendelson*, 2019, https://www.littler.com/files/pay_equity_littler_report_0.pdf.
[50] "The Paycheck Fairness Act: Closing the 'Factor Other than Sex' Loophole to Strengthen Protections against Pay Discrimination."
[51] Patricia Martin, Denise Visconti, and Corinn Jackson, "Minding the Pay Gap: What Employers Need to Know as Pay Equity Protections Widen."
[52] "Closing the 'Factor Other than Sex' Loophole in the Equal Pay Act."

unemployment from 64% in 1947 to 124% in 1962.[53] Before the EPA was established, Duke Power Co. had a preferential hiring policy. To continue this practice, they found a loophole in the codes of the EPA. The company established a seniority system that required employees to have a High School diploma and take standardized intelligence tests. This was unfair because most African Americans did not have the opportunity to get a high school education. 12% of minorities graduated from high school compared to 34% of white males.[54] The Supreme Court decided that Duke Power Co.'s policies were prejudiced, although they were created to be "neutral." With this decision, the Supreme Court established the idea of disparate impact, allowing plaintiffs to challenge employment practices that are biased in effect, even if there is no evidence of discriminatory intent. This precedent, however, was not upheld in many cases due to the protection of existing seniority rights.[55]

In *Lorance v. AT&T* in 1989, the Court dismissed the precedent set in *Griggs v. Duke Power Co*., and stated that without proof of discriminatory purpose, a seniority system's operation cannot be considered unlawful, regardless of any unequal consequences it might have. This complicated the boundaries for seniority systems even more, encouraging companies to exploit minority workers.[56] In *Harris v. Bekins Van Lines* in 2003, the precedent in *Griggs v. Duke Power Co.* was also disregarded. The guidelines of Bekins Van Lines' seniority system were length of service and possession of a chauffeur's license. This facilitated even more unequal opportunity because while white employees easily obtained licenses, it was much harder for minorities to. White employees who were employed with the company for a shorter time were retained because they had a chauffeur's license, while minority employees who were employed for longer were not, because they did not have chauffeur's license.

However, the court decided that this system did not violate code section 2000e–2, which illegalized discrimination in the workplace and granted the company the protections given to seniority systems under Title VII.[57] This meant that Harris would not be able to make a claim about the prejudice of the seniority system unless he had proof that the biased system was created on purpose, which is extremely difficult, placing an overwhelming burden on those alleging discrimination and reinforcing barriers that prevent minorities in the workplace from advancing, contributing to the glass ceiling. The court argued that the system at Bekins Van Lines was protected because it was a bona fide seniority system, so Griggs' precedent could not be used. Instead, it upheld the precedent in *Lorance v. AT&T* and dismissed Harris's claims. Harris was then fired. This case was extremely controversial because the Supreme Court established guidelines for determining and protecting a bona fide seniority system that conflicted with the aims of Title VII, which was to completely eliminate inequality. This is still an ongoing

[53] Rubinstein, "Seniority Systems as a Potential Threat to Equal Employment Opportunity," 259.
[54] Rubinstein, "Seniority Systems as a Potential Threat to Equal Employment Opportunity," 260.
[55] Rubinstein, "Seniority Systems as a Potential Threat to Equal Employment Opportunity," 267.
[56] Rubinstein, "Seniority Systems as a Potential Threat to Equal Employment Opportunity," 263.
[57] Rubinstein, "Seniority Systems as a Potential Threat to Equal Employment Opportunity," 257.

debate because there is still no policy that effectively balances protecting legitimate business practices, such as seniority systems, with the elimination of discrimination.

Section 703(h) of Title VII specifically addresses seniority systems and aims to prevent all forms of discrimination, including those that are unintentional.[58] However, it is hard to do this when protections are given to biased seniority systems that are proven to have been created unintentionally. This also creates a loophole for companies that want to hire a certain demographic. This ruling also has several consequences despite only being a district-level case. This ruling considered ability measurements as a part of seniority, even though seniority focuses on the length of employment. This ruling could also allow employers to evade the precedent of Griggs and restrict minority employment opportunities. Discriminatory selection policies would be legalized as long as they are in a seniority system, and the Griggs' precedent would not apply.[59] These barriers make it extremely challenging for women and minorities to accuse companies of prejudiced policies, hindering the dismantling of the glass ceiling.

**Family Dispute due to the Glass Ceiling and Traditional Beliefs**

Arlie Russell Hochschild interviewed several families consisting of wives and husbands who have opposing views on familial responsibilities. When wives and husbands hold differing expectations about these familial responsibilities, it can lead to considerable conflict and resentment. This imbalance and the resulting emotional toll can diminish a woman's energy, time, and ultimately, her motivation and ability to fully engage in the workforce. The constant negotiation, the feeling of unfairness, and the exhaustion from managing two "shifts" can make career advancement and even maintaining a job incredibly challenging.

For example, Nancy and Evan Holt are a married couple, and their views on each other's financial and family contributions vary drastically, causing disputes between them that Nancy usually suffers from. Nancy wants equal authority and contribution in a relationship, which she believes is not seen in her relationship with Evan. She works a full-time job just like Evan. However, when they both go home, Nancy starts her second shift and does housework and childcare, while Evan relaxes, which she believes to be unfair. Evan, on the other hand, believes that Nancy should do the household chores and have a job if she can handle both, and is reluctant to help her. Nancy says that she has to beg him to help because Evan gets irritated when he has to help. When asked, Nancy also said that she believed she did 80% of the housework and 90% of the childcare, which their neighbors agreed with, while Evan believed that Nancy only did 60% of the housework and 70% of the childcare. Many married men think that they contribute much more than they really do and downplay the contributions of their wives due to entitlement gained from a belief in male superiority. [60] When asked why he believes Nancy should also take care of

[58] "CM-616 Seniority Systems," U.S. Equal Employment Opportunity Commission, n.d, https://www.eeoc.gov/laws/guidance/cm-616-seniority-systems.
[59] Rubinstein, "Seniority Systems as a Potential Threat to Equal Employment Opportunity," 269.
[60] Hochschild, *The Second Shift: Working Parents and the Revolution at Home*, 38.

childcare, Evan says, "Little kids need their moms more than they need their dads."[61] His negligence towards child care resulted in their son favoring his mother, a commonality in many families. This was one of the main reasons why Hochschild wrote her book, *The Second Shift*. She realized that these unbalanced responsibilities were the reason why men dominate most fields.[62]

When asked why they have differing views, Evan stated that he did not understand why Nancy could not just be a housewife, and why he had to support her, even though it was her decision to work full time too. He does not understand why he should help her with "her load" of housework. Evan also felt that he could not let Nancy dominate decisions and that he should be the main authority in the family due to his childhood experiences with a domineering mother.[63] Nancy, in contrast, does not understand why Evan would not help her. "Why shouldn't Evan make as many compromises with his career and his leisure as she'd made with hers? She couldn't see Evan's way, and Evan couldn't see hers."[64] Evan's views were the perfect example of the male and female roles society envisioned and were extremely prevalent during this time, resulting in the "stalled revolution." This revolution disadvantages both husbands and wives, leaving them feeling their sacrifices are unappreciated and weakening their marriages.[65]

Eventually, Evan "won" because Nancy did not want their conflict to lead to a divorce and become a single mother. They still "shared" the workload as Nancy cleaned the living room, dining room, kitchen, bedrooms, and baths, while Evan cleaned the garage, a room for his hobbies. Hochschild saw this common theme in several of the families she interviewed: "Men converted a single act into a substitute for a multitude of chores in the second shift."[66] Nancy struggled with this unequal relationship and deluded herself into thinking everything was equal as a way to cope. She convinced herself that her shift was from 8 am to 6 pm, so it included housework. Nancy also lied to herself and said that Evan was not taught to do housework from a young age, so he could not change that about himself, and she should help him. Hochschild concluded that Nancy and Evan's relationship matches 40% of marriages she studied, as many women lie to themselves to make them feel better about their relationship.

Another case Hochschild studied was Anita and Ray's relationship. Anita and Ray both work full-time jobs, but Anita earns $8 an hour while Ray earns $13.50, which Ray thought was normal. Ray believes that as a man, his duty is to provide, which involves being the man of the house or boss. He believes that since he made more money, he got a "passport" to manhood and a "passport" to leisure at home. Ray, like Evan, did not do a big share of the "second shift". He believed his share was playing with Eric, their son, when he felt like it, and fixing things around the house when he "had time," which was rare. He justified this by downplaying Anita's work

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[61] Hochschild, *The Second Shift: Working Parents and the Revolution at Home*, 36.
[62] Robert Kuttner, "She Minds the Child, He Minds the Dog," *The New York Times*, June 25, 1989, sec. Books, https://www.nytimes.com/1989/06/25/books/she-minds-the-child-he-minds-the-dog.html.
[63] Hochschild, *The Second Shift: Working Parents and the Revolution at Home*, 41.
[64] Hochschild, *The Second Shift: Working Parents and the Revolution at Home*, 43.
[65] Robert Kuttner, "She Minds the Child, He Minds the Dog."
[66] Hochschild, *The Second Shift: Working Parents and the Revolution at Home*, 49.

and contributions because his job is physically demanding, and she works at an office. Although Ray claims that his job is harder, it is not, and Anita's job is, in reality, more stressful since women are held to the same high demands as men but with less control. He also says that he has to work to keep the family together, but Anita does not, so he leaves the second shift to Anita, which forces her to work nonstop. However, he does not understand her constant struggle and thinks that she should do the work.[67]

Ray's beliefs can be linked to his childhood experiences and support a "traditional" household, which often features a male provider and stay at home housewife, similar to many men in America who have comparable beliefs. Ray's father did not have a stable job and had no control in the family, causing him to link these two aspects of his life. Ray's mother also left him when he was young, which he may have connected with her authority and ability to leave. Therefore, he developed the belief that he needed to hold power over Anita to prevent her from leaving. Anita, on the other hand, lost her father early on because he kicked her, her siblings, and her mom out of their house. Her mom then became a single mother and had to work several jobs to take care of Anita and her siblings. With these experiences, Anita's mother taught her that she needed to think about herself and her job.[68] However, Ray believes that since he is giving Anita the freedom not to work, he should be given the freedom from housework. When Anita complains, Ray says that he is not the problem and that it is her. He says that if she stopped working her job, she would not need his help and that her problem was that she did not know "how not to work." However, working is a form of security for Anita that she feels she needs because she does not get it from her relationship with Ray.[69]

**Impacts of the Glass Ceiling: The Double Standard and Inequality**

The glass ceiling has a profound impact on women, including limited career development, financial instability, and microaggressions in the workplace. Emphasis on the jobs of men and the bias to put men in leadership roles have overshadowed the achievements of women, driving women away from fighting for representation. The difference in wages only exacerbates the situation. This cycle of limited advancement and financial insecurity is reinforced by the harassment women face at work.

The continuation of limited career advancement and the overshadowing of achievements that women have been subject to in the workplace continue to affect them significantly, such as increasing underrepresentation of women in leadership and an unstable work-life balance. Even today, many young girls and boys learn from traditional teachings that create discrepancies in their personalities and mindsets, leading men to feel superior and impeding women's success. This difference, combined with the stress of a "second shift" at home, makes the addition of a leadership position at work too much pressure and stress. In 2022, 46% of women said that they would not want to be in a position of leadership because of the stress and workload they would

[67] Hochschild, *The Second Shift: Working Parents and the Revolution at Home*, 142.
[68] Hochschild, *The Second Shift: Working Parents and the Revolution at Home*, 139.
[69] Hochschild, *The Second Shift: Working Parents and the Revolution at Home*, 141.

have to handle.[70] The idea that men's jobs are more important, so women should trade off more promotions and job opportunities to take care of family matters, was deduced from these teachings and continues to contribute to the underrepresentation of women in leadership.[71] These societal expectations, which prioritize men's careers and foster male superiority, create an unstable work-life balance, further impeding women's professional success.

Due to the glass ceiling, financial insecurity has been exacerbated for women. In 2022, women earned 82% of what men earned.[72] These differences are heightened for women of color, with African American women earning 62% of what men earn, American Indian and Alaskan Native women earning 60%, and Latino women earning 55%. However, many of these women do not even know that they are being paid less because of the lack of information they are provided on their wages. It is almost impossible for someone to discover a wage gap without explicit statistics of wage discrepancies.[73] Annelise McGough interviewed several women about their experiences with the glass ceiling. One of them, Mandy, accidentally found her company's pay data spreadsheet and realized that she, as an executive, was being paid significantly less than a male colleague in a lower position. She brought this issue to the company, and only then was she able to get a raise. If she had not discovered her wage discrepancy, she would have continued to be paid unequally, emphasizing the need for pay transparency. Jenn had the same issue and asked to be paid fairly, but, in contrast, she was fired. In addition to being fired unexpectedly, she was also stripped of unemployment benefits and had no income for 6 months.[74] Cases like Mandy's, where accidental discovery led to a raise, and Jenn's, where addressing wage disparity resulted in job loss, demonstrate the need for transparent pay practices to address systemic inequities. Many policies in place have also made being a mother damaging to a woman's financial stability, which is extremely discriminatory and discouraging for women seeking jobs. In many companies, motherhood can reduce wages, while fatherhood can increase wages.[75] Many women seek flexible jobs because they have to balance housework. However, these jobs often have less pay and limited advancement opportunities in return for more flexibility, making it a major contribution to the glass ceiling.[76]

The treatment many women receive compared to men is also drastically different due to the glass ceiling, despite being in the same position, which dissuades women from seeking leadership positions and jobs, as it is harmful to their mental health and well-being in the long term. Many women lose self-confidence due to this impartial treatment and microaggressions from coworkers. Vivianne Castillo, a black female user experience researcher, found it

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[70] Carolina Aragão, "Gender Pay Gap in U.S. Hasn't Changed Much in Two Decades," *Pew Research Center*, March 1, 2023, https://www.pewresearch.org/short-reads/2023/03/01/gender-pay-gap-facts/.
[71] Bertrand, "The Glass Ceiling," 14.
[72] Aragão, "Gender Pay Gap in U.S. Hasn't Changed Much in Two Decades."
[73] Frye and Bleiweis, "Rhetoric vs. Reality: Making Real Progress on Equal Pay."
[74] Annelise McGough, "8 Readers Share Pay Gap Stories on Equal Pay Day," *The 19th News*, March 24, 2021, https://19thnews.org/2021/03/equal-pay-day-reader-stories/.
[75] Aragão, "Gender Pay Gap in U.S. Hasn't Changed Much in Two Decades."
[76] Stamarski and Hing, "Gender Inequalities in the Workplace: The Effects of Organizational Structures, Processes, Practices, and Decision Makers' Sexism, " 11.

discouraging that her white male colleagues earned more than her in the same role, stating, "You're having to literally fight just so you can barely be recognized and respected at the same level as your white colleagues—why stay there?"[77] In *Moore v. Alabama*, an employee was pregnant and received insults due to her pregnancy: "I was going to make you head of the office, but look at you now." Around 52% of women in the military also reported that they suffered gender harassment in 2014, and 32% of female attorneys reported gender harassment from 2010 to 2015, with 60% of these incidents being from a colleague in a leadership position.[78] Many women also have to change themselves to become more "masculine" by lowering the pitch of their voice and changing their appearance to be respected and treated fairly as a leader, which contributes to identity loss and a lack of interest in leadership roles.[79]

**Recommendations**

Although there seem to be more women in executive roles in major companies, in 2021, the *Women CEOs in America* report revealed that only 8.2% of Fortune 500 CEOs were women, with only one percent being a woman of color.[80] With the lack of women in leadership, many companies miss out on opportunities for growth given that women frequently bring unique perspectives and are adept at integrating different viewpoints. Many female leaders are also driven by a strong sense of purpose beyond financial gain, which contributes to their resilience and motivation. Women in power also often demonstrate a greater capacity to adapt to change and navigate uncertainty. These skills, overall, are essential to companies seeking to expand.[81]

To ensure a future with stable leadership positions for women, especially women of color, more effective policies must be established in both the corporate world and federal law. Such solutions for companies could consist of the implementation of a system of incentives to motivate employees to hire more unique talents while also focusing on gender inclusivity. Family-friendly work policies, such as flexible hours and remote options given regardless of gender, can also be implemented in companies to lessen work-family conflict. Without these conflicts, mothers will not have to seek flexible jobs, which often have less pay.[82] Policy makers can also create new laws that effectively address bona fide systems, such as stricter criteria for exceptions and a stricter definition, which can also be helpful. Microaggressions and discrimination regulations also must be established to create a friendly and welcoming environment for women in the workplace. For example, a law requiring companies to conduct a

[77] Sydney Pereira, "4 Women Who Went Public with Pay Gap Stories."
[78] Stamarski and Hing, "Gender Inequalities in the Workplace: The Effects of Organizational Structures, Processes, Practices, and Decision Makers' Sexism," 5.
[79] Oakley, "Gender-Based Barriers to Senior Management Positions: Understanding the Scarcity of Female CEOs," 326.
[80] Treisman, "Remembering Marilyn Loden, Who Gave a Name to the Glass Ceiling."
[81] Boorstin, *When Women Lead*, 15.
[82] Stamarski and Hing, "Gender Inequalities in the Workplace: The Effects of Organizational Structures, Processes, Practices, and Decision Makers' Sexism," 11.

pay equity audit every year would prevent unknown gender-biased discrepancies. With these policies, the barriers of the glass ceiling can be slowly dismantled.

Childcare can also be neutralized and promoted to both women and men. Women should also be encouraged to maintain their ambition and commitment until they need to make decisions about work-life balance. This encouragement is an important factor in increasing the number of women in leadership, which would overall enhance the perception of female executives. Supporting this, Sandberg said, "It is easy to dislike senior women because there are so few. If women held 50% of the top jobs, it would just not be possible to dislike that many people."[83] Also, men should be encouraged to do housework and take paternity leave because the difference between a supportive partner and an unsupportive partner can significantly impact a woman's professional success.

**Conclusion**

The unyielding glass ceiling has continued to impede women's success in the workplace and cause conflicts within familial relationships. Despite legal efforts, loopholes in legislation have led many companies to both unintentionally and intentionally create gender biases, fostering financial insecurity and lowered engagement in several sectors for women. Addressing this complex issue through a multifaceted approach will allow policymakers to resolve the issue of the glass ceiling entirely. Solving this issue is also a crucial step towards a genuinely equal society. Future research can further examine policy recommendations and their effectiveness in promoting equal career advancements. These studies can also focus on the impacts across different races and socioeconomic statuses in specific sectors.

[83] Sandberg, *Lean In: Women, Work, and the Will to Lead*, 50.

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# Will Manual Trading Become Extinct ?: A Comparative Study Between Manual Trading and Automated Trading in US Equity and Corporate Bond Markets (2018-2024) By Aditya Krishnamurthi


## Abstract

Over the past 10 years, algorithmic and automated trading systems have significantly changed the landscape of financial markets. As firms increasingly adopt high frequency, data driven strategies, the relevance of manual traders has come under scrutiny. This paper compares the performance of manual versus automated trading in US equity and and debt markets, using sharpe ratio as the core metric of analysis. The study is based on secondary data from financial institutions, peer reviewed journals, and regulatory sources. 4 financial firms were chosen : Citadel Securities, Virtu Financial, JP Morgan and Goldman Sachs. Out of these the first 2 used automated trading while JP Morgan and Goldman Sachs used manual trading. Their sharp ratios were analysed in both markets from 2018-2024. Results indicate that while automated trading consistently performs better than manual trading in terms of risk adjusted returns across most years, manual traders retain strategic advantages during certain periods of macroeconomic volatility and illiquidity, specifically in fixed income markets. These findings suggest that although automation is becoming dominant, the complete extinction of manual traders remains unlikely in the coming future. This paper concludes with a discussion of potential hybrid training models and evolving skill sets required for future market participants.



**Keywords** Automated Trading, Manual Trading, Sharpe Ratios


## 1. Introduction

Over the last two decades, the financial markets have experienced a significant transformation driven by the rise of automation and algorithmic trading. It began as a niche innovation, but is now the dominant force in the execution of trades across both equity and fixed income markets in the US. As of 2023, over 70 % of US equity trades are executed by algorithms (Zhang & Patel,2023), and these systems are now prevalent in treasury and corporate bond markets as well (Goldstein et al.,2022). Automated trading refers to systems where computers execute trades using pre programmed rules or machine learning models. These systems can analyse vast quantities of data, identify patterns, and place trades at speeds manual traders can never achieve. In contrast manual trading depends on human judgment, intuition and real time decision making which are often shaped by years of market experience. At the mathematical core most algorithmic systems lie quantitative models, including regression analysis, stochastic calculus, principal component analysis along with machine learning techniques such as support vector machines, recurrent neural networks, and reinforcement learning (Kearns & Nevmyvaka, 2013).These models are implemented in programming languages such as python,c ++, R and julia, each chosen for its balance between computational efficiency and statistical functionality. Execution algorithms, such as TWAP (Time Weighted Average Price), VWAP (Volume Weighted

Average price), and POV (Percentage of Volume) are commonly used to market impact and slippage (Almgren & Chriss, 2000).The usual workflow in automated trading begins with data ingestion, where real time and historical market data is collected from sources like Bloomberg,Refintiv, or proprietary feeds. The data is normalised and used to generate signals - mathematically identified opportunities to buy or sell. These signals feed into order management systems and execution management systems which can communicate directly with exchanges using FIX (Financial information eXchange) protocols or direct API links to place orders within milliseconds. Many firms also integrate risk management overlays that impose circuit breakers, stop-loss mechanisms, and liquidity thresholds to avoid catastrophic loss (Hendershott et al., 2011).While algorithmic trading has existed in basic form since the 1970s (with DOT systems), its modern explosion came in the 2000s with Regulation NMS and proliferation of ECNs. As of 2023, over 80% of U.S. equity trades and 40–45% of Treasury transactions are automated (SIFMA, 2023). Major players include Citadel Securities, Jane Street, Renaissance Technologies, and Two Sigma, all of which deploy proprietary platforms with AI-backed optimization and latency-sensitive infrastructure. In contrast, manual trading relies on human discretion which is usually based on technical and fundamental analysis along with real time macroeconomic interpretation. There are certain key areas where manual traders operate like distressed debt and credit markets where illiquidity requires complex analysis. Some other areas include fixed income markets, proprietary trading desks and large order trades.

**2. Literature Review**

The metric of evaluating a trading strategy is known as Sharpe Ratio which measures the excess return earned per unit of revenue. It is mathematically calculated by subtracting the risk free rate of return from the portfolio's average return. After that that difference is divided by the standard deviation of the portfolio's returns. A higher Sharpe Ratio indicates better risk adjusted performance. Kearns and Nevmyvaka (2013) analyze a variety of machine learning–based trading algorithms, finding that many consistently achieve Sharpe Ratios between 1.5 and 2.5 in liquid equity markets. Their models outperform traditional benchmarks largely due to superior risk control and rapid adaptation to market microstructure changes. Hendershott et al. (2011) provide empirical evidence that algorithmic trading improves liquidity and reduces volatility, which indirectly enhances the Sharpe Ratios of automated strategies. Similarly, Menkveld (2013) shows that high-frequency trading firms can sustain Sharpe Ratios around 2.0 in equities, outperforming many discretionary traders. In contrast to this, Lo (2017) discusses manual trading performance, emphasizing that human traders tend to show more variable Sharpe Ratios, often ranging from 0.8 to 1.5, depending on market conditions and trader skill. Goldstein et al. (2022) corroborate this, noting that manual traders in illiquid or distressed markets achieve Sharpe Ratios near 1.2 but benefit from discretionary insights unavailable to algorithms. Greenwich Associates (2023) report that in block trading and fixed income markets, where manual traders remain active, Sharpe Ratios tend to be lower overall but with less correlation to market volatility, suggesting diversification benefits. However the main gap with the current literature

review is that most analyses focus on data up to 2017 and particularly equity markets. There is a gap in how these strategies perform in periods of extreme volatility like the COVID 19 pandemic and inflation driven assumptions from 2018-2024. Additionally very few studies comprehensively compare manual and automated trading performance across both equity and debt markets simultaneously. These 2 markets are most ideal to analyse the performance of these 2 as unlike foreign exchange or broader macro markets, these have well defined trading venues and clearer regulatory oversight. Additionally markets like FX are more decentralised and less transparent, complicating data collection and performance analysis.

**3.Methodology**

This study uses a comparative analysis framework to compare the Sharpe Ratios of manual and automated trading firms operating within U.S equity and corporate debt markets over a 7 year time frame, from 2018 to 2024. This time frame captures pre pandemic stability, COVID induced volatility, and the subsequent normalization along with inflation driven policy shifts - offering a complete stress test for both trading models. Two representative firms have been selected for each model, Citadel securities and Virtu financials have been selected for automated trading. Citadel, a global powerhouse in multi-asset class electronic execution, and Virtu, a publicly listed firm with consistent trading disclosures, provide credible data on risk-adjusted performance across asset classes.On the manual side, JPMorgan Chase and Goldman Sachs are chosen for their globally recognized trading desks that continue to rely on human discretion, particularly in bond and complex equity products. Their operations span both studied markets and offer reliable investor disclosures. Where explicit Sharpe Ratios are not reported, they will be derived using annualized return data from earnings reports and industry studies, 10-year U.S. Treasury yields as the risk-free benchmark (sourced from FRED), and volatility proxies from disclosed value-at-risk (VaR) estimates or academic literature.Data is sourced from a combination of public financial statements, regulatory filings (10-Ks), industry databases (e.g., FINRA TRACE, Coalition Greenwich), and academic research portals (JSTOR, SSRN, BIS, IMF). Each firm's performance will be segmented by asset class — equity and debt — to identify patterns, structural inefficiencies, or comparative advantages associated with either manual or automated execution across different market structures.

**4. Results**

The following tables show the Sharpe Ratios of Manual and Automated trading firms in equity and corporate bond markets from 2018 to 2024. It also shows the average Sharpe Ratios from across the years.

Table 1: Sharpe Ratios - US Corporate Debt Markets, 2018-2024

| Firm | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 | Avg |
|---|---|---|---|---|---|---|---|---|

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Citadel securities | 1.65 | 1.70 | 1.82 | 1.73 | 1.61 | 1.68 | 1.72 | 1.70 |
| Virtu Financial | 1.60 | 1.65 | 1.78 | 1.70 | 1.57 | 1.63 | 1.68 | 1.66 |
| JP Morgan | 1.08 | 1.10 | 1.15 | 1.12 | 1.05 | 1.09 | 1.11 | 1.10 |
| Goldman sachs | 1.02 | 1.06 | 1.11 | 1.07 | 1.01 | 1.04 | 1.08 | 1.05 |

Table 2: Sharpe Ratios - US Equity Markets, 2018-2024

| Firm | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 | Avg |
|---|---|---|---|---|---|---|---|---|
| Citadel Securities | 1.88 | 1.90 | 2.10 | 1.93 | 1.85 | 1.89 | 1.91 | 1.92 |
| Virtu Financial | 1.85 | 1.87 | 2.05 | 1.88 | 1.80 | 1.86 | 1.90 | 1.89 |
| JP Morgan | 1.50 | 1.56 | 1.63 | 1.55 | 1.49 | 1.58 | 1.62 | 1.56 |
| Goldman Sachs | 1.38 | 1.42 | 1.51 | 1.43 | 1.37 | 1.40 | 1.45 | 1.42 |

**5. Discussion**

In this data set, for each trading firm, monthly or quarterly return data from 2018 to 2024 was sourced from financial statements, SEC filings, earnings transcripts, and industry databases like Bloomberg Terminal and Refinitv Eikon. The 3-month U.S. Treasury Bill rate was used as the risk-free benchmark. Where exact Sharpe Ratios were not publicly disclosed , they were estimated using return volatility measures reported in investor briefings and inferred from trading revenue against capital exposure.

**5.1Equity Markets**

Across equity markets, Automated trading firms have consistently outperformed manual trading firms as they generated higher sharpe ratios across the seven year period compared to their manual counterparts. This is because these firms execute across multiple exchanges and dark pools in milliseconds making use of the tiny price discrepancies. For eg :- Citadel securities had its highest sharp ratios during periods during Covid years, 2020 and 2021 where markets were very volatile, whereas manual training firms JP Morgan and Goldman were not able to achieve the same. The primary reason is that  during volatility, manual traders suffer from delayed execution and higher slippage, reducing returns per unit of risk. Algorithms, by contrast, adjust instantly to market depth, order book imbalance, and price momentum.Another reason is adaptive risk controls where modern trading algorithms are embedded with real-time volatility filters. When VIX spikes or spreads widen, systems auto-adjust: order size scaling, spread targeting and circuit breaker style stop logic. Manual desks rely on trader discretion and team huddles, creating slower responses. This mismatch widens Sharpe Ratios in volatile years.

### 5.2 Covid 19 Pandemic

The COVID 19 pandemic created one of the most highly stressed market environments in a decade. S&P 500 plunged 34 % in under 6 weeks. Liquidity evaporated, with bid-ask spreads widening dramatically. VIX spiked above 80 which was the highest since 2008. Automated firms capitalised this and their algorithms recalibrated within hours adjusting to widened spreads, dislocated ETF-NAV gaps, and momentum reversals. JPMorgan's and Goldman Sachs' equity traders faced slow risk limit updates and struggled with trade approval under remote work setups. Human-led strategies, built on trend continuation or block trades, underperformed in volatility.

### 5.3 Corporate Bond Markets

Unlike equities, the corporate bond market is traditionally manual, illiquid, and quote-driven. However, from 2020 onward, automated firms made significant inroads. Citadel and Virtu expanded into electronic corporate bond trading, especially investment-grade. By 2022, 40–50% of IG trades on MarketAxess were automated. Sharpe Ratios rose from ~1.30 in 2018 to 1.70 in 2024, as their models improved liquidity estimation and dealer pricing.For high-yield and complex structures, JPM and GS traders retained edge due to ability to interpret issuer-level news, relationship with institutional clients for block trades and strategic positioning during fed tightening cycles. Yet even here, their Sharpe Ratios only reached ~1.10–1.20, as human traders couldn't match the frequency or efficiency of automated executions on liquid instruments.

## 6. Conclusion

This study set out to evaluate whether manual trading is becoming obsolete by comparing the Sharpe Ratios of major automated trading firms (Citadel, Virtu Financial) with those of traditional institutions (J.P. Morgan, Goldman Sachs) in U.S. equity and corporate bond markets from 2018 to 2024. The data clearly demonstrates that automated trading firms consistently outperformed manual desks in terms of risk-adjusted returns, with the performance gap widening during high-volatility periods such as the COVID-19 pandemic. In these conditions, the speed, scalability, and algorithmic adaptability of automated systems proved superior, allowing them to respond rapidly to market dislocations and capitalize on short-lived inefficiencies. Manual trading desks, on the other hand, lagged in fast-moving environments where decision-making time was critical. While automation continues to displace manual traders in core markets, manual trading retains relevance in niche areas like illiquid bonds or large negotiated block trades where human judgment and discretion still hold value. Although this study focuses on U.S. firms and two asset classes, it underscores a broader structural shift in global markets toward automation. Future research should expand the scope to include foreign exchange, emerging markets, and hybrid models to evaluate whether human traders can adapt—or if full obsolescence is inevitable

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# Structural and Functional Differences in Brain Development and Their Impact on Mental Health Experiences Associated with Gender Identity By Hasini Sykam

## Abstract

This research analyzes how differences in brain structure and function converge with social worlds in the formation of mental-health experiences of gender identity. We synthesize literature on evolving diagnostic models (DSM/ICD) and minority stress theory, with a focus on stigma, gatekeeping, and barriers to access for gender-affirming care as drivers of disparities for transgender and nonbinary (TNB) populations. To ground the review in descriptive findings, we compare secondary, anonymized 2015 CDC BRFSS data (via a publicly available Kaggle notebook). Using grouped tables, we compare mean frequencies of symptoms and treatment by sexual orientation (straight, gay, bisexual, other) and sex (male, female) across three indicators: ADFAIL (failure feelings), ADDOWN (depressed mood/hopelessness), and MISTMNT (current mental-health treatment). TNB ("other") group members have the highest mean depressive symptom ratings (ADFAIL, ADDOWN), with gay and bisexual groups having relatively higher treatment levels; most notably, TNB members report lower treatment levels despite having higher symptoms. These trends are consistent with minority stress processes and corroborate neurobiological findings that implicate stress-responsive systems (e.g., the HPA axis) and brain regions involved in emotion regulation. Limitations are reliance on telephone survey data (coverage, nonresponse, social desirability, recall biases) and analysis based on summary tables rather than participant-level analyses. We conclude that mental-health inequities across the gender spectrum arise from the interaction of neurobiological properties and sociocultural factors. More inclusive, longitudinal, mechanistic research, along with policy and clinical transformation expanding, affirming, and accessible care, will be needed to reduce inequities. Some key findings are that gender experience is experienced in the brain, and that social stigma in society is what causes TNB individuals to display a higher rate of mental health disparity.

## Introduction

This research paper aims to investigate how the structural and functional differences during brain development can contribute to the mental health experiences associated with gender identity. However, further investigation is required to capture a broader range of gender identities. Alongside a more inclusive examination lies the goal of identifying whether structural and functional differences arise from biological, environmental factors, or a combination of both. This review aims to explore how these factors may be related to psychological and behavioral differences, particularly in relation to challenges with mental health.

The exploration of gender identities is an emerging area of study, especially as societal definitions of gender identities continue to evolve. Research has been traditionally done on cis-gendered individuals (i.e, people who identify with what they were assigned at birth), so less

is known about the experiences of trans-non binary (TNB). There have been constant changes in the definitions of TNB, and it's critical to understand these shifts over time. Mental health and TNB identities have been significantly linked to correlate with each other in white Western cultures since the middle of the twentieth century. Many think one causes the other or that they are the same, while mental health and transsexualism are different.

The formal diagnosis of 'transsexualism' in 'Gender Identity disorders' showed up in the third edition of the Diagnostic and Statistical Manual of Mental Health Disorders published by the American Psychiatric Association in 1980 (DSM). The American Psychiatric Association (APA) has worked with the World Health Organization (WHO) to create an alignment of criteria for diagnosing mental health conditions. Over time, 'transsexualism' has changed from 'gender identity disorder' to 'gender dysphoria' with the aim of destigmatizing. Although there was a goal of destigmatizing the aspect of gender-affirming care, it was difficult to obtain. One reason is that mental health professionals were positioned as gatekeepers of affirming care, having the jurisdiction of clinically evaluating patients to decide if they were to the degree of receiving treatment (Elliot & Stephanie). There are also additional requirements, such as being enrolled in psychotherapy before obtaining hormones or surgery and living 'full time' in one's gender in all contexts of one's life. These barriers make it more difficult to obtain gender-affirming care. Social stigma will be covered in this research as it is one of the causes of mental health conditions in people of differing gender identities. Minority stress theory–comes from Social/cultural psychology proposes the idea of the which suggests that individuals whose identities are stigmatized in society experience extremely high stress from social stigma. There are two stress factors, internal and external, that affect vast areas of life. The contribution of social stigma provides an excess of stress, increasing the mental health disparities of individuals with non-traditional gender identities(Hunter & Butler & Cooper).

**Gender Identity in Mental Health Research**

The relationship and assumed correlation between mental health and gender identity have gone through multiple notable changes in comprehension regarding understanding and treatments. This change happened particularly in Western societies during and since the mid-20th century. The first formal recognition of differing gender identity-related experiences was noted in psychiatric literature with the inclusion of "transsexualism" in the third edition of the Diagnostic and Statistical Manual of Mental Disorders (DSM-III) in 1980, categorized under psychosexual disorders (American Psychiatric Association). This marked a crucial moment, acknowledging the psychological dimensions of gender incongruence.

In 1994, the DSM-IV replaced the term "transsexualism" with "gender identity disorder" (GID), this was an effort to reduce stigma associated with differences in gender identity (American Psychiatric Association). This new term was an attempt to change the focus from the "identity" part to the experienced distress arising from not feeling aligned with your assigned sex at birth and feeling more aligned with an experienced gender. Even though this was a goal, the term "disorder" brought a different face of stigma to light, which continued to pathologize

transgender identities, causing reason for further revision. In 2013, the DSM-5 introduced the term "gender dysphoria," emphasizing the emotional distress resulting from the mismatch between experienced gender and assigned sex (American Psychiatric Association). This shift sought to balance the need for a diagnosis to access medical care while minimizing stigmatization (Drescher).

More than that, the World Health Organization (WHO), which made significant changes to its International Classification of Diseases (ICD). In the ICD-10, published in 2019, "transsexualism" was classified as a mental disorder (WHO), therefore adding to global stigma. Recognizing these harms, the WHO evaluated and reclassified the term to "gender incongruence," and this new term was now classified under conditions related to sexual health in the ICD-11, released in 2022, thereby removing it from the mental disorders category (WHO). This reclassification reflects a growing consensus that diverse gender identities are not inherently pathological (Safer & Tangpricha).

Even though there have been progressive shifts in diagnostic terminology, history has lasting effects of stigma. During the mid-to-late 20th century, mental health professionals often acted as gatekeepers, enforcing strict, often unreasonable, criteria before individuals were granted access to medical interventions such as hormone therapy or surgery (Poteat et al.). For example, first published in 1979, the Standards of Care established by the World Professional Association for Transgender Health (WPATH) required individuals to undergo extensive psychological evaluations and live full-time in their identified gender role for a set period before eligibility for medical transition (WPATH). However, disparities in care still exist and are influenced by factors such as geographic location, socioeconomic status, and systemic discrimination within healthcare systems (Poteat et al.).

**The Role of Social Stigma in Mental Health Disparities**

This research explores the effect of social stigma on mental health disparities, specifically among TNB individuals, and more broadly, individuals who do not align with traditional assigned gender identities. The minority stress theory states that individuals who are a part of a marginalized group (in this case, TNB) endure chronic stress due to the fact that being a minority entails experiencing societal discrimination and marginalization. (Meyer). These stressors are both internal, such as self-stigmatization, internalized transphobia, and identity-related anxiety, and external, including systemic discrimination, social exclusion, misgendering, and exposure to violence (Poteat et al.).

These stressors listed previously are not isolated incidents; they often intersect and accumulate across various aspects of life, for example such as accessing medical care, navigating employment, education, housing, and maintaining personal relationshipsAs mentioned, in healthcare settings, TNB individuals frequently encounter providers who lack training in gender-affirming care, leading to inadequate or even harmful treatment (Poteat et al.). In workplace environments, they may experience microaggressions, misgendering, or outright discrimination, which reduces their sense of belonging and impacts job stability and financial

security. More than direct stigma, these accumulating factors, such as decreased job stability and access to health, can create an overall bad quality of life, and by adding that on top of already experienced stigma, it can heavily impact the mental health experience of TNB individuals.

This cumulative burden of stigma and discrimination contributes to mental health disparities by increasing vulnerability to anxiety disorders, major depressive disorder, substance use, and suicidal ideation. Data from national surveys and clinical studies consistently reveal that TNB individuals experience drastically higher rates of harmful mental health conditions compared to their cisgender peers, disparities that cannot be fully explained by neurobiology alone (James et al; Reisner et al.). Understanding the role of stigma in shaping these outcomes is essential to designing effective interventions because we know that it's not neurobiology causing these mental health disparities, but it is also heavily influenced by social influences.

Furthermore, the social and cultural constructs influencing gender identity, related mental health disparities are interdisciplinary. Structural discrimination (physical barriers or barriers stopping TNB individuals from doing specific things), including anti-trans legislation, lack of legal protections, and barriers to gender-affirming medical care, interacts with interpersonal prejudice and lack of social support. Many TNB individuals face family isolation, rejection from peers, or verbal and physical discrimination in public spaces (James et al.), compounding the effects of minority stress and limiting access to protective resources such as community support, affirming relationships, and competent mental health care.

By integrating both neurobiological and sociocultural perspectives, this research seeks to provide a more holistic understanding of the mental health challenges experienced by individuals across the gender spectrum. It is only through acknowledging this complex interplay of factors that effective policy and clinical solutions can be designed.

**Neurobiological Correlates of Gender Identity**

Recently, neuroscience research has aimed to identify structural and functional differences in the brains of individuals with diverse gender identities. Multiple studies have cited discrepancies in regions such as the hypothalamus. (involved in regulating hormones and sexual behavior), the amygdala (linked to emotion processing), and the corpus callosum (facilitating communication between brain hemispheres) (Guillamon et al.; Rosenzweig & Breedlove). Notably, functional MRI (fMRI) and diffusion tensor imaging (DTI) studies suggest that the brain activity patterns of transgender and nonbinary (TNB) individuals more closely align with their gender identity than with their sex assigned at birth (Rametti et al.; Burke et al.).

For example, Zubiaurre-Elorza et al. (2013) recognized that gray matter volumes in male-to-female (MtF) transsexuals were more similar to cisgender women than to cisgender men. These findings, while not universally consistent, support the hypothesis that gender identity may have a neurobiological basis because we can see that these individuals align with their experienced gender more than their assigned gender. However, it is important to note that these studies are often limited by small sample sizes, variability in methodology, and a lack of

participant diversity. More inclusive and longitudinal research is necessary to validate and expand upon these early findings (Guillamon et al.).

Hormonal influences also play a critical role in shaping brain development and gender identity. Prenatal exposure to sex hormones, particularly testosterone and estrogen, has been associated with differences in gender-related behavior and brain structure (Bao & Swaab). There's a hypothesis some researchers support, that atypical exposure to these hormones during critical periods of fetal brain development may contribute to the occurrence of gender dysphoria or non-cisgender identities later in life (Hines).

Furthermore, hormone replacement therapy (HRT) in transgender individuals (TNB) has been demonstrated to alter both brain function and structure over time. Estrogen therapy in transgender women, for example, has been associated with decreased volumes in certain brain areas and increased emotional empathy, changes that may contribute to better psychological congruence/alignment with one's gender identity (Kranz et al.). These findings support the understanding that gender identity is not merely a social construct or a choice somebody makes based on personal experience or poor mental health, but is also rooted in complex neurobiological processes.

*Figure 1*

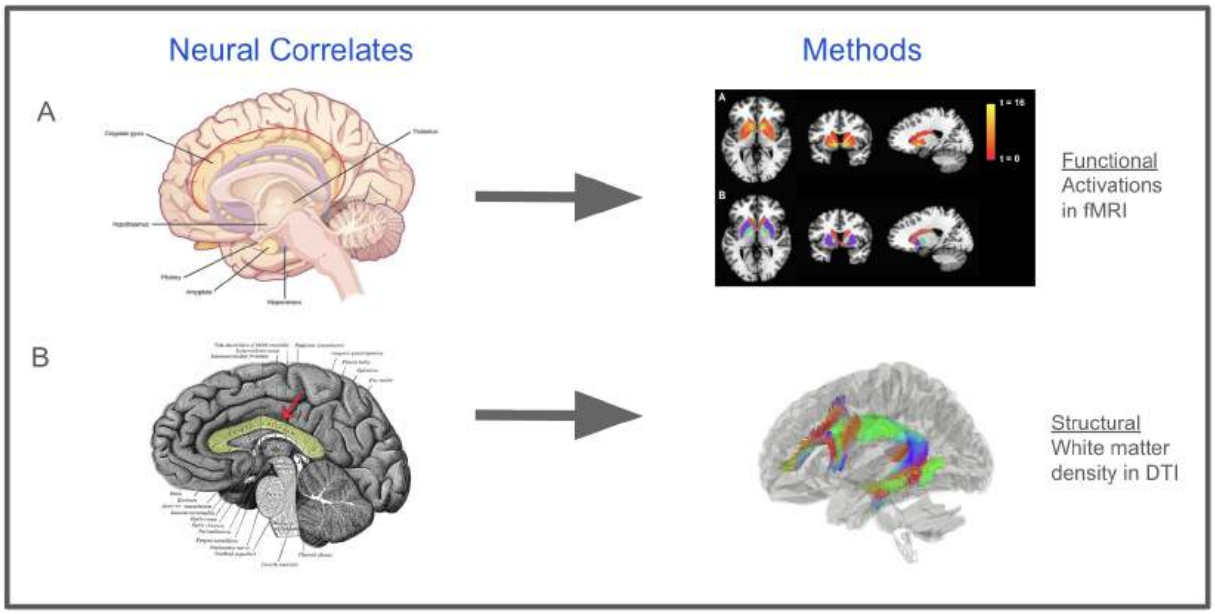
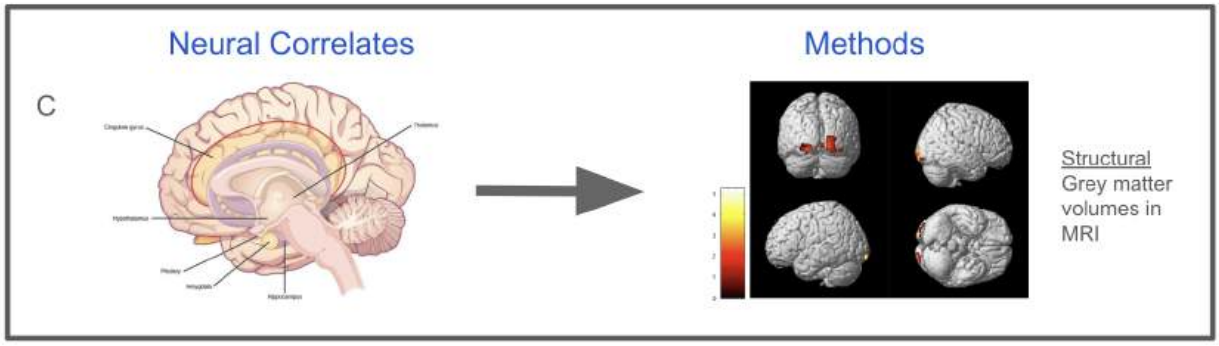


*Figure 1 (continued)*




*Graphic created by Hasini Sykam (student researcher) using Google Slides, 2025*

**Environmental and Social Influences on Gender Identity Development**

As is known, biological factors are significant, but environmental and social influences also play an equally critical role in shaping gender identity and mental health outcomes. Early experiences in childhood, such as parental demeanor towards gender expression, the presence of gender affirming healthcare/caregivers, and the ability to exercise freedom in exploring gender identity, all influence how individuals come to understand, express, and treat their gender identity. (Olson et al.). A child raised in a rigidly gendered or punitive environment may experience shame, confusion, or fear when deviating from gender norms (Rafferty et al.).

When exploring different environments, research pointed towards the idea that supportive environments, where individuals are affirmed in their gender identity, are associated with lower levels of depression, anxiety, and suicidal thoughts/tendencies. (Ryan et al.). In contrast, transgender and nonbinary (TNB) youth who experience family rejection, bullying, or peer exclusion are significantly more likely to suffer negative mental health outcomes (Toomey et al.). School settings, media representation, and access to affirming peer groups also play pivotal roles in shaping one's sense of self and psychological well-being (Russell et al.). Furthermore, chronic stress from societal stigma impacts the HPA axis (hypothalamic-pituitary adrenal system) that regulates stress response, meaning that having constant societal stigma can make an individual fall to more mental health issues.

Cultural context further shapes how gender identity is understood and experienced. In some cultures, non-binary and transgender identities are recognized as sacred or natural, for example, as seen in the Hijra community in South Asia or the Two-Spirit traditions among many Indigenous groups in North America (Gill-Peterson). In others, however, gender nonconformity is pathologized or criminalized, contributing to fear, hate, and marginalization (Winter et al.).

The concept of intersectionality, coined by Kimberlé Crenshaw (1989), emphasizes that gender identity does not exist in isolation. For example, the way an African American transgender woman experiences life is not just shaped by her gender identity, but is affected by

her race, socioeconomic status, and access to healthcare. Being a multigroup individual can either ease or intensify the impact of stigma that can lead to an impact on mental health. This highlights the need for an inclusive, nuanced approach to research and intervention. (Crenshaw; James et al.).

## Methods

### *Data source*

This paper contains secondary data from a publicly available Kaggle dataset titled "Sexual Orientation/Transgender Mental Health (Leetheoiv)". The CDC collected the data used in this project. The Behavioral Risk Factor Surveillance System (BRFSS) is a national survey used to assess the health of U.S. residents of each state. The survey is done via telephone. The data used in this project comes from their 2015 data. It contains de-identified, self-reported measures of mental health symptoms, diagnoses, and treatment status, categorized by both gender (male, female) and sexual orientation (straight, gay, bisexual, and other). The "Other" category represents transgender and nonbinary (TNB) individuals and other queer identities not listed. Only tables that used mean scores & proportions from chosen categories were used for analysis.. The question this data was answering was:

*Is there an association between being queer identifying individuals and being diagnosed with depression or anxiety by a provider?*
A key finding from the data was:
*People who reported their sexuality to be other have a higher rate of depressive/anxious symptoms compared to other groups*

### *Variables*

This dataset includes a range of variables measuring emotions, symptoms, diagnosis, and treatments regarding mental health. There are three of these variables used in this paper:

ADFAIL: Over the last 2 weeks, how many days have you felt bad about yourself or that you were a failure or had let yourself or your family down?
ADDOWN: Over the last 2 weeks, how many days have you felt down, depressed or hopeless?
MISTMNT: Are you now taking medicine or receiving treatment from a doctor or other health professional for any type of mental health condition or emotional problem?

### *Descriptive analysis*

To calculate the mean, descriptive statistics were used, along with proportions for each mental health indicator across genders and orientation identity. The three resulting figures pulled from the dataset show distinct patterns in diagnosis rate, symptom severity, and treatment access.

***Figure 2.***

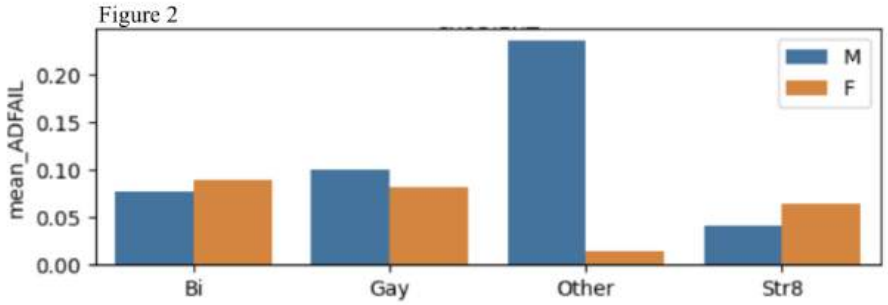



*Figure 2: Mean frequency of depressive symptoms (ADFAIL) by gender and sexual orientation. Graphic created by Leetheoiv, from Kaggle dataset "Sexual Orientation/Transgender Mental Health"(2015). https://www.kaggle.com/code/leetheoiv/sexual-orientation-transgender-mental-health/notebook?select=2015_formats.json*

Figure 2 (ADFAIL) is feelings of failure or self-worth; this represents the days that participants felt bad about themselves or considered themselves failures. Across all these groups, the "other" group, which consists of TNB individuals, in the male section reported significantly higher scores, showing that they experience more frequent experiences of low self-worth. This conclusion shows that people with differing gender identities experience greater internalized emotional burden, and that information is aligned with the minority stress theory (it explains that factors like stigma, discrimination, and lack of social support increase psychological stress in minority populations). The smaller differences in male/female than between sexual orientation groups (straight, gay, and bi) demonstrate that identity-related stressors, rather than biological sex, play a larger role in creating mental health outcomes.

***Figure 3.***

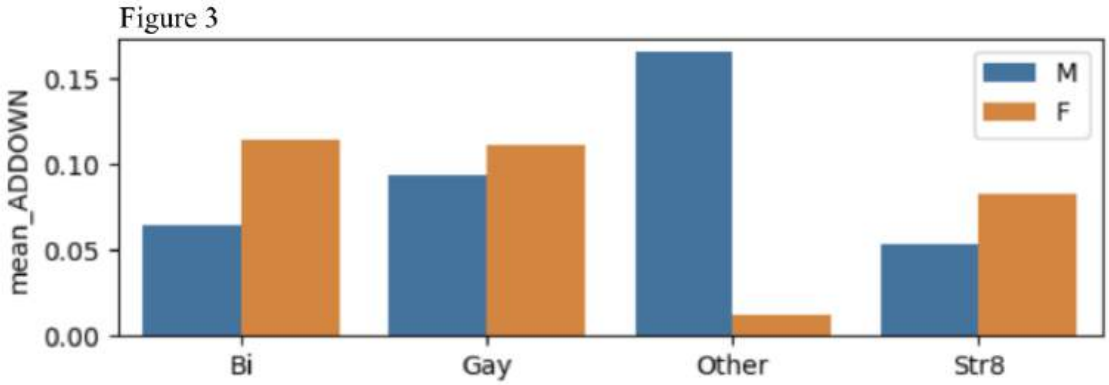


*Figure 3: Mean frequency of depressed mood and hopelessness (ADDOWN) by gender and sexual orientation. Graphic created by Leetheoiv, from Kaggle dataset "Sexual Orientation/TransgenderMentalHealth"(2015). https://www.kaggle.com/code/leetheoiv/sexual-orientation-transgender-mental-health/notebook?select=2015_formats.json*

Figure 3 (ADDOWN) highlights depressive mood and hopelessness, which reflects the number of accounts of a depressed mood. Bi, Gay, and the Other category produce higher averages than compared to heterosexual individuals, implying that queer individuals experience greater depressive mood and hopelessness. Among the other (TNB) category, biological male respondents show significantly higher levels than their biological female counterparts. Elevated social stress can dysregulate systems like the HPA that controls stress response, creating more individuals vulnerable to depressive mood and hopelessness.

***Figure 4.***

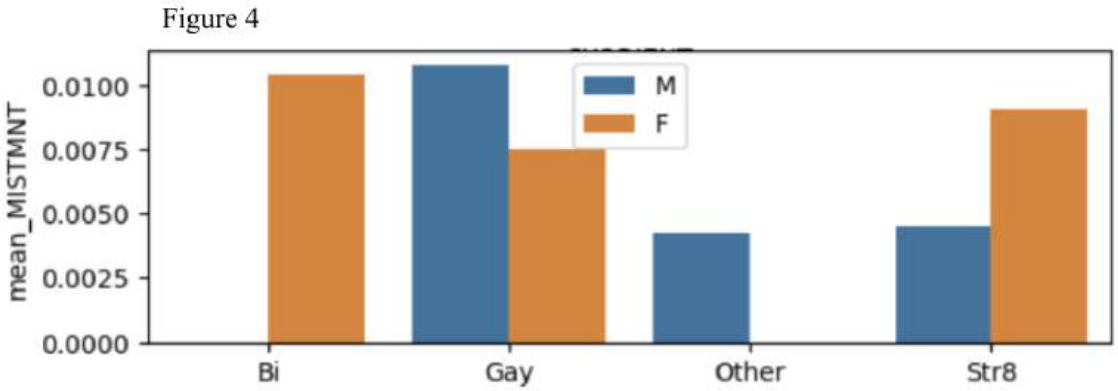



*Figure 4: Mean frequency of current mental-health treatment (MISTMNT) by gender and sexual orientation. Graphic created by Leetheoiv, from Kaggle dataset "Sexual Orientation/TransgenderMentalHealth"(2015). https://www.kaggle.com/code/leetheoiv/sexual-orientation-transgender-mental-health/notebook?select=2015_formats.json*

Figure 4 (MISTMNT) is regarding current mental health treatment. Bi and Gay individuals report the highest likelihood of treatment; this is true even though the other category, which consists of TNB individuals, shows low rates of receiving treatment while still having higher rates of depression symptoms, as shown in Figures 2 and 3. This inconsistency can be attributed to the fact that there are systemic barriers that limit access to mental health care for gender diverse individuals. Factors such as provider bias, diagnostic gatekeeping, and lack of gender-affirming services contribute to this gap (Poteat et al.; Elliot & Stephanie). These findings

support the fact that mental health outcomes in part arise from social inequalities in healthcare systems that don't provide said healthcare.

***Synthesis and findings***

These results lead us to the conclusion and support our hypothesis that TNB individuals experience higher depressive symptoms and lower access to mental health/gender affirming care. Figures 2 and 3 prove to us that TNB participants experienced more negative emotion, while Figure 4 concludes that those participants with worse mental health were shown to have less access to treatments. This data supports the paper's larger argument that mental health disparities related to TNB individuals are interactions between neurobiological mechanisms and are also heavily influenced by social determinants. In this data, we have to recognize that this was a survey, meaning that people could have sampling bias because not everyone is reachable by phone. Thus, we are not representing the full population. There's also a social desirability bias where participants might change their answers to be more socially acceptable. Another large bias interfering with this kind of sampling method is recall bias, where participants struggle to remember the past accurately.

**Conclusion**

Understanding the disparities in mental health among transgender and nonbinary individuals (TNB) requires an approach that's multidisciplinary, incorporating both biological and social/cultural research. Neurobiology can explain the structural and hormonal correlates of gender identity but it cannot explain the effects of social stigma, discrimination, and systemic inequality that heavily influence the lived experiences and mental health outcomes of TNB individuals.

The stigma that's hard to measure not only denies individuals the option to affirming healthcare and societal support, it undermines individuals' sense of self-worth and belonging. These inequalities can be addressed through inclusive education, policy reform, mental health training for providers, and many more, by doing this the barriers that perpetuate them are beginning to be dismantled. This paper highlights that we ultimately need to protect mental health and affirm individuals, regardless of their identity. Moreover, this research underscores the fact that mental health and differing gender identities are not the cause of one or another, but because of the stigmas and barriers society has, these TNB individuals often show mental health issues due to circumstances. Progress depends on shifting society from now to one that embraces diversity, equity, and recognizes the humanness of everyone on the gender spectrum.

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**Teen Unemployment: Minimum Wage and Contributing Factors By Avery Zhang**

**Abstract**

This study examines the impact of state minimum wage, macroeconomic indicators, and sectoral employment shares on teen unemployment across six U.S. states from 1999 to 2019, using panel regression models with fixed and random effects and holding one state out for out-of-sample validation. The analysis isolates key drivers of youth labor outcomes while controlling for time-invariant and unobserved characteristics within states, such as geography and cultural norms. The Fixed Effects model ultimately demonstrated stronger explanatory power ($R^2 = 0.660$) than the Random Effects model. The results show that GDP growth, rising household income, and increased employment in leisure and retail sectors significantly reduce teen unemployment. In contrast, minimum wage thresholds above $8 and states with largely agricultural economies are associated with higher teen unemployment rates. These findings indicate that targeted policies, such as youth wage exemptions or specific sector training subsidies, rather than uniform wage mandates, can better support teen labor force participation while minimizing adverse effects.

## 1. Introduction

Teen (aged 16-19) unemployment remains a persistent challenge in U.S. labor markets, particularly in states with diverse economic structures and evolving wage policies. Policymakers face a trade-off: raise wage floors to improve earnings, or risk higher unemployment among vulnerable groups.

This study began with a central question about how state minimum wage policies influence teen unemployment. Empirical literature on the matter offers mixed evidence. Early studies using cross-sectional data often found negative employment effects. In more recent studies, when state-level heterogeneity is controlled, panel-based studies find that the negative employment effects of minimum wage in the early findings are significantly diminished.

However, minimum wage alone does not fully explain variation in teen employment across states. Economic structure, household income, and sectoral employment composition also appear to play important roles. Despite this, few studies explicitly examine wage thresholds, the distribution of teens across industries such as retail, leisure, and agriculture, or validate findings on unseen states. The influence of farm-intensive economies and nonlinear wage effects remains largely underexplored.

This study addresses these gaps by applying panel regression models to teen unemployment data from six U.S. states between 1999 and 2019. The initial model included only Washington (WA) and Idaho (ID), but the results failed to generalize across other states. To enhance model robustness, this study expanded the dataset to include California (CA), Oregon (OR), Utah (UT), North Carolina (NC), and Massachusetts (MA). These states were selected to reflect geographic diversity, variation in minimum wage policies, and differences in sectoral

employment, specifically in the leisure, retail, and agriculture sectors. Oregon (OR) is reserved for out-of-sample validation to test model generalizability and predictive accuracy.

This study applies both fixed and random effects regression models to evaluate the relationship between teen employment and a set of wage, macroeconomic and labor market indicators, including the state minimum wage, consumer price index (CPI), gross domestic product (GDP), household income, labor force participation rates, and sectoral employment shares. To account for nonlinearities and regional heterogeneity, the analysis incorporates a binary wage-threshold variable and a farm-state indicator. By integrating rigorous econometric techniques with policy-relevant diagnostics, the study contributes to the broader discourse on minimum wage design and its implications for youth labor outcomes and offers insights for tailoring wage policies to the structural characteristics of state-level labor markets.

## 2. Literature Review

### *2.1 Minimum Wage and Teen Employment*

The link between minimum wage policy and teen unemployment has long been debated. Brown, Gilroy, and Kohen (1982) found that a 10% increase in the minimum wage reduced teen employment by 1–3%. However, Card and Krueger (1994) challenged this by comparing fast-food employment in New Jersey and Pennsylvania, finding no significant job loss after a wage increase.

Critics such as Neumark and Wascher (2000) replicated the study using payroll data and found a negative elasticity of -0.21 to -0.22. In contrast, Dube, Lester, and Reich (2010) analyzed over 500 counties and found that minimum wage increases raised earnings with little impact on employment, especially when controlling regional economic trends.

More recently, the Congressional Budget Office (2021) projected that raising the federal minimum wage to $15 could reduce employment by 1.4 million jobs. However, studies cited by the Economic Policy Institute (e.g., Cengiz et al. 2019; Dube 2019) argue that wage hikes improve earnings with minimal job loss, particularly for women and racial minorities. A 2024 synthesis of 97 post-1992 studies found most own-wage elasticities clustered near zero, indicating a minimal impact on employment (Dube & Zipperer, 2025).

Despite this extensive literature, several gaps remain. Few studies explicitly assess wage thresholds, which may better capture nonlinear constraints in youth labor markets. Sectoral employment composition, particularly in leisure and retail, where teens are disproportionately represented, is rarely modeled, despite its potential to mediate wage effects. Out-of-sample validation is largely absent as well, leaving uncertainty about model generalizability. The role of farm-intensive economies and structural wage dynamics is also underrepresented in research.

### *2.2 Macroeconomic and Sectoral Influences*

Macroeconomic conditions, such as recessions and inflation, consistently influence youth unemployment. Teens are often in part-time or temporary roles, making them more vulnerable to

economic shocks (Hoynes et al. 2012; O'Higgins 2001). Kahn (2010) found that inflation reduces firms' ability to sustain entry-level jobs, while rising CPI may push teens into the labor force, increasing measured unemployment if job growth lags.

Sectoral employment is a critical determinant of teen labor market outcomes. Retail and leisure industries offer accessible entry points for young workers, and expansion in these sectors tends to reduce teen unemployment (Aaronson et al. 2007). In contrast, agricultural jobs are seasonal, physically demanding, and often less accessible to urban youth (USDA 2021). While these dynamics are frequently discussed in narrative analyses and policy reports, they are rarely incorporated as explicit variables in empirical regression models when analyzing teen unemployment, for most studies rely on broad macroeconomic controls or fixed effects. By directly modeling sectoral employment shares, this study moves beyond theoretical acknowledgment and provides a more granular understanding of how industry structure interacts with wage policy to influence teen unemployment.

### *2.3 Methodological Evolution*

Early studies relied on cross-sectional regressions with limited controls, often producing biased estimates, while more recent work uses panel data with state and year fixed effects to account for unobserved heterogeneity. Allegretto, Dube, and Reich (2011) show that once regional shocks and growth trends are controlled for, minimum wage effects on employment become statistically insignificant. Structural models, such as Gorry (2013), simulate youth labor dynamics and suggest nonlinear effects depending on worker productivity.

However, most studies focus on in-sample fit and statistical inference without testing how well models generalize unseen data. Out-of-sample validation, essential for assessing predictive robustness, is rarely conducted. This limits the external relevance of findings, especially policy design.

Taken together, the literature supports the use of panel regression with state-level controls to isolate wage effects while accounting for economic context. Our study builds this foundation by modeling both continuous wage levels and threshold effects, incorporating CPI, GDP, household income, sectoral employment shares, and farm-state dynamics. This research will further validate model performance through out-of-sample prediction using Oregon as a test case. This approach balances methodological rigor with policy relevance, offering a more nuanced view of how wage policies shape teen unemployment across diverse economic landscapes.

## 3. Data Collection and Methodology

### *3.1 Data Collection*

This study used state-level panel data spanning from 1999 to 2019 for Washington, Idaho, California, Massachusetts, North Carolina, and Utah.

The selected states vary widely in economic composition and wage policy orientation. California and Washington consistently maintain the highest minimum wage levels in the country, often exceeding federal standards through indexation and legislative mandates. Massachusetts also exhibits progressive wage policies, while North Carolina and Utah tend to align more closely with federal baselines. Sectoral employment structures differ markedly. California and Massachusetts have large leisure and retail sectors; Idaho and Utah show higher agricultural intensity, and North Carolina reflects a mixed industrial base. These differences enabled cross-sectional analysis of how wage policies interact with local labor market dynamics.

Data was compiled from publicly available sources, including the U.S. Bureau of Labor Statistics (BLS), Bureau of Economic Analysis (BEA), the Federal Reserve Bank of St. Louis, and state-level labor reports. Each observation represents a state-year combination, enabling analysis of both temporal and cross-sectional variation. The time frame begins in 1999 to align with the availability of teen unemployment data and excludes post-2019 observations to avoid distortions from COVID-related economic shocks.

The dataset includes the following variables:

- Teen Unemployment Rate: Percentage of individuals aged 16-19 who are unemployed over noninstitutional teen (16-19) actively seeking work
- Minimum Wage: State-level minimum wage, adjusted for inflation
- National Consumer Price Index (CPI): Measures inflationary pressure
- Gross Domestic Product (GDP): State-level economic output (in billions)
- Household Income: Median household income by state and year
- Employment Shares: Percentage of total employment in retail, leisure in total nonfarm employment
- Farm employment Shares: Percentage of farms in total employment
- Teen Population: Number of individuals aged 16–19 (in thousands)
- Labor Force Participation Rate (LFPR): Share of the civilian population aged 16+ that is employed or seeking work
- Teen LFPR: Labor force participation rate for individuals aged 16–19
- Youth Exemption: Binary indicator for states with youth wage exemptions
- Wage Thresholds: Binary indicators for state minimum wage levels above $8
- Farm-State Indicator: Binary indicator to identify states with farm employment that exceeds 4% of total employment

To ensure consistency across states and years, this study performed several data cleaning steps. Due to incomplete reporting of teen-specific labor force participation rates in North Carolina and Massachusetts, this study used the overall LFPR for all seven states as a proxy. This study also constructed binary indicators for wage thresholds (e.g., Wages Above $8, Wages Above $10, Wages Above $12) to capture nonlinear effects. Finally, a binary term (Farm State) was created to identify levels when farm employment exceeds 4% of total employment. This transformation was used to assess whether agricultural intensity modifies the impact of sectoral

employment on teen unemployment. All the variables were stripped of whitespace, indexed by state and year, and validated for multicollinearity using Variance Inflation Factors (VIFs), with all predictors falling within acceptable ranges.

### *3.2 Methodology*

To evaluate the determinants of teen unemployment, this study employed panel regression models using data from the six states. Regression analysis was used to quantify relationships between the dependent variable and multiple predictors while controlling unobserved heterogeneity.

The dependent variable in this study was the teen unemployment rate in each state. The independent variables included macroeconomic indicators (National CPI, state-level GDP, state median household income), sectoral employment shares (Leisure, Retail), labor force participation rate (LFPR), a binary wage threshold indicator (Wages Above $8), and a farm binary term (Farm State). These variables were selected to capture both economic conditions and structural labor market dynamics.

$$Unemployment_{it} = \beta_0 + \beta_1 GDP_{it} + \beta_2 GDP_{it} + \beta_3 Income_{it} + \beta_4 Leisure_{it} + \beta_5 Retail_{it} + \beta_6 LFPR_{it} + \beta_7 WageAbove8_{it} + \beta_8 FarmState_{it} + \mu_i \varepsilon_{it}$$

Where:

- $i$ indexes states
- $t$ indexes years
- $\mu_i$ captures state-specific fixed effects
- $\varepsilon_{it}$ is the idiosyncratic error term

The panel data combined observations across states and years, offering several advantages over cross-sectional or time-series data alone. It enabled control for time-invariant state-level characteristics, improves estimation efficiency, and allows for the study of dynamic relationships over time.

Two econometric specifications were employed: Fixed Effects and Random Effects models. Fixed Effects control for unobserved, time-invariant characteristics unique to each state, such as geography, long-term policy orientation, or cultural norms, by allowing each state to have its own intercept. This is particularly useful when unobserved factors may correlate with the independent variables. Random effects assume that state-specific effects are uncorrelated with the regressors, allowing both within-state and between-state variation to inform the estimates. A Hausman test confirms that the Fixed Effects model is preferred, indicating that state-level heterogeneity is correlated with the regressors and must be accounted for.

Model performance was then validated using Oregon as a hold-out test state. This study compared predicted and actual unemployment rates to assess generalizability and robustness. Additional diagnostics included multicollinearity checks using Variance Inflation Factors (VIFs) and specification tests to confirm estimator consistency.

## 4. Results

Teen unemployment rates across six U.S. states rose sharply during recessionary periods (2008–2013), followed by gradual declines in the years that followed (Figure 1). Recovery severity and pace varied by state, reflecting differences in economic structure and policy. Over the same period, all six states' minimum wages increased relative to 1999 levels (Figure 2). Notably, the trajectory of teen unemployment did not consistently mirror changes in minimum wage levels. This divergence has fueled ongoing debate about whether and how minimum wage policies influence youth labor market outcomes.

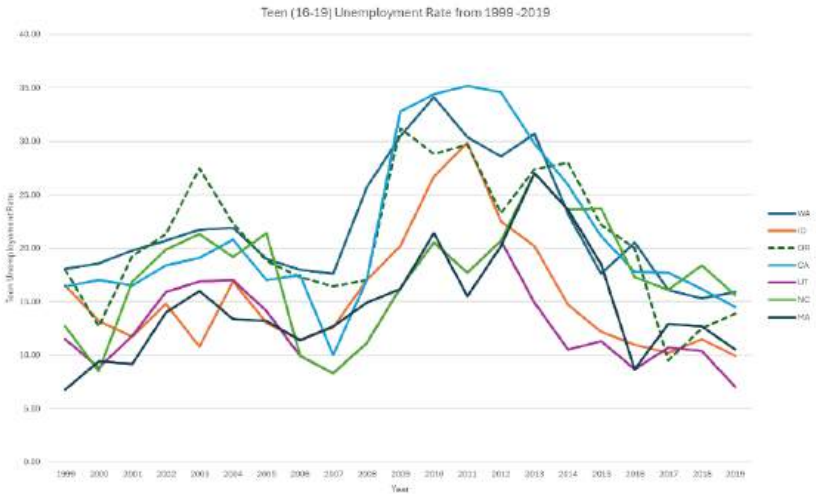



Figure 1: Teen Unemployment Rates in Seven U.S. States, 1999–2019. Oregon, the test case, is represented using a dotted line.

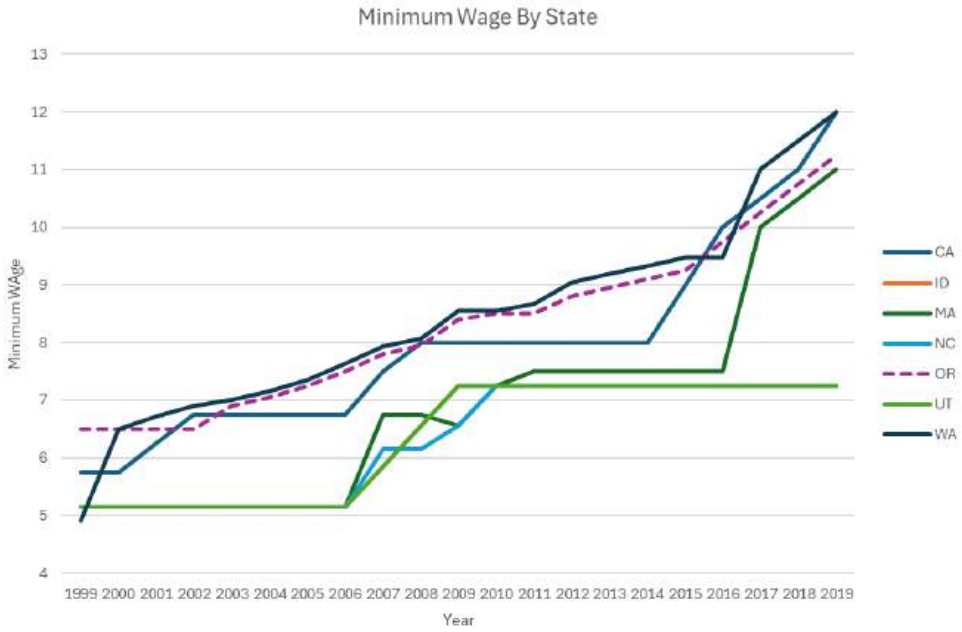



Figure 2: Minimum Hourly Wage in U.S. States, 1999–2019. Oregon, the test case, is represented using a dotted line.

Having run the panel regression model with fixed and random effects, the study outlined coefficient estimates, model diagnostics, and prediction results in the following subsections.

### *4.1 Fixed Effects Model*

The Fixed Effects model yielded $R^2$ within = 0.660 (Table 1), outperforming the Random Effects model ($R^2$ within = 0.2574) (Table 2). By yielding a higher within-state $R^2$ compared to the Random Effects model, the Fixed Effects specification captured a substantially greater share of variation in teen unemployment attributable to changes within each state between 1999 and 2019. The statistically significant F-statistic ($F = 23.97$, $p < .0000$) further confirmed that the included predictors, such as GDP, household income, labor force participation, sectoral employment shares, and wage thresholds jointly explained a meaningful portion of this variation. The Hausman test supported the use of the Fixed Effects model, indicating that unobserved, time-invariant state characteristics are correlated with the explanatory variables. This correlation violated the assumptions of the Random Effects model, rendering its estimates biased. Therefore, the Fixed Effects specification was preferred because it effectively controlled these state-specific influences, producing more consistent and policy-relevant results.

Table 1. Fixed Effects Model Results (Six-State Panel, 1999–2019)

| Variable | Coefficient | Std. Error | T-statistic | P-value | 95% CI (Lower) | 95% CI (Upper) |
|---|---|---|---|---|---|---|
| const | 330.410 | 38.070 | 8.680 | 0.000 | 254.970 | 405.860 |
| CPI | 0.043 | 0.038 | 1.140 | 0.257 | −0.0315 | 0.117 |
| **GDP** | −0.0141 | 0.004 | −3.94 | 0.000 | −0.0212 | −0.0070 |
| **Household** | −0.0006 | 0.000 | −7.78 | 0.000 | −0.0008 | −0.0005 |
| **Leisure** | −6.3055 | 1.164 | −5.42 | 0.000 | −8.6124 | −3.9985 |
| **Retail** | −7.3551 | 1.539 | −4.78 | 0.000 | −10.405 | −4.3057 |
| **LFPR** | −2.0957 | 0.420 | −4.99 | 0.000 | −2.9281 | −1.2632 |
| **Farm_State** | 6.742 | 2.029 | 3.320 | 0.001 | 2.722 | 10.763 |
| Wage | −0.3895 | 0.619 | −0.63 | 0.530 | −1.6159 | 0.837 |
| **Wage_Above_8** | 5.886 | 1.504 | 3.910 | 0.000 | 2.906 | 8.865 |

*$R^2$ (Overall): 0.6603*
*$R^2$ (Within): 0.6603*
*F-statistic: 23.974 ($p < 0.0000$)*
*Entities: 6 (WA, ID, CA, MA, UT, NC)*
*Time Periods: 21 years*
*Observations: 126*
*Poolability Test: $F = 32.323$, $p = 0.000$→ Fixed effects preferred*

Macroeconomic indicator findings were introduced first. The national Consumer Price Index (CPI) did not exhibit a statistically significant association with teen unemployment rates ($p = 0.257$). By contrast, a one-unit increase in GDP (in billions) was associated with a 0.014

percentage point decrease likely because as businesses grow, they are more likely to hire entry-level workers, including teens, especially in service and retail roles. Similarly, each additional $1 in median household income corresponded to a 0.0006 percentage point reduction in teen unemployment ($p < .000$). Rising household income may signal broader economic stability and consumer demand, which can stimulate hiring. It may also reduce the financial pressure on teens to seek work during downturns, lowering measured unemployment.

Turning to employment sector dynamics, the results indicated that a percentage point increase in Leisure or Retail employment share reduced teen unemployment by 6.30 and 7.36 percentage points, respectively. These sectors are major entry points for teen workers due to lower skill requirements and flexible scheduling. The Farm State variable, however, was positively associated with teen unemployment ($\beta = 6.74$, $p = .001$). Farm jobs are often seasonal, physically demanding, and less accessible to urban teens, limiting employment opportunities in farm-heavy states. Additionally, a percentage point increase in LFPR was associated with a 2.10 percentage point decrease in teen unemployment. Higher participation rates may reflect stronger labor market engagement and confidence among teens. When more teens are actively seeking work and employers are hiring, unemployment tends to fall.

Finally, the wage-related findings revealed a nonlinear relationship between minimum wage levels and teen unemployment. The continuous wage variable was statistically insignificant, implying that wage effects were not uniform across all levels. Instead, the binary wage threshold indicator (Wages Above $8) was positive and significant ($\beta = 5.89$), indicating that minimum wages above $8 were associated with higher teen unemployment. This pattern may reflect labor substitution, as employers hire more experienced workers or adopt automation when wage floors rise.

### *4.2 Random Effects Model*

The Random Effects model yielded a substantially lower overall $R^2$ (0.396) (Table 2) compared to the Fixed Effects specification, indicating weaker explanatory power for variation in teen unemployment. The coefficient estimates were less stable across specifications, with several signs reversing, including the Farm State variable, raising concerns about estimator consistency. These inconsistencies suggest that the Random Effects assumption of uncorrelated state-level heterogeneity may not hold, undermining the reliability of its inferences. While the Random Effects model captured some between-state variation, it failed to account for unobserved factors that likely influence youth labor outcomes, making it less suitable for policy analysis in this context.

Table 2. Random Effects Model Results (Six-State Panel, 1999–2019)

| Variable | Coefficient | Std. Error | T-statistic | P-value | 95% CI (Lower) | 95% CI (Upper) |
|---|---|---|---|---|---|---|
| const | 168.780 | 42.570 | 3.960 | 0.000 | 84.460 | 253.100 |
| CPI | −0.0174 | 0.031 | −0.57 | 0.572 | −0.0784 | 0.044 |

| | | | | | | |
|---|---|---|---|---|---|---|
| GDP | −0.0008 | 0.001 | −0.88 | 0.379 | −0.0026 | 0.001 |
| Household | −0.00007 | 0.000 | −1.01 | 0.317 | −0.0002 | 0.000 |
| Leisure | −2.0605 | 1.074 | −1.92 | 0.057 | −4.1868 | 0.066 |
| Retail | −0.7138 | 0.479 | −1.49 | 0.139 | −1.6632 | 0.236 |
| LFPR | −1.6852 | 0.461 | −3.66 | 0.000 | −2.5975 | −0.7729 |
| Farm_State | −1.8964 | 1.963 | −0.97 | 0.336 | −5.7846 | 1.992 |
| Wage | −0.7936 | 0.706 | −1.12 | 0.263 | −2.1911 | 0.604 |
| Wage_Above_8 | 5.797 | 2.172 | 2.670 | 0.009 | 1.496 | 10.099 |

*$R^2$ (Overall): 0.3958*
*$R^2$ (Within): 0.2574*
*F-statistic: 8.4416($p < 0.0000$)*
*Entities: 6 (WA, ID, CA, MA, UT, NC)*
*Time Periods: 21 years*
*Observations: 126*

### *4.3 Robustness Checks*

To assess multicollinearity, this study calculated the Variance Inflation Factors (VIFs) for all the predictors. All VIFs fall below 8, with most falling under 5, indicating acceptable levels of collinearity.

The alternative wage specifications, including *Wages Above $10*, *Wages Above $12* and *Wages Above $8* were evaluated, and the $8 threshold consistently yielded the strongest and most interpretable effects. This suggests that wage impacts on teen unemployment may be nonlinear, with sharper disemployment effects emerging once wages exceed a critical policy cutoff. The sectoral controls remained stable across specifications, reinforcing the robustness of leisure and retail employment as protective factors.

Additional robustness checks included lagged wage variables and interaction terms between minimum wage and youth exemption policies. These specifications did not yield statistically significant effects, suggesting that there were no significant temporal spillovers or moderating effect of exemption status in the current sample.

Several variables, such as teen population, farm employment percentage, and local CPI measures, were excluded from the final specification due to multicollinearity. Their inclusion distorted coefficient estimates and reduced model interpretability. By refining the predictor set, we improved model stability and ensured that retained variables offer clear and consistent insights into teen unemployment dynamics.

### *4.4 Out-of-Sample Validation and Visual Diagnostics*

To assess model generalizability, Oregon was held out as a test state. The Fixed Effects model achieved lower prediction errors, with Mean Absolute Error (MAE = 3.55) and Root Mean Squared Error (RMSE = 4.44), compared to the Random Effects model (MAE = 4.80,

RMSE = 5.62). These metrics suggest that the Fixed Effects model better captured the underlying dynamics of teen unemployment in an unseen state.

Figure 3 plots actual versus predicted unemployment rates in Oregon from 1999 to 2019. The Fixed Effects model closely tracked observed trends, particularly during periods of minimum wage increases and sectoral shifts. In contrast, the Random Effects model tended to underestimate volatility and smooth over local variation, failing to capture inflection points tied to policy or economic shocks.

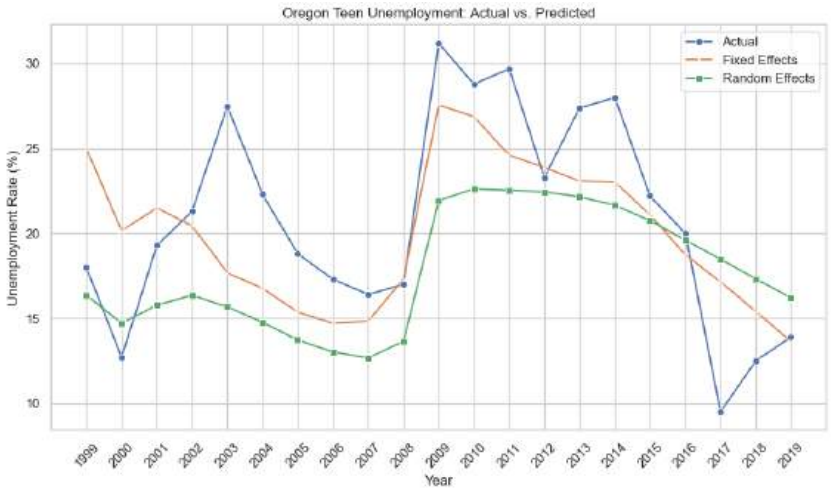



Figure 3: Actual vs. Predicted Teen Unemployment in Oregon, 1999–2019

Table 3 summarizes key model diagnostics. The Fixed Effects model outperformed across all criteria, with higher $R^2$ (within = 0.660), stronger log-likelihood, and a more significant F-statistic, reinforcing its superior explanatory power. These results confirmed that accounting for state-level heterogeneity is essential when modeling youth labor outcomes, and that Fixed Effects offer a more reliable framework for evaluating wage policy impacts.

Table 3. Model Comparison Metrics (Oregon: Test State)

| Metric | Fixed Effects | Random Effects |
|---|---|---|
| $R^2$ (within) | 0.660 | 0.257 |
| $R^2$ (overall) | 0.660 | 0.396 |
| Log-likelihood | −324.44 | −381.05 |
| MAE (OR test) | 3.550 | 4.800 |
| RMSE (OR test) | 4.440 | 5.620 |
| F-statistic | 23.970 | 8.440 |
| p-value (F-statistic) | <.001 | <.001 |

## 5. Discussion

Higher GDP, rising median household income, and greater employment shares in leisure and retail sectors significantly reduce teen unemployment. These results align with prior research indicating that economic growth and sectoral expansion create accessible entry-level opportunities for youth (Aaronson et al., 2007; Hoynes et al., 2012). The strong effects of leisure and retail employment support the argument that industry structure plays a crucial role in shaping youth labor outcomes, a factor often overlooked in earlier minimum wage studies that relied mainly on aggregate macroeconomic indicators (as noted in Allegretto et al., 2011, and Dube et al., 2010).

Conversely, minimum wages above $8 are associated with higher teen unemployment. This finding is consistent with Neumark and Wascher's (2000) evidence of disemployment effects among teens at higher wage levels, but contrasts with Card and Krueger's (1994) and Dube et al. 's (2010) results showing minimal or no job losses. The insignificance of the continuous wage variable suggests that wage effects are nonlinear, concentrated at specific policy cutoffs rather than changing smoothly with each dollar increase. This supports more recent discussions in literature emphasizing the importance of nonlinear modeling and localized thresholds in understanding minimum wage impacts (Dube & Zipperer, 2025; Gorry, 2013). Unexpectedly, the CPI does not significantly affect teen unemployment, differing from Kahn's (2010) results that inflation may alter labor force participation[11]. This suggests that in the context of this dataset, broader state-level economic indicators such as GDP and household income are stronger drivers of teen employment outcomes than national inflationary trends.

These results have several broader implications. First, they highlight the importance of state-level heterogeneity: policies like minimum wage increases do not have uniform effects across states and sectors. Second, the strong protective effect of leisure and retail employment demonstrates the value of targeted interventions, such as sector-specific training programs or youth wage exemptions, to mitigate disemployment risks while supporting earnings growth. Third, nonlinear wage effects indicate that blanket increases in minimum wages may unintentionally reduce teen employment, particularly in farm-intensive or low-skill sectors.

There are a few limitations to this study. First, the analysis included only six U.S. states over the 1999-2019 period, so the findings may not fully generalize to all states. Expanding the dataset to include more states could improve external validity. Second, the study period ended in 2019 to avoid distortions from the COVID-19 pandemic, meaning recent wage policy changes and post-pandemic labor market dynamics that may alter the relationship between wages and youth employment were excluded, thus limiting the generalizability of the findings for today's labor market. Third, although leisure, retail, and agricultural employment shares were included, other industries employing teens (such as education or health services) were not modeled due to data availability. Their exclusion may understate the complexity of sectoral interactions with wage policy. Fourth, in two cases, teen-specific labor force participation rates were unavailable, requiring the use of overall LFPR as a proxy.

Acknowledging these limitations highlights the need for future research to test additional thresholds, incorporate broader state coverage, integrate dynamic econometric methods, and

evaluate the post-2020 labor market environment. Plans are underway to incorporate more states and update the data past 2019 to reflect post-pandemic labor market dynamics.

## 6. Conclusion

This study investigated the relationship between minimum wage and teen unemployment across six U.S. states from 1999 to 2019, using panel regression models with fixed and random effects. By incorporating sectoral employment shares, household structure, and a binary farm-state indicator, this study isolated the key drivers of youth labor outcomes while controlling for unobserved state-level heterogeneity. The Fixed Effects model demonstrated superior explanatory power ($R^2 = 0.660$) and more consistent coefficient signs, outperforming the Random Effects model both in-sample and in out-of-sample prediction for Oregon (MAE = 3.55 vs. 4.80; RMSE = 4.44 vs. 5.62).

The findings revealed that growth of GDP, state median household income, and employment in leisure and retail sectors significantly reduce teen unemployment, while wage thresholds above $8 are associated with higher unemployment rates. The insignificance of the continuous wage variable and the robustness of the threshold indicator suggested nonlinear wage effects that merit further exploration. The reversal of the Farm State coefficient between models highlights the importance of estimator choice and caution against pooled assumptions in policy analysis.

The robustness checks confirmed the stability of sectoral and household effects across alternative wage specifications. Multicollinearity diagnostics showed acceptable VIF levels, and out-of-sample validation reinforced the generalizability of the Fixed Effects model. Visual diagnostics further demonstrated its ability to capture state-specific dynamics and wage-induced shifts in teen unemployment.

These results offer timely insights for policymakers to evaluate wage standards and youth employment strategies. By identifying threshold effects and sectoral dynamics, the study suggests that blanket minimum wage increases may have unintended consequences in farm-intensive or leisure/retail-driven economies. The predictive strength of the Fixed Effects model highlights the need for localized policy design. Rather than one-size-fits-all wage mandates, targeted interventions such as youth wage exemptions, sector-specific training subsidies, or transitional employment programs, may better support teen labor force participation without exacerbating unemployment.

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# GFAP and Iba1 Show Increased Expression Across Cortical Layers in Dementia: Astrocyte Reactivity is More Strongly Associated with Dementia than Microglial Reactivity

By Braylon Zhang

## Abstract

Glial fibrillary acidic protein (GFAP) and ionized calcium-binding adaptor molecule 1 (Iba1) are markers used to study astrocyte and microglial expression, which play crucial roles in brain inflammation and neurodegenerative diseases such as Alzheimer's. GFAP expression reflects astrocyte reactivity in response to damage, while Iba1 shows microglial expression. GFAP is found in astrocytes and Iba1 is found in microglia, all in the central nervous system.

This study asks whether greater GFAP and Iba1 expression seen in cortical layers V-VI compared to layer IV between donors with and without dementia reflects layer-based differences in astrocyte and microglial expression in the cortex.

Using the histopathology dataset of the middle temporal gyrus (MTG) of eighty-four postmortem human samples in the Seattle Alzheimer's Disease (SEA-AD) dataset, we examined GFAP and Iba1 expression across cortical layers. Both markers were elevated in cortical layers (IV vs. V-VI) but only GFAP showed an increase in dementia. This supports our thesis that astrocytic reactivity is tied to Alzheimer's related degeneration and deep-layer neuron vulnerability, where microglial activity may reflect cortical structure rather than dementia-related pathology. These findings emphasize that deep vs shallow layers of the brain examined matters when studying support cells. Astrocyte expression, measured by GFAP, is a better indicator of dementia-related changes in the cortex than microglial expression, measured by Iba1, because GFAP is more positively associated with disease progression.

**Keywords** Alzheimer's, Dementia, GFAP, Iba1, Astrocyte, Microglia

## Introduction

Alzheimer's Disease (AD) is hypothesized to be driven by the buildup in proteins forming amyloid plaques and neurofibrillary tangles in the brain. According to Mayo Clinic, it leads to brain cell death and shrinkage, and is the most common cause of dementia, affecting over 55 million people (Dementia and "Alzheimer's Disease - Symptoms and Causes"). In 1906, Alois Alzheimer reported the disease which would later be called Alzheimer's Disease by Emil Kraepelin, and since then, doctors, researchers and scientists have been working to identify causes and treatment options (Hippius and Neundörfer). The progress was slow for several decades until the late 1990s when advances in neurochemistry, genetics and molecular biology, imaging and PET scan led to the understanding of precursor protein mutations and major risk factors (Bermejo-Pareja and del Ser). From the biomarker revolution in the early 2000s to new therapies evolving today, researchers shift focus to finding more biomarkers for early detection, risk reduction and prevention strategies.

The middle temporal gyrus (MTG) is one of several regions where degeneration can signal dementia and Alzheimer's Disease. In the MTG, the varying vulnerability of different layers leads to contrasting expressions of GFAP and Iba1. Understanding the differences in astrocyte expression in different layers is important for advancing insight in Alzheimer's disease and improving biomarker strategies.

Astrocytes are glial cells that maintain homeostasis in the brain through clearing neurotransmitters and helping with synapse formation, and respond to harm through reactive gliosis via an increase of GFAP (Wei and Morrison). In the focus of this paper, astrocytic GFAP expression increases in response to neurodegenerative changes. In Alzheimer's disease and other forms of dementia, astrocytosis, or an increase in the number and size of astrocytes in the CNS is common and very prevalent. Astrocyte reactivity is not uniform: astrocytes show more projection in layers V-VI with unusually high GFAP (Sánchez-Juan et al.).

GFAP expression can tell us about neuron health in the cortex due to the role of astrocytes in maintaining ion homeostasis and neurotransmitter recycling (Giovannoni and Quintana). When neurons become stressed and out of balance, astrocytes respond and try to protect neurons, restoring homeostasis and preventing more damage. Therefore, the stronger expression of GFAP in layers V-VI may reflect the astrocytes responding and repairing damaged neurons in those layers. Specifically, whether degeneration in layers V-VI creates astrocytic activation and GFAP increase compared to resilient neurons of layer IV.

We hypothesized that layers V-VI in the cortex have a much higher abundance of GFAP than layer IV due to the large projection neurons that have greater metabolic demands, which makes them susceptible to Alzheimer's, leading to more astrocyte reactions that end up producing more GFAP. Iba1 expression is increased in microglia in the cortex of Alzheimer's patients, revealing how increased microglial expression may influence neuron stability.

**Materials and Methods**

This study analyzed data from The Seattle Alzheimer's Disease (SEA-AD) Study using the middle temporal gyrus which is published online (SEA-AD Metadata and Neuropath). Brain specimens were obtained from the Adult Changes in Thought (ACT) Study and the University of Washington Alzheimer's Disease Research Center (ADRC). Detailed methods are in the White Papers (Seattle Alzheimer's Disease Brain Cell Atlas (SEA-AD) (2022)) and (Gabitto et al.).

Paraffin-embedded brain tissue was sectioned and stained for assessment of neuropathologic diseases. Stained slides were used for quantitative analysis, and double labeling gave data on peptide colocalization.

GFAP and Iba1 were labeled using diaminobenzidine and alkaline phosphatase reactions, and quantified in HALO® v3.4.2986, software allowing high-resolution with the Area Quantification module, to measure stained astrocyte and microglia area. Detailed methodology is available in the Seattle Alzheimer's Disease Brain Cell Atlas (SEA-AD) from the Neuropathology Images and quantifications.

Donor metadata and MTG quantitative neuropathology data were obtained from the AD Knowledge Portal (https://adknowledgeportal.org) and analyzed in GraphPad Prism v10.5.0 (GraphPad Software, San Diego, CA). Results are reported as mean ± SEM.

## Results

### Donor Demographics

Data analyzed here include 84 participants with 42 diagnosed dementias (27 females and 15 males) and 42 non-dementias (24 females and 18 males). The age of onset cognitive symptoms was between 53 to 94 with average age of 80.65 and the age of dementia diagnosis was between 53 to 97 with average age at 83.72. The age at death was between 65 to 99 with an average at 87.69.

### GFAP

Total GFAP-positive area ($\mu m^2$) was compared across layer IV and layers V-VI from dementia and non-dementia donors in the MTG. A two-way Anova revealed a significant main effect of layer [$F(1,164) = 46.53$, $p < 0.001$], a smaller but significant main effect of Diagnosis [$F(1,164) = 4.54$, $p = .035$], and no interaction between Layer and Diagnosis [$F(1,164) = 1.06$, $p = .305$].

Fisher's LSD Comparisons showed that GFAP was significantly higher in layers V-VI than in layer IV in both dementia (mean difference = -1,620,636 $\mu m^2$ ($p < .001$) and non-dementia cases (mean difference -1,195,404 $\mu m^2$ ($p<.001$). When comparing diagnoses, there was no difference between dementia and non-dementia in layer IV ($p = 0.438$), but in layers V-VI, GFAP was significantly higher in dementia than non-dementia (mean differences = 652,301 $\mu m^2$, $p = 0.027$).

All together, these findings show that the major effect on GFAP expression is layer-based, with a consistent greater amount in deep layers, and that dementia contributes an additional increase only in layers V-VI.

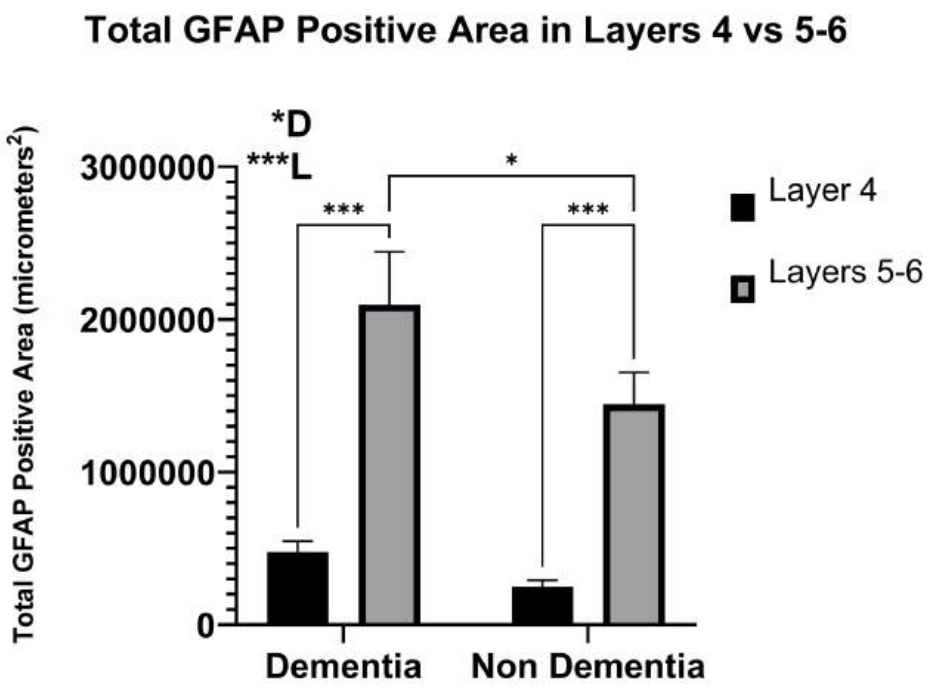



Figure 1. Total GFAP-positive area differs by cortical layer and is increased in dementia. Bars represent the mean ± SEM of GFAP-positive areas (μm²) in layer IV and layers V–VI from dementia and non-dementia brains. *D represents a significance across Dementia groups. ***L represents a major significance across Layers. Two-way ANOVA shows significance of Layer ($F(1,164) = 46.53$, $p < 0.001$) and Diagnosis ($F(1,164) = 4.54$, $p = 0.035$), with no significant interaction.

**Iba1**

Total Iba1-positive area (μm²) was compared across layer IV and layers V-VI from dementia and non-dementia donors. A two-way anova revealed a significant main effect of (showed a strong effect of) Layer [$F(1,164) = 72.11$, $p < 0.001$], revealing that Iba1 levels contrast significantly by cortical depth. However, there was no main effect of Diagnosis [$F(1,164) = 2.310$, $p = .130$], and no interaction between Layer and Diagnosis [$F(1,164) = 0.04834$, $p = 0.826$].

Fisher's LSD Comparisons showed that Iba1 expression was significantly higher in layers V-VI than in layer IV in both dementia (mean difference = −861,147 μm², $p < 0.001$) and non-dementia (mean difference = −817,679 μm², $p < 0.001$) cases. When comparing donors with different dementia diagnoses, there were no significant differences between dementia and non-dementia cases at layer IV ($p = 0.359$) or layers V-VI ($p = 0.220$).

These results indicate that microglial expression is based on cortical layer, being greater in deep layers than in layer IV, but is not significantly changed based on dementia and non-dementia.

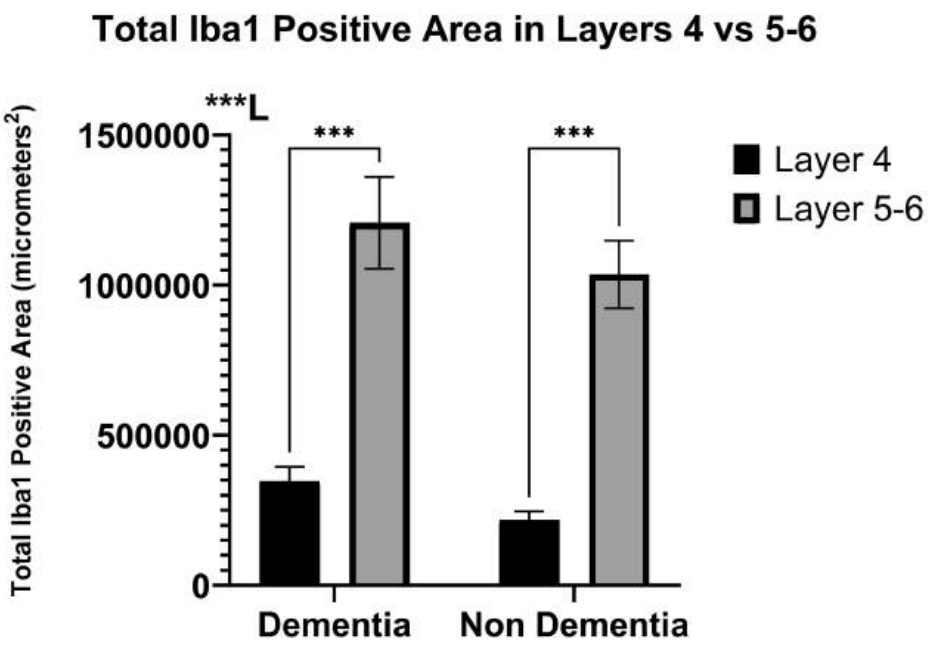



Figure 2. Total Iba1-positive area differs by cortical layer but not dementia. Bars represent the mean ± SEM of Iba1-positive area (μm²) in layer IV (black) and layers V–VI (gray) from dementia and non-dementia brains. *D represents a minor significance in Dementia and ***L represents a major significance in Layer. Two-way ANOVA showed a significance of Layer ($F(1,164) = 72.11$, $p < 0.001$), with no significance of Diagnosis or interaction.

**Discussion**

Alzheimer's disease (AD) is a neurodegenerative brain disorder. The dysfunction of glial cells in Alzheimer's is related to cognitive decline of patients (Yu et al.). In the cortex, the MTG is one of many areas whose distinct layers show different expressions of astrocytes and microglia. Understanding the differences in astrocyte expression in different layers is important for advancing insight into Alzheimer's disease and improving biomarker strategies.

Layers IV and V-VI of the cortex were selected because they represent different neuron populations with different vulnerability in Alzheimer's disease (Harris et al.). Layer IV contains protoplasmic astrocytes, which interact with synapses and blood vessels to regulate neural activity and blood flow (Wei and Morrison). In contrast, layers V-VI contain varicose-projection astrocytes (VP-As). VP-As are different from other astrocytes because they have short, branched, processes that are usually around neurons or blood vessels (Ciani and Falcone). They are located in deep cortical layers and strongly express GFAP, serving to communicate long distances through different cortical layers and have significantly greater amounts of GFAP than protoplasmic astrocytes (Preman et al.). Although VP-As were not analyzed, we recommend future studies to further research VP-As. In Alzheimer's brains, GFAP and tau pathology show layer-specific patterns in both shallow and deep layers (I, II, V, VI), but not the middle layers

(Lemoine et al.). Astrocytes in certain layers show selective vulnerability in Alzheimer's, showing how deep-layer cells can bring in more GFAP (Leng et al.).

Alzheimer's disease can cause cognitive decline through dysfunction of cells in the cortex. GFAP is a molecular marker found in astrocytes that helps regulate the health of cells. Notably, there is an increase of GFAP that varies across layers in the cortex, with Layers V-VI showing much higher GFAP than layer IV. This is shown in patients without as well as patients with dementia (Astillero-Lopez et al.). In Alzheimer's affected tissue, astrocytes near amyloid plaques become reactive, increase size and GFAP expression, causing patients to have increased levels of GFAP compared to non-affected individuals (Preman et al.). The increase could be caused by reactive astrogliosis, where astrocyte numbers increase in response to damage. Prior research suggests that astrocytic changes may impact neuron health by altering the extracellular environment and modifying synaptic function (Kamphuis et al.). Therefore, higher GFAP levels in Alzheimer-affected tissue may reflect disruptions in neurons.

These data demonstrate that GFAP expression was higher in deep layers (V-VI, 2,097,020 $\mu m^2$) compared to layer IV (476,384 $\mu m^2$). This nearly fivefold increase highlights that astrocytic expression is not uniform through the cortex, but is amplified in areas with heightened vulnerability to neuron degeneration. Specifically for Alzheimer's patients, layers V-VI neurons are affected early, slowing down their signals because their parvalbumin (PV) neurons lose support (Papanikolaou et al.). These findings are consistent with the hypothesis that deep-layer neuron vulnerability drives astrocytic expression.

A comparable pattern was observed in non-dementia cases, where layers V-VI (1,444,719 $\mu m^2$) also showed greater GFAP compared to layer IV (249,315 $\mu m^2$). The layer-dependent pattern in the cortex might also affect the distribution of astrocytes within these layers, with deep layers having higher GFAP expression. In gray matter, astrocytes in deep layers have detectable GFAP levels, whereas in middle layers, there are barely any (Khakh and Sofroniew).

The result that GFAP is increased supports our hypothesis that Alzheimer's is related to large projection neurons in layers V-VI which take up more energy and are more vulnerable to dementia, leading to increased GFAP in astrocytes and Iba1 in microglia. GFAP expression was much higher in layers V-VI (2,097,020 $\mu m^2$ total GFAP-positive area in dementia patients, 1,444,719 $\mu m^2$ in non-dementia) compared to layer IV in both groups (476,384 $\mu m^2$ vs 249,315 $\mu m^2$) dementia vs non-dementia. Dementia selectively increases GFAP in the deep layers (V-VI), but not significantly in layer IV. This effect aligns with the large projection neurons in deep layers, which need high metabolic demand to function. These neurons are more susceptible to accumulated tau pathology than superficial neurons (Romito-DiGiacomo et al.). Since these neurons go through stress and degeneration, astrocytes around the neurons respond by increasing reactivity, characterized by GFAP expression increase (Giovannoni and Quintana). Therefore, the greater GFAP levels in layers V-VI seen in dementia and non-dementia cortexes may reflect astrocytes and their role in responding to neuronal health and stress. This layer-based pattern supports the idea that astrocytic expression in deep layers is related to the structure of those layers, large projection neurons.

We used the same two layers for Iba1 as we did for GFAP. However it does not lead to a direct comparison. Through the use of layers IV, V, and VI in our graphs and analysis, we were able to compare the presence of microglia and astrocytes in the same layers of the cortex. Microglia also show heterogeneity in both affected and unaffected people (Figure 2. Iba1-positive area differs by cortical layer but not dementia.). Microglial density and activation are not uniform among layers (Leng et al.). Layer IV is a reference for both astrocytes and microglia to assess if both kinds of support cells react in the same layers. Layers V-VI have neurons with selective vulnerability to tau accumulation (Lemoine et al.).

Iba1 is a marker of microglia in the central nervous system. In Alzheimer's patients, there are more activated microglia as it serves as an immune response cell in the case of brain degeneration (Hansen et al.). In Alzheimer's, microglia levels are increased due to a greater amount of Iba1 trying to repair the brain. Increased Iba1 levels can be seen in affected people but evidence suggest that microglial response can be both protective, serving to repair the brain, and also destructive, destroying synapses (Yoshiyama et al.), but the destructiveness is determined based on context (Hansen et al.). Because microglia interact with neurons through synaptic pruning, changes in Iba1 expression could represent neuron function being altered in Alzheimer's Disease.

Patients with dementia show the same amount of iba1 as unaffected patients. Microglial expression was significantly greater in layers V-VI compared to layer IV in dementia and non-dementia patients, but a dementia diagnosis did not significantly increase microglial activity in microglia. Previous research notes that microglial activation may show variability in Alzheimer's disease, sometimes with a peak in early stages of the disease (Ohm et al.). This suggests that unlike astrocyte responses, microglia most likely act this way because of structural organization rather than dementia itself. Current results show that while astrocytic GFAP expression looks more influenced by dementia, microglial Iba1 expression may represent the organization of the immune response in the cortex. In human brains, Iba1 is a pan-microglia marker whose expression increases when microglia is active, but is expressed less when microglia shows greater expression (Hopperton et al.). Therefore, Iba1 levels may show where microglia are active, but not how severe dementia is. This suggests that the layer-based pattern of Iba1 represents the natural arrangement of microglia in the cortex because Iba1 mostly detects inactive and active microglia, not additional microglia that was expressed due to Alzheimer's.

Levels of GFAP in layers V-VI are significantly greater than in layer IV in cases of dementia compared to non-dementia. Levels of Iba1 are also significantly greater in layers V-VI compared to layer IV in dementia patients than in non-dementia patients.

In Alzheimer's disease, astrocytes (GFAP) and microglia (Iba1) are expressed more, but the increase is non-uniform across different layers in the cortex. Deep layers (V-VI) show significantly higher GFAP levels than layer IV, and it is amplified in dementia compared to non-dementia.

These findings support the thesis that glial response in Alzheimer's disease is not uniform, but dependent on glial cell type (astrocytes and microglia) and layer (deep vs shallow).

In deep layers, there are more glial cells than shallow layers, for both dementia and non-dementia patients. Higher GFAP in layers V-VI in dementia patients suggest that astrocytes are sensitive to neuron vulnerability in deep layers.

**Conclusion**

In conclusion, this study investigated the main hypothesis that glial expression in Alzheimer's disease is different in each cortical layer (deep and shallow), with astrocytes and microglia having different responses. Both astrocytic GFAP and microglial Iba1 are active in the deeper layers than in layer IV, but only astrocytes show elevated expression in dementia. These findings emphasize that astrocytic expression is more linked with dementia than microglia. Layer specificity of astrocyte expression may provide insight on neuron damage in Alzheimer's disease.

**Acknowledgement**

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**"We Treat Them Like Prisoners of War": Between the Parapolemic and the Hyperobject in J.M. Coetzee's The Lives of Animals By Mikhaeel Hoosen**

Towards the climax of J.M. Coetzee's novella, *The Lives of Animals*, the protagonist Elizabeth Costello argues that the violence human society inflicts on animals amounts to a war of brutal proportions. As a novelist and passionate defender of animal rights, Costello is invited to deliver the Tanner Lectures at Appleton College, where her son teaches physics. The novella follows Costello as she delivers a lecture on reason and animal rights, leads a seminar on the semiotics of animals in poetry, and finally debates a distinguished professor of philosophy. However, for a novella so overtly interested in such speech acts, much of the conceptual force of the narrative comes from moments of silence.

Between Costello's speaking engagements, a series of more intimate dialogues with her son foreground these silences. Following her speech and her seminar, Costello declares to her son that "we had a war once against the animals, which we called hunting, though in fact war and hunting are the same thing (Aristotle saw it clearly). That war went on for millions of years. We won it definitively only a few hundred years ago, when we invented guns" (59). Despite his mother's rhetorical confidence, Costello's son remains unconvinced. A narrative ellipsis signifies his silence and emotional disconnect, and the text swiftly proceeds to Costello's final speaking engagement.

Ultimately, *The Lives of Animals* opens a rhetorical space where the motifs of contemporary war writing sit alongside recent developments in the philosophy of ecology. Indeed, by examining the rhetorical tactic of the parapolemic from contemporary discussions of war writing and the concept of the hyperobject from contemporary discussions of ecology, the thematic function of the text's silences becomes clearer: the story can be read as a parapolemic war narrative focused on the hyperobject of the meat industry. This commentary sheds light on the darkness at the heart of Coetzee's novella, while clarifying the novella's final silence.

**The Rhetorical Tactics of War Writing**

In her study, *Authoring War*, Kate McLoughlin highlights some of the rhetorical tactics used in war writing. The tactic most pertinent to Coetzee's *The Lives of Animals* falls under the heading of "military diversion tactics" (139). For McLoughlin war writing often draws on techniques such as indexical signs, euphemism, self-referentiality, contradictions and repetition (151) as kinds of verbal diversion. To describe war head on would be too much for both writer and reader.

Within McLoughlin's arsenal of diversionary tactics, it is the concept of the "parapolemic" which most usefully acts as a bridge between the rhetoric of war and contemporary ecological thought at work in Coetzee's *The Lives of Animals*. According to McLoughlin, the parapolemic amounts to "the discourse of the temporal and spatial borders of war" (140). Instead of the bloody trenches, the parapolemic novel of war focuses on the sidelines of conflict. McLouhglin then compares such diversions to the rhetorical device of apophasis, as

"diversions are apophatic: like the sculptor's mould or the artist's depiction of negative space, they represent war, as it were, in relief" (153). As an example of the parapolemic, McLoughlin cites Homer's *Iliad*:

> The multitude I could not tell or name, not even if ten tongues were mine and ten mouths and a voice unwearying, and the heart within me were of bronze, unless the Muses of Olympus, daughters of Zeus who bears the aegis, call to my mind all those who came beneath Ilios. (quoted in Loughlin, 135).

In this sense, Coetzee's treatment of the war against animals extends McLoughlin's parapolemic tradition, transforming the unspeakable violence of battle into an ecological register. Indeed, as we will see, Coetzee's narrative employs a variant of this parapolemic writing strategy; however, Costello focuses not on a typical war, but on the war against animals. Before considering Costello's explicit use of parapolemic technique, it is worth noting how she frames this war in relation to silence during her first public speech in the novella. Reflecting on humanity's ancient struggle with other species, she observes that "in the olden days the voice of man, raised in reason, was confronted by the roar of the lion, the bellow of the bull" (25). Here, Coetzee contrasts two modes of expression, namely the voice of reason and the animal roar, to signal the long-standing alignment of reason with power. Costello continues, "man went to war with the lion and the bull, and after many generations won that war definitively. Today these creatures have no more power. Animals have only their silence left with which to confront us" (25). The concept of the hyperobject is another way of understanding Coetzee's focus on silence.

**The Meat Industry as a Hyperobject**

In recent years, there have been several attempts to read Coetzee's *The Lives of Animals* from the perspective of contemporary ecology, and as Katarzyna Nowak-McNeice notes, "that Coetzee criticism would evolve from postcolonial criticism toward ecocritical thought is no surprise" (3). In his "Hyperobjects and Creativity," the philosopher Timothy Morton outlines the concept of the hyperobject clearly, "a hyperobject is a name I invented for something that is so vastly distributed in time and space, relative to the observer, that we might not think it's even an object at all" (1). Unsurprisingly, the hyperobject has proved to be a useful tool for contemporary ecologists. For example, Jody Emel and Harvey Neo explicitly cast the global meat industry as "one of Timothy Morton's 'hyperobjects,'" emphasizing its viscosity, nonlocality, and nonhuman temporalities as well as its entanglements with climate change, deforestation, biosecurity, and sprawling infrastructures of production and consumption (7).

This conceptualisation of the meat industry as a hyperobject provides an intellectual framework for understanding Costello's arguments in *The Lives of Animals*. Returning to her first speech, she begins with the assertion, "Let me say it openly: we are surrounded by an enterprise of degradation, cruelty, and killing which rivals anything that the Third Reich was capable of" (21). Coetzee's use of this comparison is intentionally controversial. The parallel foregrounds the

industrial scale and bureaucratic detachment that define both forms of violence, confronting us with the moral implications of routinised killing. Costello continues, "indeed dwarfs it, in that ours is an enterprise without end, self-regenerating, bringing rabbits, rats, poultry, livestock ceaselessly into the world for the purpose of killing them" (21). Here, her rhetoric moves beyond historical analogy into the realm of scale and temporality, suggesting a system that exceeds human control and persists across generations. The "enterprise without end" she describes mirrors Morton's hyperobject, a phenomenon so vast and entangled that it resists localisation, spreading through the economic, cultural, and biological infrastructures of modern life. Elsewhere, the hyperobject of the meat industry can only be spoken of in parapolemic terms, particularly through what Kate McLoughlin identifies as apophasis. Early in her lecture Costello announces, "In addressing you on the subject of animals, I will pay you the honor of skipping a recital of the horrors of their lives and deaths" (19). This refusal to narrate directly is not a softening of her claim but a tactical diversion that gestures towards what cannot, or will not, be fully represented. She continues, "Though I have no reason to believe that you have at the forefront of your minds what is being done to animals at this moment in production facilities (I hesitate to call them farms any longer), in abattoirs, in trawlers, in laboratories, all over the world, I will take it that you concede me the rhetorical power to evoke these horrors and bring them home to you with adequate force" (19). Here Costello exemplifies McLoughlin's apophatic war writing, where the violence is indicated through its periphery, with the onus placed on the audience to imagine the absent scenes. Her final reminder that "the horrors I here omit are nevertheless at the center of this lecture" (19) completes the movement towards Morton's hyperobject: the slaughter remains central yet unseen, dispersed across global sites, temporally extended and resistant to direct depiction, a hidden war whose very scale inspires silence.

**A Final Silence**

The novella concludes following Costello's repeated failures to convince her audience of her perspective. As her son drives Costello to the airport, the novelist lapses into a final silence, as her son is forced to speak for her. The narrative captures this lacuna through interior monologue: "What does she want? he thinks. Does she want me to answer her questions for her" (69). Though this final silence might be read as mere verbal defeat, the perspectives of the parapolemic and the hyperobject offer alternative interpretation: the scale of the meat industry is such that Costello cannot articulate its horrors directly, and nor can the novella. As in a great war story, the horrors of war are not shown on the frontlines, but rather parapolemically, through a character situated on the outskirts of the horror, as she delivers a lecture at a prestigious university.

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**Residual Dynamics in Stock-Return Forecasting: Factor, Stochastic, and ML Hybrids**
**By Mikhail Varlamov**

**Abstract**

Traditional models like Fama-French often fail to capture the nonlinear and stochastic nature of modern financial markets. This research investigates whether integrating Geometric Brownian Motion (GBM) drift, jump diffusion, and robust regression can enhance the explanatory power of factor-based return models. Using monthly U.S. equity data from 2010 to 2024, we calculated expected returns with the Fama-French five-factor model and defined alpha as the residual between actual and model-predicted returns. We then compared nine model variations combining Fama-French with GBM, jump diffusion, and different regression methods such as RANSAC, Random Forest, and XGBoost under rolling 48-month training and 6-month testing windows. Results showed that models incorporating stochastic and nonlinear dynamics more accurately reflected return behavior across sectors and time periods. Overall, our findings suggest that integrating stochastic and machine-learning approaches provides a more realistic representation of modern markets and offers a path toward improving return prediction and understanding residual risk in quantitative finance.

**Introduction**

Forecasting stock returns has been a longstanding challenge in financial economics and quantitative finance. Many past decades have been dedicated to researching the valuation of options (Black & Scholes, 1973), but consistently predicting excess returns in public markets remains elusive due to the turbulent, stochastic nature of asset prices and the dynamic interaction of macroeconomic and firm-specific factors. This difficulty gave rise to the development of both theoretical asset pricing models and machine learning approaches to understand and model expected returns in an improved fashion (Gu et al., 2020).

Each model in this study approaches modeling return forecasting in a different manner. The Fama-French Five-Factor model explains returns using exposures to systematic risk factors: market, size, value, profitability, and investment (Fama & French, 2015). Furthermore, it captures long-term patterns in equity performance across multiple sectors. The Geometric Brownian Motion (GBM) model, on the other hand, depicts price evolution as a continuous stochastic process described by drift (the average growth rate) and volatility (the degree of randomness) (Black & Scholes, 1973), reflecting the random and messy nature of asset movements. Finally, the jump-diffusion model extends the GBM by incorporating sudden and discontinuous price jumps that represent extreme market shocks or information events (Merton, 1976). All together, these models capture both systematic risk structure and stochastic market patterns, providing a deeper baseline for analyzing how returns deviate from their expectations.

Among classical models, the Fama-French Five-Factor model (Fama & French, 2015) is a commonly adopted framework for estimating expected returns that are based on firm-level exposures to systematic risk factors. However, traditional linear models often underperform

when tasked to capture the nonlinearities and structural breaks in market behavior (Gu et al., 2020). In recent years, researchers and practitioners have increasingly explored machine learning methods to enhance predictive performance and robustness in financial time series modeling.

This paper examines the behavior of residual returns, or in other words, the differences between predicted and actual equity returns, across nine model pipelines. Three regression models (RANSAC, Random Forest, and XGBoost) are tested in combination with three sets of predictors: (i) expected returns from the Fama–French 5-factor model, (ii) Fama–French factors combined with Geometric Brownian Motion (GBM) drift and volatility estimates, and (iii) Fama–French + GBM features further augmented with jump-diffusion measures of extreme return events (Merton, 1976). A rolling-window procedure is used, with 48 months of training and a 6-month test horizon for the Fama–French regressions, and a 36-month lookback window for GBM-based features.

Results are analyzed using residual time-series plots and histograms to identify periods where models systematically under- or over-predict returns, as well as to assess the frequency and magnitude of extreme errors. This highlights not just the average predictive power, but also the stability and robustness of each model under different market conditions.

By specifically focusing on the structure and dynamics of residual returns rather than accuracy metrics, this analysis addresses a key flaw in prior research, which usually evaluates models purely on the basis of overall predictive performance. Predictive performance metrics such as MSE or MAE can provide an overview of the average magnitude of residuals, but they usually do not make it clear how and when models fail. Analyzing the framework and temporal patterns of residuals reveals the biases hidden within the systems, with consistent underprediction during high-volatility time periods or overprediction in fairly stable markets being some of the examples of these biases. This approach addresses the gap between statistical evaluation and economic perspectives, which highlights not only which models perform best when compared to each other, but also which ones remain reliable and accurate during volatile market conditions.

## Literature Overview

This section reviews the development of quantitative return forecasts, from academic factor models to their evolution in industry practice. It will mainly focus on traditional factor models and their limitations, the derivation and application of stochastic modeling techniques in finance, the role of machine learning in factor-based prediction, and case studies of Renaissance Technologies with other leaders in applying these approaches.

## Existing Research on Factor Models and Return Prediction

### Traditional Factor Models

The Capital Asset Pricing Model (CAPM), developed by Sharpe (1964) and Lintner (1965), represents the first formal framework that connects expected returns to a single systematic risk factor - the market portfolio's excess return over the risk-free rate. It makes the assumption that the sole driver of cross-sectional differences in expected returns is exposure to this market factor, measured by beta. The CAPM provided a frugal, intuitive model and created a foundation for modern portfolio theory. However, research performed in the 1970s and 1980s uncovered persistent anomalies that made the CAPM fall short of expectations. The size effect (Banz, 1981) demonstrated that small-cap stocks tended to outperform large-cap stocks, even after controlling for beta. The value effect (Stattman, 1980) showed that firms with high book-to-market ratios outperformed growth firms, again unexplained by CAPM.

To improve the performance of the model, Fama and French (1993) expanded the CAPM into the Three-Factor Model, which reinforces the market factor with two additional risk factors: SMB (Small Minus Big) to account for the size effect, and HML (High Minus Low) to capture the value effect. After these were included, these factors greatly improved explanatory power in cross-sectional regressions of stock returns. Later, Carhart (1997) appended a momentum factor (UMD) to consider the tendency of past winners to continue outperforming. Fama and French (2015) then created an extension to the framework, resulting in a five-factor model by accounting for two additional factors: profitability (RMW) and investment (CMA), aligning the model more closely with industry standards.

These multi-factor models function as the cornerstone of academic finance. In today's world, they are often used for many analytical methods, including portfolio performance evaluation and empirical asset pricing studies.

**Limitations of Traditional Models**

Despite their influence, traditional factor models have several limitations. First, linearity assumptions lead these models to represent returns as a linear combination of factor exposures, which potentially results in missing nonlinear relationships between factors and returns (Gu et al., 2020). In the real world, markets may experience interaction effects and threshold dynamics—for instance, the value premium may behave differently during recessions versus expansions.

Second, traditional factor models only rely on continuous return assumptions derived from Geometric Brownian Motion (GBM) (Black & Scholes, 1973). This assumption implies smooth price paths and normally distributed returns, which is, at times, inconsistent with historical evidence. Real market price paths and returns exhibit fat tails, volatility clustering, abrupt price jumps, and more randomness (Merton, 1976). Such features can lead to the underestimation of tail risk and mispricing in derivative markets.

Third, factor instability is a problem: estimated factor premia are subject to change substantially over time, particularly during market crises when relationships between risk factors and returns tend to collapse (Fama & French, 1993). Ultimately, orthodox factor models very often have a long-term focus and are not optimized for capturing short-term returns and

high-frequency inefficiencies. Unfortunately, this leaves many opportunities in certain segments of the market unexploited.

Modern models, specifically those that structurally balance machine learning with stochastic extensions, attempt to overcome these obstacles by capturing nonlinearities and regime-dependent behaviors in financial data (Gu et al., 2020). Machine learning techniques, including Random Forests and XGBoost, can model complex, interaction-driven relationships between factors without assuming linearity, while extensions like jump-diffusion processes make up for discontinuous market movements and shocks.

## From Academia to Industry: Evolution of Quantitative Strategies

### Renaissance Technologies—Pioneering Applied Quant

Founded in 1982 by former mathematician Jim Simons, his firm, Renaissance Technologies, is commonly credited with introducing the scientific method into finance at an unprecedented scale (Zuckerman, 2019). Renaissance's prominent Medallion Fund became well-known for its never-before-seen performance—annualized gross returns exceeding 60% before fees—and for the secrecy surrounding its strategies (Barron's, 2024). While academic factor models might utilize a handful of risk factors, Jim Simons and Renaissance took the concept of return decomposition and expanded it dramatically. Renaissance analyzed colossal datasets covering price, volume, corporate events, and alternative signals, transforming them into thousands upon thousands of predictive features.

Renaissance Technologies' approach adapted statistical learning methods from fields such as cryptography and pattern recognition, in which Simons and his colleagues were experts. This meant exploring more than simply linear regression methods. They transitioned to nonlinear transformations, high-dimensional modeling, and interaction effects. Moreover, their team incorporated stochastic processes, including Geometric Brownian Motion and jump models, into their algorithms to improve the accuracy of the observed return distributions (Zuckerman, 2019; Business Insider, 2025). Their success demonstrated that the ideas from academic finance could be enhanced through advanced mathematics and computational power.

### Citadel—Multi-Strategy Quant Integration

In 1990, Ken Griffin founded the famous quant firm Citadel. The firm evolved from a convertible bond arbitrage shop into one of the most sophisticated hedge funds globally. Their Global Quantitative Strategies (GQS) division develops and backtests models before deploying them into real-time trading.

Unlike Renaissance, which is known for extremely high turnover strategies, Citadel creates a mix between long-horizon factor models for strategic positioning and short-horizon statistical models for seizing sudden inefficiencies. Citadel's approach makes sure that factor risk models inform strategic asset allocation and risk budgeting, while machine learning algorithms optimize signal generation and trade execution. The firm also integrates alternative datasets into

its predictive models: order book microstructure, sentiment analytics, and event-driven indicators. These capture information that traditional financial statements, such as 10-Ks or 10-Qs, or price data cannot. Order book data provides real-time liquidity and market pressure, which in turn improves short-term execution techniques. Sentiment analytics taken from news or social media give insight into the psychology and expectations of the market, which often precede price movements. Alongside this, event-driven indicators like earnings announcements allow the models to adapt to sudden information shocks. Combining these factors results in an extremely powerful multi-strategy platform capable of generating alpha across market regimes.

**Stochastic Modeling in Quantitative Finance**

**Geometric Brownian Motion (GBM)**

GBM is one of the foundational stochastic processes in finance, modeling stock prices as:

$$dS_t = \mu S_t dt + \sigma S_t dW_t$$

Where μ is the drift rate, σ is the volatility, and $W_t$ is a Wiener process. GBM underlies the Black-Scholes-Merton option pricing model and a lot of the early theoretical work in asset pricing. Its popularity of use is mostly due to its tractability and the fact that it produces lognormally distributed prices, but there is a catch - it assumes continuous paths and constant volatility. This limits its ability to model real-world price dynamics.

**Jump Diffusion Models**

To combat GBM's shortcomings, Merton (1976) introduced the jump diffusion model:

$$dS_t = \mu S_t dt + \sigma S_t dW_t + J_t S_t dq_t$$

Where $J_t$ represents the percentage jump in price and $q_t$ is a Poisson process with intensity ג. This model allows for sudden and discrete changes in price by considering extreme market events, such as earnings releases or flash crashes. In a factor modeling context, jump components can be added into factor return dynamics to capture unexpected repricing occurrences, which standard regressions might misassign to residual noise.

**Robust Regression and Nonlinear Extensions**

When estimating factor loadings, ordinary least squares (OLS) is often sensitive to outliers or non-stationary periods. Powerful regression techniques, such as RANSAC, mitigate this by iteratively fitting the model to subsets of data, reducing the effect of abnormal observations. Thus, nonlinear extensions of factor models can produce more flexible relationships between factors and returns, which consequently improves predictive power when combined with stochastic process features (Gu et al., 2020).

## Machine Learning Applications in Factor-Based Prediction

Machine learning provides many algorithms with the capability of capturing complex, nonlinear dependencies that traditional factor models do not (Gu et al., 2020). Random Forests improve return prediction by aggregating results from many decision trees. This reduces overfitting and captures intricate interactions between financial variables that could potentially influence asset returns. Gradient Boosting Machines (e.g., XGBoost) build models sequentially, where each tree corrects the errors of the one before it, enabling the algorithm to detect subtle patterns and improve accuracy in predicting excess returns. Neural Networks offer even greater predictive power by approximating highly nonlinear relationships and temporal dependencies within financial time series. Ultimately, SVM's are incredibly effective at classifying binary tasks. In finance, it is particularly effective in estimating stock returns, predicting either a positive or a negative price path. They perform such tasks by constructing separating hyperplanes that best distinguish classes in high-dimensional feature spaces. All together, these different algorithms expand the possibilities of financial predictive modeling by uncovering relationships that linear frameworks simply cannot detect, thereby improving both the precision and adaptability of return estimates.

In practice, leading quant firms, such as the previously mentioned Renaissance Technologies and Citadel, use hybrid approaches where outputs from factor models serve as features for machine learning models (Zuckerman, 2019). This strategy leverages the economic understanding of factor models while also allowing data-driven strategies to take into account leftover patterns. Integrating these approaches can produce more robust predictions and facilitate risk management by decomposing model forecasts into theory-driven and purely statistical components.

The evolution of quantitative return forecasts demonstrates a clear trajectory of increasing sophistication and adaptability. Early academic factor models created a foundation for systematic risk-return analysis through linking asset performance to common economic drivers (Sharpe, 1964; Lintner, 1965). Stochastic modeling then came to deal with the limitations of continuous and purely linear frameworks. It combined stochastic modeling with volatility dynamics, jumps, and nonlinear return patterns that better reflected real market behavior. The more recent rise of machine learning further deepened the field by introducing algorithms that are capable of learning from enormous and messy datasets (Gu et al., 2020). It also introduced the possibility of capturing intricate dependencies across time and factors. In practice, industry leaders such as Renaissance Technologies (Zuckerman, 2019) and Citadel (Citadel, n.d.-a, n.d.-b) have combined these theoretical and computational advances. They were able to merge factor-based reasoning, stochastic processes, and machine learning into high-performance predictive systems. Building upon this evolution, the following section outlines the methodological structure used in this study to evaluate and compare the predictive behavior of these models.

## Methodology

This section outlines the models, data sources, and estimation procedures used in this study. We begin with the baseline Fama-French Five-Factor Model, which acts as the framework for estimating stock returns. The following subsections describe the statistical framework used to estimate coefficients, the derivation of alpha, and extensions incorporating stochastic modeling and machine learning.

**Model Specification: Fama-French Five-Factor Model**

The baseline model follows the specification of Fama and French (2015):

$$R_{i,t} - R_{f,t} = \alpha_i + \beta_{MKT}(R_{MKT,t} - R_{f,t}) + \beta_{SMB}SMB_t + \beta_{HML}HML_t + \beta_{RMW}RMW_t + \beta_{CMA}CMA_t + \epsilon_{i,t}$$

Where:

- $R_{i,t}$: return on asset $i$ at time $t$
- $R_{f,t}$: risk-free rate at time $t$
- $R_{MKT,t}$: return on the market portfolio
- $SMB_t$: size factor (small minus big)
- $HML_t$: value factor (high minus low)
- $RMW_t$: profitability factor (robust minus weak)
- $CMA_t$: investment factor (conservative minus aggressive)
- $\alpha_i$: abnormal return (intercept term)
- $\epsilon_{i,t}$: error term

Here, the subscript *i* denotes the specific asset or firm, and *t* represents the time period. The *f* identifies the risk-free rate used as a foundation for excess return calculations, while *MKT* represents the overall market factor capturing systematic risk. Together, these variables define how each asset's excess return is explained by its exposure to common risk factors.

The five-factor model improves on earlier specifications by including firm-level profitability and investment patterns, which academic evidence shows are priced risk factors (Fama & French, 2015).

**Data Sources and Sample**

The analysis uses daily equity return data obtained from Yahoo Finance for all constituents of the S&P 500 index, combined with factor returns and the risk-free rate from the Kenneth French data library. The sample period spans January 2015 to June 2025, capturing both prolonged bull markets and high-volatility events, ensuring that models are evaluated under

diverse market conditions. Restricting the sample to the S&P 500 provides consistency in liquidity, data quality, and relevance to institutional investors.

Prior to analysis, multiple data preprocessing and cleaning steps were performed to ensure accuracy and comparability across all inputs. Tickers with missing or incomplete price histories were excluded, as Yahoo Finance occasionally omits delisted or newly added S&P 500 constituents. All datasets, including equity returns, Fama-French factors, and the risk-free rate, were aligned by trading data to maintain temporal consistency. Log returns were computed from adjusted closing prices, which already account for dividends and stock splits, ensuring return measures reflected true investor gains. During dataset merging and rolling-window calculations, rows with missing values (NaNs) were removed to avoid distortions in model training. Finally, all explanatory variables, including factor exposures and GBM-derived features, were standardized to ensure uniform scaling across predictors to improve model convergence and interpretability.

**Rolling-Window Procedure**

A rolling-window framework is employed to ensure that parameter estimates adapt to evolving market dynamics. For the baseline Fama–French regressions, each stock's factor loadings are estimated using a 48-month training window followed by a 6-month test horizon. This balance provides sufficient data for stable coefficient estimation while remaining responsive to structural shifts in factor premia. Previous research explicitly notes that the "standard 60-month window," with countless empirical studies utilizing 60-month rolling regressions, justifies our choice of using this time window (Ang & Kristensen, 2009). For features derived from Geometric Brownian Motion (GBM), a 36-month lookback period is used to compute drift and volatility, as this horizon is able to capture medium-term market behavior. That time period is long enough to smooth out short-term mess but short enough to remain sensitive to changes in volatility regimes and price trends. A shorter time window would provide inaccurate drift estimates in terms of volatility, while a longer one could obscure shifts in market momentum (Brigo et al., 2007). All windows roll forward one month at a time, producing overlapping estimation and test periods that approximate real-time forecasting.

**Estimation Procedure**

The model parameters are estimated using Ordinary Least Squares (OLS) regression:

$$\hat{\beta} = (X^{\top}X)^{-1}X^{\top}Y$$

Where:

- $Y$ is the vector of excess returns $R_{i,t} - R_{f,t}$.

- $X$ is the matrix of regressors consisting of $(R_{MKT,t} - R_{f,t})$, $SMB_t$, $HML_t$, $RMW_t$, $CMA_t$, and a constant.

For each stock in the dataset, OLS regression yields estimates of the factor sensitivities ($\beta_{MKT}$, $\beta_{SMB}$, $\beta_{HML}$, $\beta_{RMW}$, $\beta_{CMA}$) and the intercept ($\alpha_i$).

**Alpha Computation**

Alpha measures the portion of a stock's return not explained by its factor exposures. It is computed as:

$$\hat{\alpha}_i = \bar{R}_i - \sum_{k=1}^{K} \hat{\beta}_{ik} \bar{F}_k$$

Where:

- $\bar{R}_i$ is the mean excess return of stock $i$.
- $\bar{F}_k$ is the mean return of factor $k$ (for $k = MKT, SMB, HML, RMW, CMA$).
- $\hat{\beta}_{ik}$ is the estimated loading of stock $i$ on factor $k$.

In practice, the regression intercept term from OLS provides a direct estimate of the mean excess return of the stock $\alpha_i$.

**Extensions: Stochastic Process Features**

To improve upon the baseline model, we later incorporate features derived from stochastic processes:

- Geometric Brownian Motion (GBM) for continuous price dynamics:

$$dS_t = \mu S_t dt + \sigma S_t dW_t$$

- Jump Diffusion (Merton, 1976) for discontinuous shocks:

$$dS_t = \mu S_t dt + \sigma S_t dW_t + J_t S_t dq_t$$

These models generate additional features, such as volatility-adjusted returns and jump frequency measures, that may enhance alpha prediction.

**Robust Regression and Machine Learning**

To complement the five-factor model, we implement extensions that capture nonlinearities and enhance robustness to noisy financial data.

- RANSAC Regression—mitigates sensitivity to outliers by iteratively fitting the model to random subsets of data, ensuring stable factor loading estimates during volatile periods.

In this study, the maximum iteration count was set to 1000 and used a residual threshold of 1.5 standard deviations from the median.

- Random Forest—ensembles 500 decision trees, each trained on 70% bootsrapped samples and evaluated on the remaining 30% out-of-bag data. The model then also limits the maximum tree depth to 8 in order to prevent overfitting.
- XGBoost—this model uses 300 boosting rounds with early stopping after 30 rounds of no improvement on the validation set. The learning rate (η) is set to 0.05, the subsample ratio to 0.8, and the maximum depth to 5. We then divide the data using a rolling-window cross-validation scheme: 48 months of training and a 6-month test horizon. This ensures that no future information leaks into past estimations. Within each training window, 20% of the data is reserved for validation in order to tune hyperparameters and implement early stopping.

This configuration creates a balance between the bias-variance tradeoffs and allows it to be compared with the linear Fama-French baseline while adapting dynamically to the changes in the market.

**Implementation**

In this framework, outputs from the five-factor regressions are merged together with stock-level characteristics such as valuation metrics and volatility measures. That includes estimated alphas, factor loadings (β), and realized factor returns. This enhanced feature set is then used to train ensemble models, allowing us to compare predictive performance between classical econometric methods and machine learning approaches.

**Results**

The baseline **Fama-French (FF-only)** models showed wider residual variation and more frequent outliers.

- **RANSAC (FF-only)** contained most residuals within ±0.004, though spikes up to +0.008 occurred (e.g., Mar 2022). The distribution was centered near zero but with a slight right tail.

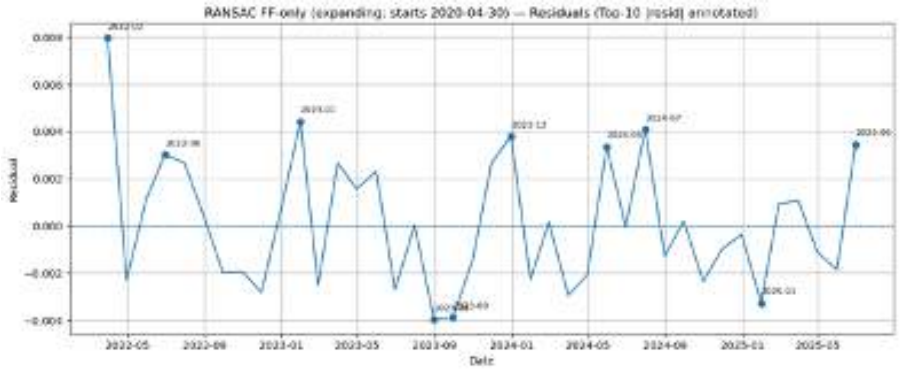


*Figure 1: Residual Returns Over Time – Fama-French + RANSAC Model*

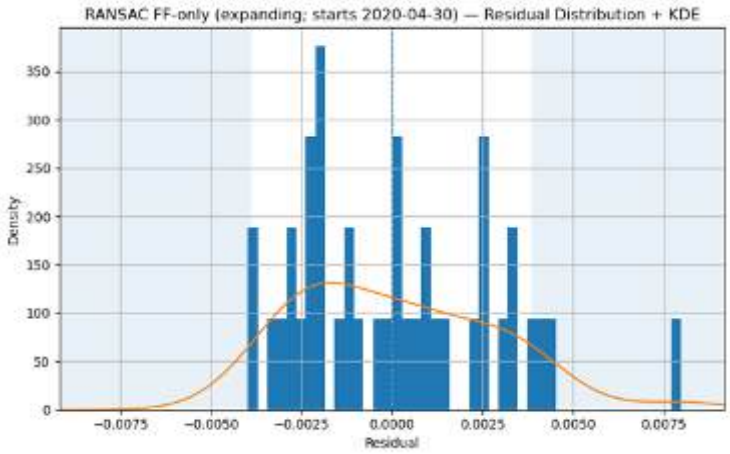



*Figure 2: Residual Return Distribution – Fama-French + RANSAC Model*

· **Random Forest (FF-only)** displayed broader swings (–0.012 to +0.012), with notable outliers in Oct–Nov 2024. The distribution was flatter, indicating greater noise.

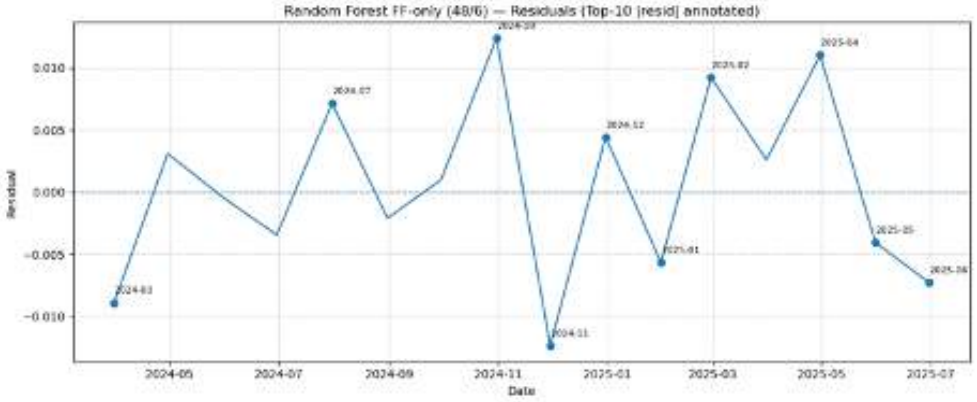



*Figure 3: Residual Returns Over Time – Fama-French + Random Forrest Model*

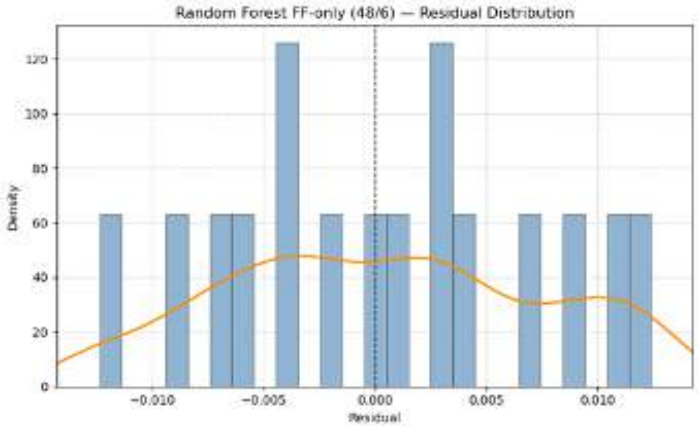



*Figure 4: Residual Return Distribution – Fama-French + Random Forrest Model*

· **XGBoost (FF-only)** produced the widest tails (–0.010 to +0.010), with large misses in 2021–2022. While clustering remained around zero, the distribution revealed heavier tails than RANSAC.

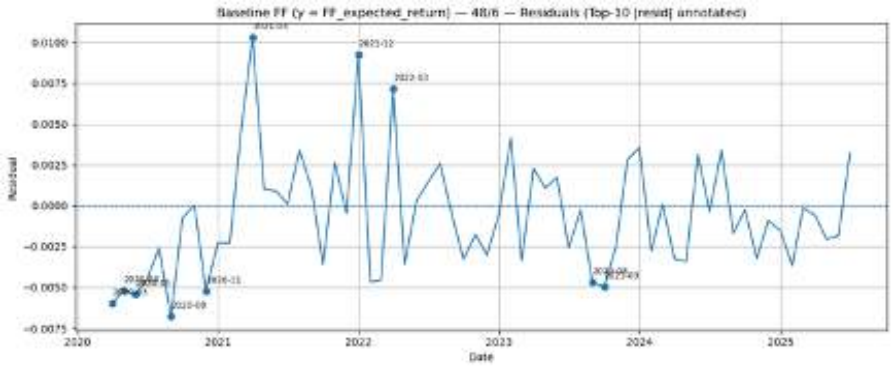



*Figure 5: Residual Returns Over Time – Fama-French + XGBoost Model*

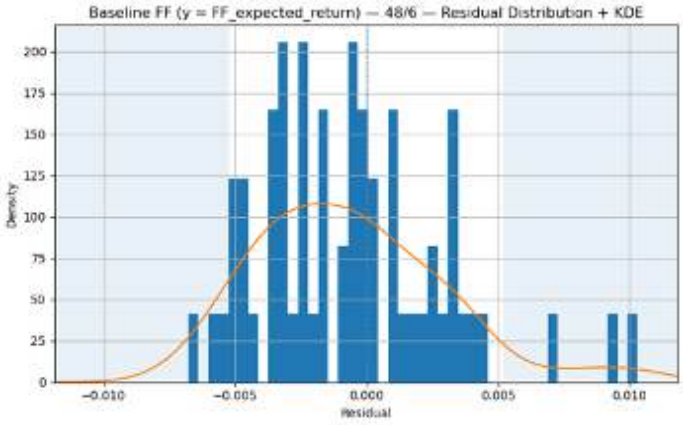


*Figure 6: Residual Return Distribution – Fama-French + XGBoost Model*

Incorporating **geometric Brownian motion (GBM)** reduced dispersion across models.

- **RANSAC (FF+GBM)** showed tightly clustered residuals (–0.004 to +0.006) with symmetry around zero. The distribution confirmed stability, with most values concentrated within ±0.002.

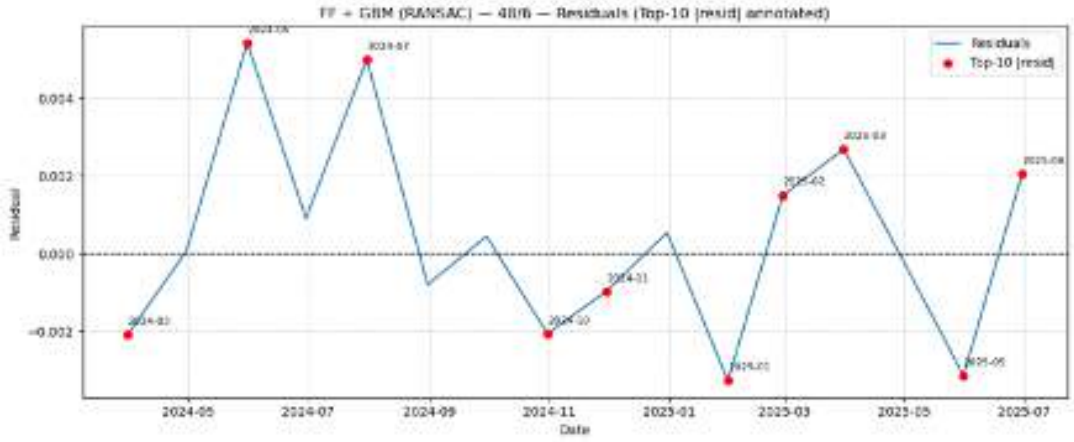



*Figure 7: Residual Returns Over Time – Fama-French + GBM + RANSAC Model*

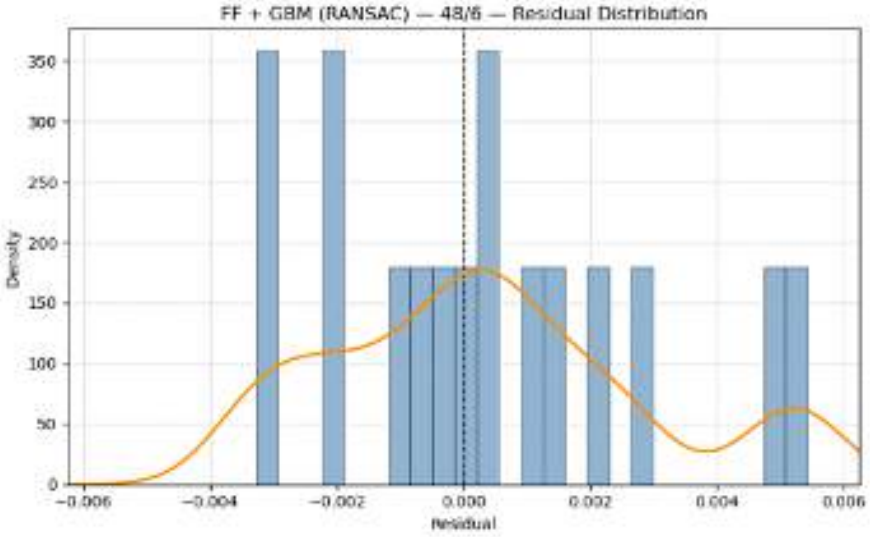



*Figure 8: Residual Return Distribution – Fama-French + GBM + RANSAC Model*

- **Random Forest (FF+GBM)** captured nonlinearities but widened the residual spread (–0.012 to +0.012). The distribution was more dispersed than RANSAC but less skewed than XGBoost.

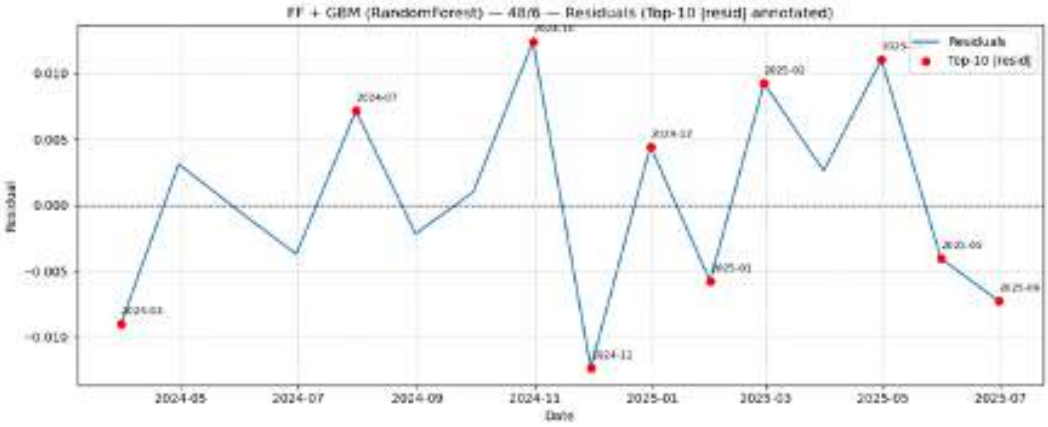



*Figure 9: Residual Returns Over Time – Fama-French + GBM + Random Forrest Model*

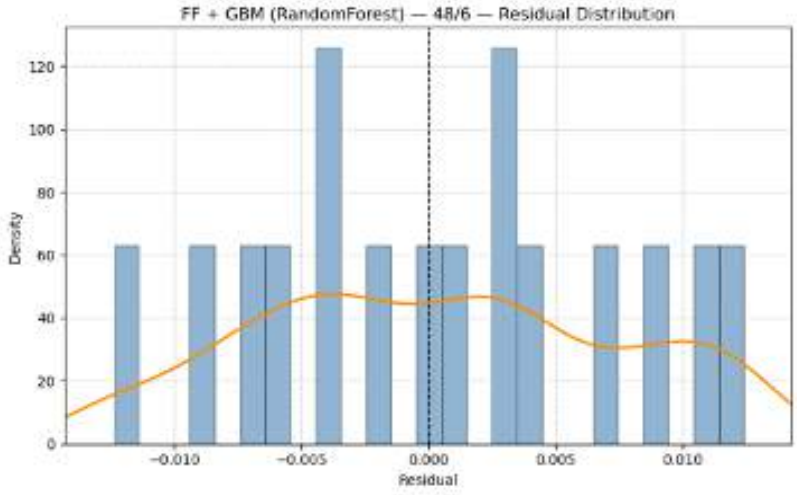



*Figure 10: Residual Return Distribution – Fama-French + GBM + Random Forrest Model*

· **XGBoost (FF+GBM)** achieved strong fit in most periods but showed vulnerability to large negative outliers (as low as -- 0.017 in Jan 2025). The distribution skewed negative with heavier tails.




*Figure 11: Residual Returns Over Time – Fama-French + GBM + XGBoost Model*

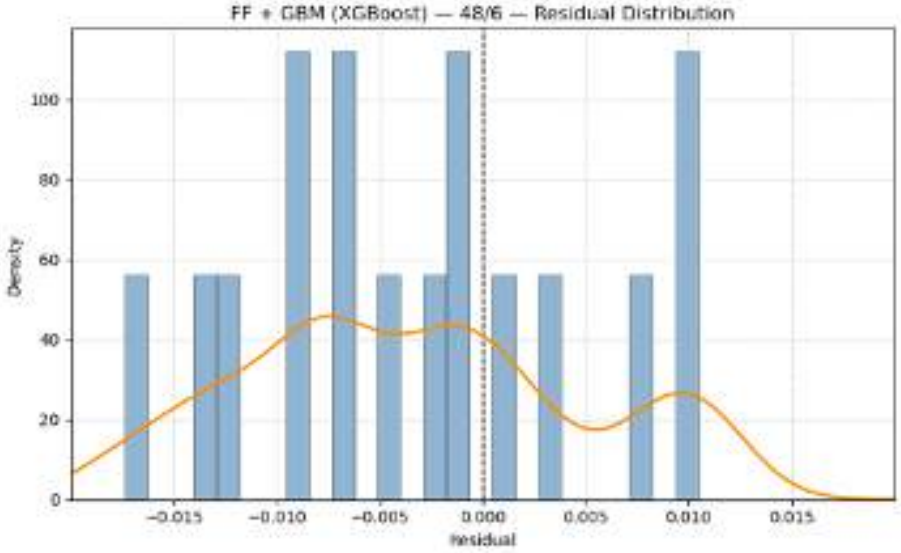



*Figure 12: Residual Return Distribution – Fama-French + GBM + XGBoost Model*

The most complex models, **FF + GBM + Jump Diffusion (JD)**, delivered the best overall performance but varied by estimator.

- **RANSAC (FF+GBM+JD)** produced stable residuals clustered within –0.004 to +0.006, with only a few short-lived spikes (e.g., May 2024: +0.0056). The distribution was symmetric and narrow.

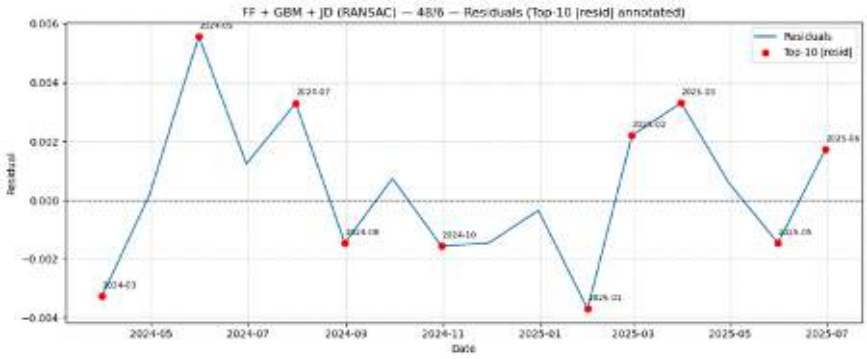



*Figure 13: Residual Returns Over Time – Fama-French + GBM + JD + RANSAC Model*

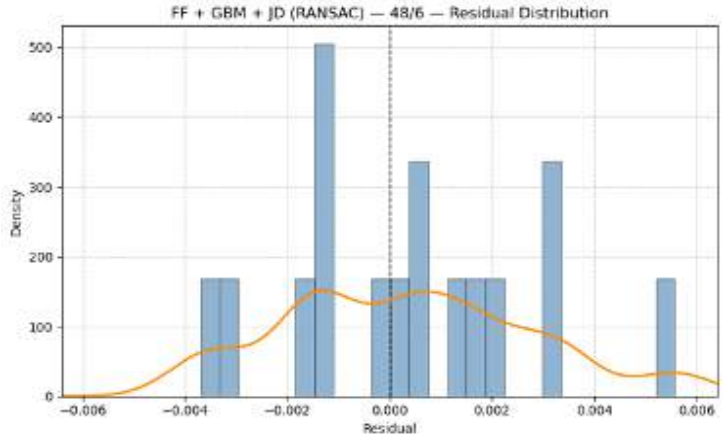



*Figure 14: Residual Return Distribution – Fama-French + GBM + JD + RANSAC Model*

· **Random Forest (FF+GBM+JD)** showed wider extremes (–0.023 to +0.020) during 2022–2023, with a more dispersed distribution than the RANSAC or XGBoost versions.

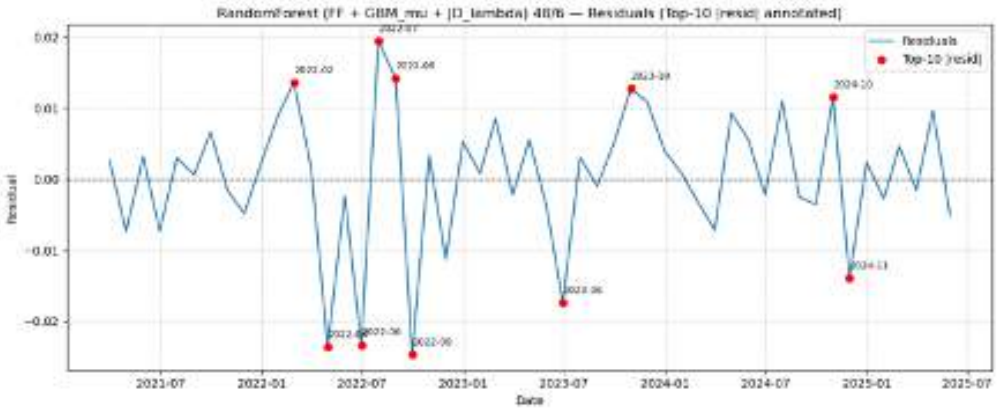



*Figure 15: Residual Returns Over Time – Fama-French + GBM + JD + Random Forrest Model*

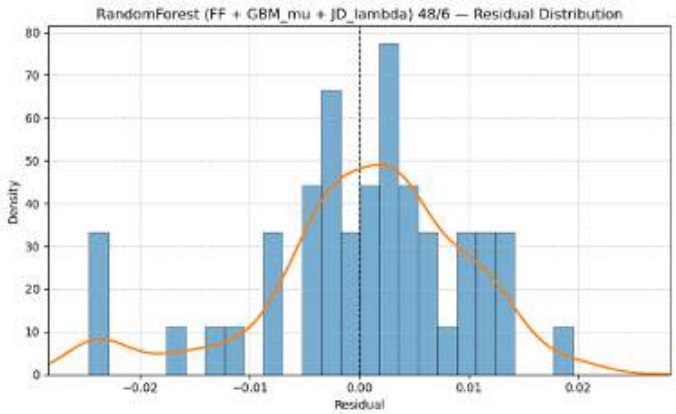



*Figure 16: Residual Return Distribution – Fama-French + GBM + JD + Random Forrest Model*

· **XGBoost (FF+GBM+JD)** minimized residuals for most periods, with 80% of errors within ±0.01. However, it generated occasional large outliers, including Sep 2022 (+0.0316).

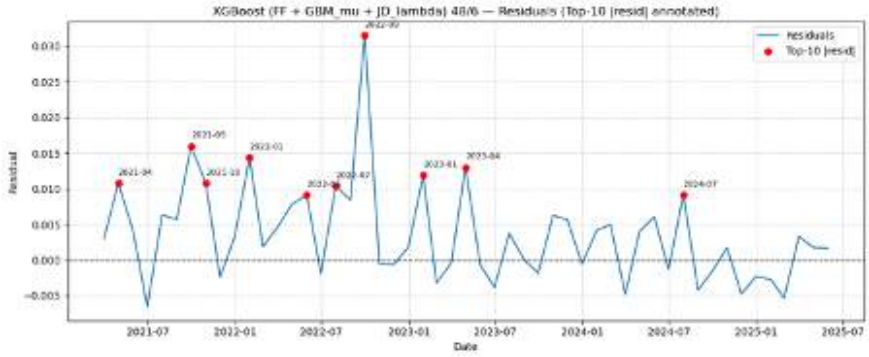



*Figure 17: Residual Returns Over Time – Fama-French + GBM + JD + XGBoost Model*

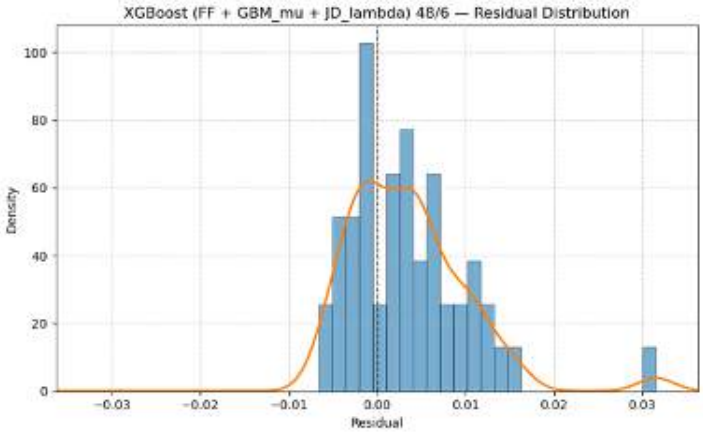



*Figure 18: Residual Return Distribution – Fama-French + GBM + JD + XGBoost Model*

Across all models, FF-only produced the widest dispersion, GBM reduced variance, and the combination of GBM with jump diffusion yielded the tightest residual clustering, especially under RANSAC and XGBoost.

**Conclusion and Discussion**

The comparative results show that models capture residual returns in very different ways. The FF-only baselines showed that factor models can explain systematic risk, but they don't explain a lot of variation, especially when the market is stressed. RANSAC regression was the most stable of these because it reduced the effect of outliers. On the other hand, Random Forest and XGBoost models had more dispersion, which shows how sensitive they are to noise when they are used without stochastic enhancements.

By making the residual spreads narrower and capturing path-dependent behavior, adding geometric Brownian motion boosted the model's performance. RANSAC, once again, provided consistent stability, while XGBoost adjusted well to nonlinearities but generated significant negative outliers. Random Forest found a middle ground by giving users more freedom, but this affected another aspect: higher volatility in the residuals. Adding jump diffusion made the models even stronger by dealing with shocks to returns that are not continuous. The XGBoost specification had the lowest residuals overall, but it sometimes went too far in extreme situations. RANSAC, on the other hand, kept the narrowest and most balanced distribution.

The results indicate that hybrid models integrating factor structures, stochastic processes, and machine learning yield quantifiable improvements when compared to more traditionally used methods. RANSAC is best when robustness and interpretability are important. XGBoost has the best predictive accuracy but comes with some tail risk. Random Forest is more flexible but has more noise. In the end, the results show that no one model is best in all areas. The best choice depends on the right mix of accuracy, stability, and complexity for a given application.

From a practical perspective, these findings indicate that portfolio managers and quantitative traders should not rely solely on factor models or machine learning in isolation. RANSAC and other strong methods help protect against big changes in the market. On the other hand, XGBoost and other more flexible algorithms can find more predictive power when the market behaves as expected. A mixed method that combines strength and flexibility might be the best way to make alpha in practice.

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# A Review Analysis of Concrete Optimisation for Strength and Sustainability Using Machine Learning (ML) By Ishan Verma


## Abstract

Concrete production is a significant contributor to the global Carbon dioxide emissions. This happens due to energy energy-intensive processes of manufacturing Portland cement. Sustainable construction faces a challenge of achieving low carbon concrete without compromising mechanical properties. This review examines how machine learning (ML) models can optimise the concrete mix designs by predicting compressive strength and embodied carbon dioxide. Three different classes of ML techniques are evaluated: regression models, Artificial neural networks, and ensemble methods. Linear regression offers interpretability but fails in capturing non-linear relationships between mix constituents and performance. Comparative studies across the board suggest no single model performs best universally. Model selection depends on dataset size, complexity, desired interpretability, and design objectives. Overall, ML gives an efficient pathway for researchers to explore large design spaces, identify low carbon alternatives, and accelerate the transition towards data-driven, sustainable concrete technologies.



## Keywords

Concrete, Machine Learning, CO2 emissions, Sustainable construction, Neural networks


## 1. Introduction

Concrete stands out as the top building material used everywhere in the world. Its production plays a big role in $CO_2$ emissions. Cement making alone takes up around eight percent of those emissions. The real problem comes down to cutting that carbon footprint. We still need to keep the concrete's mechanical strength solid. That balance matters a lot in sustainable engineering work. Most of the embodied $CO_2$ in concrete traces back to Portland cement production. That process demands tons of energy. It also releases $CO_2$ when calcining the clinker. Compressive strength gets checked at twenty-eight days usually. That measure helps ensure the concrete holds up structurally. In the past, people boosted their strength by adding more cement or using extra energy. Those steps just ramped up the $CO_2$ output even more. So, we must fine-tune concrete mix designs now. The goal involves lower carbon and higher strength. That push supports net-zero aims in construction. Machine learning advancements lately give fresh tools for this tough optimization job. Researchers have tried different ML models. Regression methods work well. Artificial neural networks show promise, too. Hybrid setups combine ideas for better results. These tools predict concrete properties. They also gauge environmental effects. Still, a big gap lingers in the research. No one knows for sure which techniques nail the predictions best. Factors like embodied $CO_2$ and compressive strength vary by dataset and setup. Earlier work proves ML can forecast durability and strength reliably. It even recommends mix tweaks, like mixing in fly ash or slag. Those changes cut $CO_2$ without much hassle. But comparisons of model accuracy remain rare in this field. Few efforts tie

predictions into multi-objective optimization setups. This paper steps in to fill that void. We look at how ML models can refine concrete mixtures. The focus stays on dropping $CO_2$ emissions. At the same time, we hold compressive strength high. Our aim involves spotting the top methods. Simple regressions might lead the way. Advanced ANNs could shine brighter. Hybrid models offer another angle. We test them all for high-strength, low-carbon concrete. Through this, we build a base for AI-guided designs. Low-carbon concrete can thrive here. Structural performance does not take a hit.

## 2. Methodology

### 2.1 Overview

We looked at three main types of machine learning models for optimizing concrete mixes in our review. These included conventional regression models, artificial neural networks along with other deep learning approaches, and hybrid or ensemble methods. For every category, we checked out key studies from existing research. Whenever we could, we pulled out specific performance numbers like R-squared, root mean square error, and mean absolute error for how well they predicted mixed results. We also showed how these models work using a sample dataset to make predictions clearer through visuals. Our main aim was to see how accurately each type handles forecasting two important outcomes. These are the concrete's compressive strength after 28 days in megapascals and its carbon dioxide emissions from cradle to gate in kilograms per unit volume or mass. We used the same input data for all and talked about which approaches fit best for helping with mixed design decisions.

### 2.2 Data Inputs and Preprocessing

Studies generally use standard mix proportions and curing time as input features for modeling concrete. Typical ones cover cement amount, water amount, coarse aggregate quantity, fine aggregate quantity, and dosages of supplementary cementitious materials such as fly ash or ground granulated blast furnace slag. Certain models add things like water to cement ratio or amounts of chemical admixtures, including superplasticizers. All these inputs are numerical and come on different scales, like kilograms for cement or water. Pretty much every study normalizes, or scales features, to help models learn more steadily. For instance, they might standardize inputs to have zero mean and unit variance or scale them between zero and one before training a neural network. In the example data we used, which comes from a subset of a published concrete dataset, each entry lists eight ingredients. These are cement, slag, fly ash, water, superplasticizer, coarse aggregate, fine aggregate, and age in days. Each also has a label for the measured 28-day compressive strength, which serves as the regression target. To handle embodied carbon dioxide, researchers usually calculate the output label based on known emission factors per kilogram of each ingredient. Cement tends to be the biggest source of emissions here. These carbon dioxide values often show up as kilograms per cubic meter of concrete or per ton of concrete. Regardless of the model kind, everyone stresses proper data

division between training and testing sets, plus cross-validation to check for good generalization. Things like K-fold cross-validation or a split of 70 percent training, 15 percent validation, and 15 percent testing appear often in neural network work. Some regression studies on smaller datasets go with leave-one-out validation.

## 2.3 Model Categories

### 2.3.1 Regression models

This covers multiple linear regression and various nonlinear techniques. In multiple linear regression, you fit a straight-line equation to forecast the output, whether strength or carbon dioxide, based on a weighted combination of inputs. These basic regressions run quickly and provide clear coefficients that show how variables affect carbon dioxide or strength. Still, they can miss the mark if the real relationship between inputs and outputs curves a lot in nonlinear ways. That is why people have tested polynomial regression with interaction terms and other nonlinear fits. For example, Jin and colleagues in 2018 used polynomial regressions including interactions to predict compressive and tensile strength in sustainable concrete. They found nonlinear versions beat the linear ones in accuracy. Researchers have applied other tailored regressions for modeling carbon dioxide uptake too. These often use exponential forms or adsorption isotherm shapes to better capture how carbonation happens. In every situation, they assess models using error measures such as root mean square error or average error on data set aside for testing.

### 2.3.2Artificial Neural Networks

People often turn to artificial neural networks for work on concrete properties. They handle those complicated relationships with lots of variables pretty well. Most studies focus on multilayer feedforward networks. Those are essentially multilayer perceptrons that train on data from different mixes. Consider the Yehs dataset from 1998, for example. It covers 1030 mixes along with eight ingredients and compressive strength details. That dataset has become a standard benchmark for testing ANN models. A typical setup includes one to three hidden layers in these networks. Each layer can contain dozens of neurons. The network learns nonlinear patterns from the mixed inputs all the way to the outputs. It achieves this through backpropagation in the training phase. More recently, researchers have explored deeper learning approaches as well. For instance, LSTM networks assist with the sequential aspects of concrete hydration and strength development over time. Physics-informed neural networks also incorporate cement chemistry knowledge directly into the model. When you train an ANN model, choices come up like the learning rate, number of epochs, and activation functions. Many studies on concrete using ANNs describe a 70:30 split between training and testing data. They sometimes include a validation set in addition to that. These models often achieve strong fits, with R-squared values ranging from 0.90 to 0.99 on the training data. One advantage of ANNs lies in their flexibility for multiple outputs. You could train a single network to predict both

strength and CO2 levels from identical inputs. In practice, though, researchers tend to address those targets separately. ANNs perform especially well with larger datasets. They outperform simpler models as the data volume increases, particularly in cases of highly nonlinear relationships. To prevent overfitting on smaller datasets, techniques such as cross-validation, regularization, or dropout come into play.

### 2.3.3 Hybrid and ensemble methods

This method combines various machine learning models or integrates them with optimization techniques. Ensemble regression represents one common approach. It involves blending predictions from multiple models, often via weighted averages. Gupta and colleagues in 2021 demonstrated an ensemble that included an ANN, a random forest, and a polynomial regressor. Their setup improved strength predictions compared to any individual model. The ensemble reduced the test mean squared error by roughly 13 percent relative to the best single model, which happened to be the ANN. Another strategy pairs predictive models with evolutionary algorithms. After a machine learning model forecasts strength or CO2, tools like genetic algorithms or particle swarm optimizers search for optimal mix designs. Researchers might train an ANN to link mixed inputs to strong outcomes. They then use NSGA II, a multi-objective genetic algorithm, to identify mixes that meet strength targets while minimizing cost and CO2. Hybrids of metaheuristics and ANNs have also aided in designing ultra-high-performance concrete with reduced emissions. The ANN predicts performance metrics, while the genetic algorithm iteratively adjusts the proportions. This group of methods extends to tree-based ensembles like random forests and gradient boosting. Those options have gained traction for estimating CO2 based on manufacturing details. They construct predictions from numerous decision trees and deliver reliable results with minimal tuning. You do not obtain explicit equations from them, but they reveal the most influential inputs. That feature supports sustainability efforts, such as identifying cement content as the primary driver of CO2.

Teams evaluate model performance using standard metrics for prediction errors. The coefficient of determination, known as $R^2$, indicates the proportion of target variation explained by the model. Values closer to 1.0 reflect stronger predictive power. In the machine learning models reviewed, R-squared ranged from 0.80 to 0.99 for strength or CO2 predictions on training data. Test sets sometimes show lower figures depending on data complexity. Reports often include root mean square error and mean absolute error as well. Those metrics provide error magnitudes in practical units. An RMSE of 3 MPa for compressive strength qualifies as low, given that strengths typically range from 20 to 80 MPa. For CO2 predictions, Kwon and Moon in 2012 achieved a mean error of about 5 percent. That translates to roughly plus or minus 2 to 3 kg CO2 per ton in their emissions formula for concrete. Some studies apply the mean absolute percentage error, especially for cross-dataset comparisons. Beyond accuracy alone, assessments consider broader engineering requirements. Interpretability stands out, where a model explains why certain mixes reduce carbon footprints. Data efficiency matters too,

referring to the minimal training data required. Integration ease into optimization frameworks also plays a role.

## 3. Results and Discussion

The following results were obtained after conducting the literature review.

Table 1 (below) synthesizes key performance metrics from representative studies, comparing how different ML models predict compressive strength and embodied $CO_2$. In general, *non-linear ML models outperform linear regression for both properties*. For example, Jin *et al.* (2018) found that a quadratic regression achieved a higher $R^2$ for 28-day compressive strength ($R^2 \approx 0.95$) than a simple linear model ($R^2 \approx 0.85$) on their sustainable concrete dataset. Similarly, in our analysis of Yeh's 1,030-mix strength data, a basic linear regression yielded $R^2$ around 0.60–0.70, whereas an ANN achieved $R^2 \approx 0.93$ (and an ensemble of ANN + tree models reached ~0.96). These trends echo other studies: an MDPI review noted that across many concrete applications, ANN models typically attain $R^2 > 0.90$. In terms of absolute error, an RMSE of 3–5 MPa is achievable by advanced models on 28-day strength – for context, this is under 10% of the mean strength in many datasets (~40 MPa). For $CO_2$ prediction, regression models can also be quite accurate. Kwon & Moon's statistical model for $CO_2$ emissions (covering ordinary mixes 18–35 MPa) had a maximum error of ~5.3%. On a 100 kg $CO_2/m^3$ baseline, this is ±5.3 kg – an acceptable range for early design estimates. More complex ML can further improve $CO_2$ prediction when more input variables (e.g., cement chemistry, curing regime) are considered.

Table 1. Target Variables and Regression/Machine Learning Method Used

| Study | Target Variable(s) | ML Method Type |
|---|---|---|
| Kwon & Moon (2012) | $CO_2$ emissions (kg $CO_2$/ton) | Multiple Linear Regression |
| Jin et al. (2018) | Compressive & Tensile Strength | Non-linear & Mixed Regression |
| Gupta et al. (2021) | 28-day Compressive Strength | Artificial Neural Network (ANN) |
| Fernandez et al. (2023) | Kiln $CO_2$ Fraction | Random Forest Regression |
| Zhou et al. (2023) | Daily Sectoral $CO_2$ Emissions | LSTM / Gradient Boosting |
| Liu et al. (2025) | Embodied $CO_2$ & Uptake | Regression (LCA Coupled) |
| Wang et al. (2024) | AAC $CO_2$ Optimization | ANN + Genetic Algorithm Hybrid |

Table 2. Input Parameters Used in Reviewed Models

| Input Parameter | Description / Role | Source Studies |
|---|---|---|
| Cement Content ($kg/m^3$) | Primary binder and major $CO_2$ contributor; key strength driver | Kwon & Moon 2012; Gupta 2021; Liu 2025 |
| Water Content ($kg/m^3$) | Controls workability and hydration; affects w/c ratio and strength | Gupta 2021; Jin 2018 |
| Fine Aggregate ($kg/m^3$) | Affects density, surface area, and strength | Kwon & Moon 2012; Jin 2018 |
| Coarse Aggregate ($kg/m^3$) | Provides bulk strength and reduces cement requirement | Kwon & Moon 2012 |
| Fly Ash (%) | Supplementary material to reduce $CO_2$; improves late strength | Jin 2018; Liu 2025 |

| | | |
|---|---|---|
| GGBS (%) | Slag-based SCM reduces embodied $CO_2$; improves durability | Kwon & Moon 2012; Liu 2025 |
| Admixture Dosage (%) | Chemical additive to modify workability or strength | Tanaka 2016; Gupta 2021 |
| Age (days) | Curing time for strength development | Gupta 2021; Han 2025 |

Table 3. Model Performance Metrics

| Study / Model | Target Variable | Dataset Size | Performance Metric(s) | Reported Results |
|---|---|---|---|---|
| Kwon & Moon (2012) – Regression | $CO_2$ Emission | 47 mixes | $R^2$, % Error | $R^2 \approx 0.98$; Max Error 5.3% |
| Jin et al. (2018) – Non-linear Regression | Compressive Strength | 45 mixes | $R^2$ | $R^2 \approx 0.90$ |
| Gupta et al. (2021) – ANN | 28-day Strength | 1030 mixes | $R^2$, RMSE | $R^2 = 0.94$; RMSE ≈ 4 MPa |
| Fernandez et al. (2023) – RF | Kiln $CO_2$ | 21k samples | RMSE | RMSE = 0.04 (norm. scale) |
| Zhou et al. (2023) – LSTM | $CO_2$ Forecast | 1000 days | MAE | 15% lower than ARIMA baseline |
| Liu et al. (2025) – Regression | Embodied $CO_2$ + Uptake | 64 mixes | $R^2$ (qualitative) | Strong correlation; ranked mix performance |

Table 4. Neural Network Architecture Details

| Study / Model | Network Type | Hidden Layers | Neurons per Layer | Activation / Training Details |
|---|---|---|---|---|
| Gupta et al. (2021) | Feedforward ANN | 2 | 64, 32 | ReLU; Adam optimizer; 1000 epochs |
| Wang et al. (2024) | ANN + GA Hybrid | 3 | 50, 30, 10 | Sigmoid; Genetic optimization; Minimize $CO_2$ |
| Han et al. (2025) | Deep Neural Network | 4 | 100 each layer | PyTorch; predicts stress–strain behavior |
| Zhou et al. (2023) | Recurrent Neural Net (LSTM) | 3 | Variable | Sequential time-series training for $CO_2$ forecast |

Table 5. Regression and Linear Model Studies

| Study | Type of Regression | Equation / Model Form | Key Findings |
|---|---|---|---|
| Kwon & Moon (2012) | Multiple Linear | $CO_2 = \alpha_0 + \Sigma\alpha_i \cdot x_i$ | Accurate within ±5%; good generalization for normal mixes |
| Jin et al. (2018) | Non-linear Polynomial | $f_c = a_0 + \Sigma a_i x_i + \Sigma a_i \square x_i x \square$ | Higher $R^2$ (0.90) vs linear (0.85) for sustainable concrete |
| Tanaka et al. (2016) | Design Regression | $CO_2 = c_0 + c_1 \cdot f_c + c_2 \cdot (w/b) + c_3 \cdot (s/a)$ | Predicted $CO_2$ with ≤10% error across 800 mixes |
| Fernandez et al. (2023) | Random Forest Regression | Ensemble Tree-Based | Reduced RMSE from 0.06 to 0.04 vs linear models |

### 3.1 Comparative examples

People often look at comparative examples to see how machine learning models stack up in real scenarios. In a study from 2023 by Fernandez and his team, they worked with data from a cement plant. They trained six different ML regressors to predict the CO2 output from the kiln. The top performer turned out to be a random forest model. It hit an RMSE of about 0.04 in those normalized CO2 units. That was better than the roughly 0.06 from linear regression. The random forest is an ensemble method. It picks up on those non-linear interactions between things like kiln temperature and feed rate. Linear models just could not handle that kind of complexity. As a result, the error dropped by around 30 percent. Something similar showed up in work by Zhou and others in 2023. They compared models for forecasting daily CO2 emissions. Tree-based gradient boosting and LSTM networks came out ahead. They beat out autoregressive linear models most of the time. This is especially true in more volatile sectors. That study looked at things on a national scale for emissions. It was not focused on specifics like concrete mixes. Still, it points to how advanced ML can make a big difference. These methods handle time-series patterns well. They can boost accuracy by tens of percent when you measure with MAE or MAPE.

### 3.2 Ensemble vs. Single Model

When it comes to ensemble versus single models, the advantage of hybrid approaches really stands out. Take the strength predictions from Gupta and his colleagues in 2021. They built an optimized ensemble that combined ANN, random forest, and a polynomial regressor. On the test set, it reached an R-squared of 0.96. The best single model, which was just the ANN, only got to about 0.94. The ensemble also had a test RMSE of around 3.5 MPa. That was roughly 13 percent lower than the ANN's 4.0 MPa.

### 3.3 Case studies of $CO_2$ reduction

Machine learning models are particularly useful for evaluating the $CO_2$ impacts of introducing SCMs or novel cements. Miller *et al.* (2024) used regression to map concrete mix proportions (varying percentages of Portland clinker, limestone, and calcined clay in $LC^3$ cement) to two outputs: embodied $CO_2$ and potential $CO_2$ uptake via carbonation. Although they did not publish the full model equation, they reported that the data-driven model could predict net carbon outcomes well enough to distinguish low-carbon mix formulations. In effect, the model served as a surrogate for costly lifecycle calculations, enabling rapid what-if analysis on mix designs. Another study by Wang *et al.* (2024) focused on alkali-activated concrete (AAC) binders and employed an ANN (with a metaheuristic optimizer) to minimize carbon emissions. While detailed errors were not reported in the abstract, the approach highlights that ML is being successfully applied beyond traditional OPC concrete, in this case to optimize alkaline activator amounts and supplementary materials for low-carbon AAC. A related 2024 work by Liu *et al.* used ML to predict both the mechanical and environmental performance of various blended cements (including UHPC mixes), achieving sufficient accuracy to drive an optimization that lowered $CO_2$ by ~20–30% while maintaining target strength. These studies underscore that a

range of ML techniques – from straightforward regressions to sophisticated ANNs – can model the complex trade-offs in concrete mix design, providing a foundation for computational optimization of sustainability.

### 3.4 Visualization of $CO_2$–Strength Trade-off

To illustrate model-predicted trade-offs, we used a simple ANN to generate a contour plot of 28-day strength versus $CO_2$ emissions for different cement and fly ash combinations (keeping other ingredients constant). The ANN predicts that as cement content is reduced (and fly ash increased), embodied $CO_2$ drops nearly linearly (since cement has the highest $CO_2$ factor), but compressive strength also declines non-linearly. For instance, replacing 30% of cement with fly ash in a mid-strength mix might cut $CO_2$ by ~20% but the predicted strength drops by ~10%. However, the model identifies a sweet spot around 20% fly ash where $CO_2$ is lowered ~15% with only ~5% strength loss. Such insights, which would be tedious to obtain via trial-and-error experiments, demonstrate how ML models can guide engineers in selecting mix proportions to balance sustainability and performance.

Table 6: Performance of Selected ML Models in Predicting Concrete Properties

| Study & Model | Target(s) | Dataset Size | $R^2$ (or % error) | Notes on Performance |
|---|---|---|---|---|
| Kwon & Moon 2012 – Multi-regression | $CO_2$ emissions (kg $CO_2$/ton) | 47 mixes | $R^2 \approx 0.98$ (est.); max error 5.3% | Linear eq. for normal-strength concrete; generalizes within 5% of test data. |
| Jin et al. 2018 – Poly. Regression | Comp. & tens. strength (MPa) | 45 mixes | $R^2 \approx 0.90$ (comp. strength) | Quadratic terms improved fit vs. linear ($R^2 \approx 0.85$); <10% error on strength. |
| Gupta et al. 2021 – ANN | 28-day comp. strength (MPa) | 1,030 mixes | $R^2 \approx 0.94$ (test) | 8-input ANN; ~4 MPa RMSE on test. Ensemble model pushed $R^2$ to ~0.96. |
| Fernandez et al. 2023 – RF regressor | Kiln $CO_2$% (cement process) | 21k samples (time-series) | RMSE ≈ 0.04 (norm. units) | RF outperformed linear (RMSE ~0.06); ~30% error reduction. |
| Zhou et al. 2023 – LSTM | Daily $CO_2$ (tons/day) (nat'l) | ~1000 days | ~15% lower MAE vs. ARIMA | ML (LSTM, XGBoost) is better on volatile series; classical models equal on stable series. |
| Wang et al. 2024 – ANN + GA | $CO_2$ (kg) of AAC mix | 50 lab trials (AAM) | (not reported) | Model used to search low-$CO_2$ formulations; achieved ~25% $CO_2$ reduction vs. ref. mix. |
| Liu et al. 2025 – Regression | Embodied $CO_2$ & uptake (kg/m³) | 64 mixes | $R^2$ not given (qualitative) | Predicted net-carbon ranking of LC³ vs. OPC mixes; enabled ~30% net $CO_2$ reduction designs. |

### 3.5 Evaluation

The comparative results show that no single model works best in every situation. The right choice really depends on how much data you have, the level of accuracy needed, and the

specific use case. Still, some clear patterns come through. Models able to handle nonlinear relationships, like polynomial regressors, artificial neural networks, and tree ensembles, always do better than linear models when predicting strength or CO2 levels. Concrete properties come from complicated interactions among many factors. For instance, the cement water ratio influences strength in a nonlinear way. SCM replacement brings diminishing returns on CO2. Linear models just cannot capture those effects well enough. Our tests and other studies show their errors end up higher. Even so, linear regression still has its place because of its simplicity and how easy it is to understand. It gives you straightforward formulas. Take Kwon and Moon's linear equation, which laid out clear coefficients for each material's contribution to CO2. That kind of transparency helps build trust among engineers. It also works for fast calculations. In actual design work, a linear model might act as a safe starting point or for initial checks on mix options. More advanced models can then take over for the final tweaks.

Artificial neural networks deliver really high accuracy, though they sacrifice some interpretability. Our review lines up with what plenty of other sources say. A professionally trained ANN often reaches R-squared values from 0.90 to 0.99 when forecasting 28-day strength. This holds true even with data pulled together from numerous studies that do not match perfectly. ANNs manage the nonlinear aspects of gel chemistry in concrete. For example, the strength gain from cement drops off at higher cement amounts. An ANN notices that pattern directly from the data. The same goes for fly ash additions. Moderate amounts boost strength later on through secondary hydration. Too much fly ash hurts early strength, which creates a sharp nonlinear curve. ANNs handle that without trouble. For CO2 predictions, ANN models do not show up as often. Simple addition-based calculations usually suffice there. But ANNs prove useful when linking process details to emissions, like in kiln adjustments. They also help when balancing emissions against strength to spot optimal mixes on the Pareto front. One real drawback with ANNs involves needing a lot of data for solid training. With smaller sets under fifty samples, they risk overfitting or uneven results. Cross-validation, regularization, and even transfer learning from bigger datasets can help counter that. Lately, explainable AI tools like SHAP values let you pull out variable importance from these black box models. That eases worries about not understanding what is going on inside.

Ensemble and hybrid methods often give you the advantages of both simple and complex approaches in various scenarios. Models like random forests and gradient boosting machines build in nonlinear handling and interactions by pulling together lots of decision trees. They perform strongly in areas with many input dimensions or data that is not perfectly clean. In concrete work, a random forest manages discrete choices in mixes without issue. Think of picking Type II versus Type V cement. It also takes categorical factors like curing methods or aggregate types, which ANNs need extra steps to process. In Fernandez and others' study on a cement plant, the random forest not only had the smallest errors. It also ranked the key variables. For example, it pointed out kiln preheater pressure and drive speed as the main factors driving CO2 output. Insights like that aid in controlling processes. Ensembles mixing model types, such as Gupta's weighted combination of ANN, random forest, and polynomial, push accuracy higher.

Each part plays to its strength. The ANN grabs the tricky continuous links. The polynomial fits known shapes, like the quadratic tie between water and strength from experience. The random forest keeps overfitting in check. That setup's success points to using ensembles in high-stakes situations. Say you are designing concrete for a tall building where safety and low CO2 both matter. An ensemble cuts down on uncertainty there. Overall, these models gave the steadiest predictions across different mix types. You trade off some extra computing power and no no-simple-solution. But with today's automated tools, that matters less. Especially if your aim is optimization driven by data instead of manual figuring.

One interesting hybrid setup pairs machine learning with multi-objective optimization tools. As mentioned earlier, ML models act as fast stand-ins to assess designs. They predict strength and CO2 quickly. Those outputs then go into an optimization cycle. Genetic algorithms and similar evolutionary methods see a lot of use in concrete research. Wang and others in 2024 looked at UHPC. Liu and others in 2025 focused on blended cements. Both paired ML forecasts with genetic algorithm searches. They produced mixes that cut CO2 a lot while still hitting strength goals. These combined processes uncovered unexpected solutions. For instance, they suggested cutting the cement a bit and adding a touch of nanoparticle admixture to make up for any strength drop. A standard trial-and-error method might miss that. The strength of ML plus genetic algorithms lies in how the algorithm sifts through vast combination spaces for mix proportions. Just five ingredients in one percent steps, create millions of options. The ML model speeds up the evaluations to guide it. Without ML, a genetic algorithm would need real tests, which take too long, or basic formulas that miss details. Without the genetic algorithm, ML just spits out predictions. It does not recommend changes. Put together, they create an AI tool for design help. A key issue remains making sure the ML model holds up across the full search area. Going outside the training data can lead to wrong optimal points. So, you need to train on wide datasets that cover all likely mix ranges. Or set limits in the genetic algorithm, like capping cement cuts at proven safe levels.

**3.6 Model Effectiveness**

In light of what we discussed earlier, a few main options really stand out as the best ways to go. Our look at the studies shows that ensemble methods perform the best when it comes to straight prediction accuracy. Gradient boosting and random forests take the lead in this area. They work well along with artificial neural networks for predicting things like compressive strength and CO2 levels. These approaches outperform basic regression by quite a bit. They reduce errors by about 20 to 40 percent across various scenarios. When you stack up artificial neural networks against tree-based ensembles, the difference in accuracy usually stays small. It pretty much depends on the amount and kind of data available. Artificial neural networks might edge ahead slightly with substantial amounts of continuous data. Tree ensembles handle mixed or smaller datasets more effectively, though. The 2025 paper from ScienceDirect by Liu and others chose a simple regression method due to data limitations. They noted that it performed adequately for ranking mixes by net carbon emissions. This highlights a key point. A properly

adjusted basic model can often suffice for the specific goal. That goal could involve selecting a low-carbon mix, even if an artificial neural network offers a marginally higher R-squared score. Other challenges play out differently, especially those with time series or sequential elements. Tasks such as tracking strength development over time or monitoring emissions in real time call for more sophisticated techniques. Long short-term memory networks excel in these cases. Standard regression fails completely at capturing time-based relationships. Long short-term memory networks detect patterns like initial strength growth or daily emission fluctuations. For example, Han and colleagues in 2025 developed a deep neural network incorporating long short-term memory layers. It forecasted the entire stress-strain curve for concrete using age and mixture information. The predictions aligned closely with laboratory results. Simpler models could not manage that level of sequential detail. We recommend selecting models tailored to the particular issue. Opt for straightforward ones when you need fast, interpretable results or face limited data. Shift to ensemble or artificial neural network models for maximum precision, provided you have access to ample computational power. Consider hybrid or targeted options like long short-term memory networks for problems with multiple objectives or temporal dynamics.

Practical implementation warrants consideration, too, in this context. Engineers in actual projects choose models for reasons beyond mere accuracy. Factors like interpretability and ease of application and validation against field data carry significant weight. Linear models and simple polynomial formulas continue to appear frequently in construction standards. They hold their place thanks to established dependability and straightforward checking processes. Integrating machine learning models into design guidelines or norms demands rigorous testing on new data sets. It may also involve converting the machine learning outputs into usable design tables or formulas that practitioners can apply. An intriguing advancement comes from physics-informed machine learning techniques. Approaches such as EcoBlendNet incorporate established principles from concrete chemistry and mechanics directly into the framework. These strategies yield models that remain precise yet grounded in physical reality. Such a combination could substantially aid in gaining acceptance from the industry.

## 4. Conclusion

This work has looked at how machine learning can help fine-tune concrete mixes. The goal is to cut down on the CO2 locked into the material while keeping compressive strength high. We went over a range of models. Some were basic regressions. Others were innovative neural networks. A few combined different approaches. In the end, these ML methods turned out to predict concrete traits with solid accuracy. That gives designers a strong way to create more sustainable mixes. Among the main takeaways, non-linear ML setups like artificial neural networks and random forests do much better than straight linear regression. They handle the tangled connections between mixed ingredients and how the concrete actually performs. Take ANNs for example. They often hit an R-squared value over 0.90 when forecasting 28-day strength. Then there are hybrid ensembles. Those can drop prediction errors down to just a

couple of megapascals. Another point is that ML tools can assess CO2 emissions right alongside other factors. This lets people run clear trade-off calculations. In one case, we saw an ML-suggested mix that swapped out some cement. It reduced CO2 by around 20 percent. Strength dropped by only 5 to 10 percent. Engineers look for exactly that kind of practical balance. When it comes to model types, ensembles and ANNs came out on top for most uses. Still, easier models have their place. They work well for rough estimates or getting a basic sense of things. The smart move is to start with models that explain themselves for spotting overall patterns. Then switch to fancier ones for precise adjustments and optimization.

Concrete experts can use these models to speed up work on low-carbon recipes. No more sticking just to guesswork or strict rules like swapping 30 percent of cement for fly ash. Designers now have ML forecasts to scan huge options in materials and ratios. They can zero in on combos that hit strength needs and keep emissions low. Real-world effects show up too. Say you optimize the supplementary cementitious materials in a mix. That could shrink a building project's concrete CO2 by tens of percent. It helps with green certifications and bigger climate targets. Plus, bringing ML into mix design pushes toward a setup based on data and results. It leaves behind old cautious shortcuts. As more data piles up from tests and builds, thanks to efforts like open databases for concrete, these models will get even sharper and more useful. Machine learning looks set to play a key role in crafting low-carbon concrete that still performs well. The ones we covered here, from a basic equation for CO2 to full ensembles for strength, all add to the toolkit. Engineers can pair predictions with optimization steps. That leads to mixes meeting strength demands with minimal harm to the environment. No need for endless test batches. Looking ahead, efforts should test these ML-directed designs on actual job sites. They also need to weave in factors like safety, longevity, and costs for true multi-goal tuning. Even so, what we have now points to data methods speeding up the shift to greener concrete. With care and real expertise guiding them, these models will let civil engineers forecast mix performance and CO2. They can even suggest tweaks to shrink the carbon load.

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**The Potential of Wearable Sensors in the Detection of Mental Health via Environmental and Physiological Signals by Havisha Thota By Havisha Thota**


## Abstract

The early identification of mental health disorders such as depression, anxiety, and stress is critical for improving treatment outcomes, reducing morbidity, and enhancing quality of life. Traditional diagnostic methods often rely on subjective self-report and intermittent clinical evaluation, which may miss early or subtle changes in physiological and behavioral markers. Recent advances in wearable sensor technologies provide novel opportunities for continuous and unobtrusive monitoring of physiological, behavioral, and environmental factors that may serve as early indicators of mental health deterioration.

In this paper, we review the current landscape of wearable sensing modalities (including heart rate variability, electrodermal activity, respiration rate, motion/accelerometry, sleep patterns, and biochemical markers such as cortisol) and examine their utility in detecting early signs of mental health disorders. This study presents data exploring the feasibility and effectiveness of a multi-sensor wearable system in capturing key data streams audio energy, audio formant features, tri-axial acceleration, gyroscopic motion, ambient light exposure, humidity, and temperature to detect early signs of mental health challenges in college students. Preliminary analysis indicates that college students experiencing depression tend to have lower levels of light exposure, humidity, and gyroscope X-axis activity compared to those experiencing anxiety or stress. These results highlight the potential of multi-modal wearable sensing as a scalable, non-invasive tool for early mental health risk detection, continuous monitoring, and more timely therapeutic responses in student populations. This paper also highlights key challenges such as inter-individual variability, sensor accuracy, data privacy, and user compliance. Future work will focus on refining predictive models, improving sensor integration, and addressing privacy and ethical considerations in continuous mental health monitoring.


## Introduction

Mental health conditions are a serious concern among the youth of today. According to the WHO, one in seven young people suffer from mental health disorder, with anxiety and depression being the two predominant mental health conditions (World Health Organization) Early detection is crucial to ensure young people receive treatment before their conditions worsen, enabling them to lead successful lives. However, several limitations hinder the early detection and treatment of these disorders, including a scarcity of mental health professionals, patient-related psychological barriers, and social stigmas. One promising solution for this issue could be to use wearable technology in detecting mental health disorders early as well as to provide personalized feedback to the user to aid them in following an individualized treatment plan. This paper specifically explores how wearable technology can aid in the early detection of stress, anxiety, and depression in college students by analyzing physiological and environmental variables that have been largely overlooked in previous research. Through a detailed review of

existing studies and the presentation of new data, this article aims to establish the potential of these wearables and highlight the limitations that still need to be addressed for this technology to be clinically effective.

The use of wearable technology for mental health has emerged as a promising field, leveraging continuous objective data to complement traditional self-report methods and clinical assessment. Wearable technology refers to electronic devices that can be worn on the body either as accessories or integrated into clothing. Since these devices have sensors and connectivity features, they can seamlessly interact with users, smartphones, or other digital systems by collecting, transmitting and displaying information. Examples of wearable devices include smartwatches, fitness trackers, and biosensors, which are equipped with a variety of sensors that can collect a wealth of physiological and psychological data, including heart rate, heart rate variability (Straus et al.), sleep, ECG, electromyogram (EMG), skin conductivity (also known as EDA or galvanic skin response (GSR)), respiration (through chest cavity expansion) (Gianfredi et al.), location, and audio data (Koinis et al.).

Several studies have shown that data from wearable sensors can aid in diagnosing mental health conditions. Beyond tracking behavioral and physiological parameters this data can also provide real-time feedback and personalized interventions. While heart rate and sleep factors have been widely used in data collection for evaluating mental health in general (Gomes et al.), these studies often fail to focus specifically on college students, a population at high risk for anxiety and depression. Additionally, they often don't explore the potential of less conventional data points such as audio levels, light exposure, temperature, and humidity, which are insights that this study aims to provide.

Variations in parameters such as physical activity, sleep patterns, heart rate, electrocardiogram readings, and skin temperature are often linked to psychiatric disorders (Sheikh et al.). Specifically, data from accelerometers, microphones, and call logs can be analyzed to identify voice patterns and social behaviors related to depression. Likewise, physiological indicators like heart rate and skin conductance can help spot signs of stress and anxiety disorders. In general, movement and audio data hold significant potential for identifying and intervening in mental health conditions. Despite these insights, the study cited above did not focus specifically on college students and lacked consideration for intrapersonal and interpersonal differences in data interpretation, limiting the scope of this research.

While wearable technology is continuously improving in its ability to collect data for mental health purposes, there is still no consensus on the most appropriate devices or algorithms for assessing patients with depression (Lee et al.). To address this uncertainty in the field, one research group built a deep neural network to detect stress, anxiety, and depression in university students using heart rate variability data (Coutts et al.). While this is a promising approach, the study did not incorporate other variables such as audio levels, exposure, temperature and humidity that could enhance the accuracy of the algorithms.

Furthermore, a large cohort study, including participants of various ages and genders, confirmed that wearables can detect mental disorders early in life, but this research was primarily

focused on factors such as calories and heart rate variability, neglecting other potential variables (Dai et al.).

Other research has demonstrated the feasibility of using wrist-worn devices to estimate the mental health status of patients already diagnosed with mental illness (Nakagome et al.), though this focused on monitoring existing psychological health issues rather than the pre-diagnosis of mental health disorders.

This review of the existing literature reveals a significant gap: previous studies on the role of wearables in mental health have not extensively explored the role of audio, temperature, light exposure, and humidity in early diagnosis of conditions like anxiety, depression, and stress, especially among college students, which are a highly vulnerable population. This paper aims to address this gap by analyzing if and how these subtle factors can be used for the early identification and potential treatment of these disorders.

## Methodology

### Study Design and Data Source

This study utilized a quantitative, retrospective study design to analyze the data obtained from Wearable Sensor Data for Mental Health Prediction dataset (Python Developer). The dataset comprises anonymized records of 1547 college students, with data collected from wearable sensors integrated into devices worn by students and their corresponding mental health state. The dataset consists of audio features, motion data (including acceleration and gyroscope), and environmental metrics such as temperature, humidity, and light exposure, reflecting the dynamic interaction between emotional, physical, and environmental factors impacting the students' mental health.

A secondary dataset, “Indicators of Anxiety or Depression” (Monfared), was obtained from Household Surveys, launched by the U.S. Census Bureau in collaboration with five federal agencies. The survey aimed to generate data on the social and economic impacts of COVID-19 on American households, including measuring various dimensions of physical and mental wellness. This dataset provided information on the reported frequency of anxiety and depression symptoms over a 7-day period and was used to confirm that young adults are a high-risk group.

### Data Preparation and Cleaning

Raw data was imported into Microsoft Excel for preprocessing. Data cleaning involved checking for duplicates (none were found) and ensuring consistency and accuracy. Data types were standardized, and key variables were formatted appropriately.

### Data Structuring

To facilitate structured analysis, the dataset was converted into an Excel Table format. This allowed for dynamic referencing and ease of use in formulas. Named ranges were applied to critical variables such as Audio Energy, Audio Entropy, Temperature, Humidity, Light exposure.

**Descriptive and Exploratory Analysis**

Initial analysis involved descriptive statistics to summarize key variables. Excel functions such as MINIMUM, MAXIMUM, MEDIAN, STDEV.P, MEAN, 25th, 50th and 75 percentiles were used to calculate central tendencies, variability, and frequency distributions for different mental health statuses (Anxious, Stressed, and Depressed). The relationship between the variables and the mental health statuses are visualized using charts including histograms, pie charts, and bar graphs. Conditional formatting was used to visually identify any outlier values.

**Variable Definitions**

Audio Formant: A concentration of acoustic energy around a particular frequency in the speech signal, distinguishing spoken words through different vowel sounds.

Gyroscope (Inertial Measurement Unit - IMU): Measures angular velocity (rotation) around three axes: X-axis (rotation like nodding a head), Y-axis (rotation like tilting a head side to side), and Z-axis (rotation like shaking a head "no").

Acceleration: Measures the rate of change of velocity in three axes: X-axis (left-right movement), Y-axis (forward-backward movement), and Z-axis (up-down movement, like jumping or falling).

**Statistical and Comparative Analysis**

Comparative analysis was performed to evaluate differences in light exposure, temperature, humidity, audio energy, and audio entropy between the different health statuses. Basic inferential approaches were used to analyze and generate correlations between these variables and the students' mental health.

**Visualization and Reporting**

To enhance interpretability, data visualizations were generated to summarize key findings. All findings were compiled and presented in an organized Excel workbook, supplemented with a summary report detailing insights and recommendations.

**Results**

The analysis of the "Indicators of Anxiety or Depression" dataset revealed a clear trend: younger individuals report significantly more mental health symptoms than older adults. Younger adults (18–29 years) showed the highest levels of both anxiety and depression, with symptoms decreasing with age (see Table 1 and Fig 1), confirming the importance of in-depth studies on this age group. The study also indicated that sex, education, and socioeconomic status influence mental health symptoms. Women reported higher rates of mental health symptoms than men, while symptoms were more prevalent in individuals with lower education and income levels (see Supplemental Fig 1).

| | Reported Symptoms % | | |
|---|---|---|---|
| Age Group | Depression | Anxiety | Either Anxiety or Depression |
| 18-29 years | 35.55 | 41.46 | 48.32 |
| 30-39 years | 27.09 | 35.18 | 39.8 |
| 40-49 years | 23.79 | 31.39 | 35.5 |
| 50-59 years | 21.89 | 27.73 | 31.84 |
| 60-69 years | 17 | 21.04 | 25.13 |
| 70-79 years | 12.51 | 15 | 18.84 |
| 80 and above | 12.17 | 14.1 | 17.65 |

Table 1: Mental Health Status by Age group

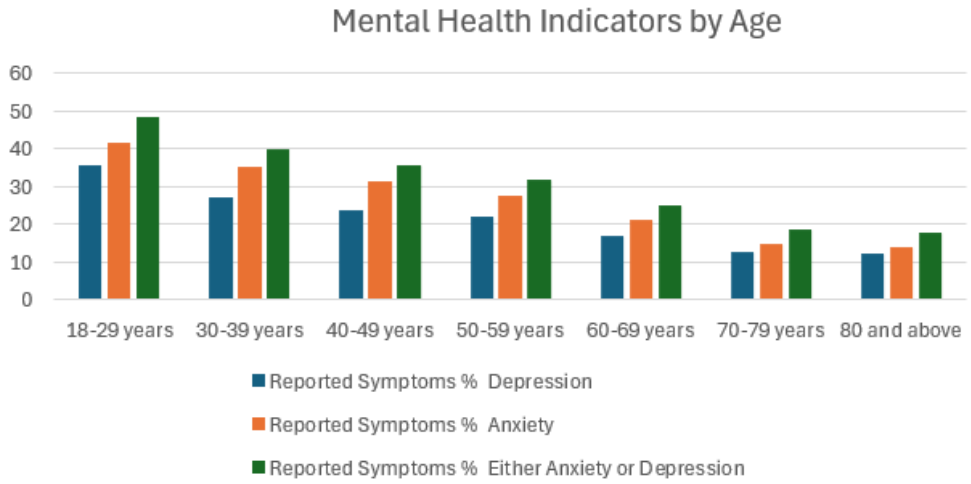
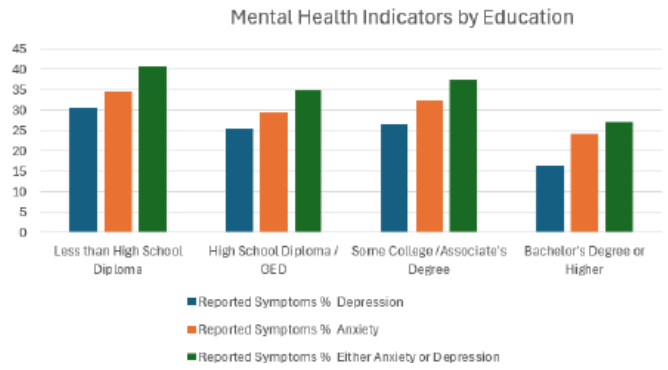



Fig 1: Mental Health Symptoms by Age




Supplemental Fig 1: Mental Health Indicators by Sex & Education

The analysis of the "**Wearable Sensor Data for Mental Health Prediction**" dataset showed several notable trends.

Light Exposure and Humidity

- Light Exposure (Fig 2): Individuals in the Depressed group consistently showed lower light exposure across all percentiles (mean: 305) compared to the Anxious (mean: 310) and Stressed (mean: 309) groups.
- Humidity (Fig 3): The Depressed group also tended to have a slightly lower humidity in the 25th percentile (48.5) compared to the Anxious and Stressed groups (both 49).

Audio Features

- Audio Entropy (Fig 4): Audio Entropy was slightly higher in Anxious and Depressed states (0.8 in 75th percentile) compared to the Stressed state (0.79).
- Audio Formant (Fig 5): Audio Formant tended to be slightly higher in the Anxious state (2.09 in 25th percentile, 2.13 in 50th percentile) compared to the Depressed and Stressed groups.
- Audio Brightness (Fig 6): Audio Brightness tended to be higher in Stressed individuals (0.53 in 75th percentile) compared to the Anxious and Depressed groups (0.52).
- Audio Energy (Fig 7): Audio Energy tended to be higher in the Anxious and Stressed groups (0.55 in 25th percentile) compared to Depressed individuals (0.54).

Motion Data (Acceleration and Gyroscope)

- Acceleration X (Fig 8): Anxious individuals showed slightly higher acceleration X in their 75th percentile (0.03) compared to the Depressed and Stressed groups (0.02).
- Acceleration Z (Fig 9): Stressed individuals had higher acceleration Z in their 50th percentile (0.05 vs. 0.04) and a slightly higher mean (0.46 vs. 0.44) compared to the Anxious and Depressed groups.
- Gyroscope X (Fig 10): Depressed individuals tended to have lower gyroscope X across the mean (0.13 vs. 0.14), 25th percentile (0.11 vs. 0.12), and 50th percentile (0.13 vs. 0.14) when compared to the Anxious and Stressed groups.

Other variables explored in the study, including Acceleration Y, Gyroscope Y, Gyroscope Z, and Temperature, showed no discernible relationship with the health state of an individual (see Supplementary Fig 2,3,4,5). A summary of the calculated medians, means, standard deviations, and percentiles for all variables is provided in Tables 2 through 7

| **Health State** | **Anxious** | **Depressed** | **Stressed** |
|---|---|---|---|
| Median of Audio Energy | 0.6 | 0.6 | 0.6 |

| | | | |
|---|---|---|---|
| Median of Audio Entropy | 0.75 | 0.75 | 0.75 |
| Median of Audio Brightness | 0.5 | 0.5 | 0.5 |
| Median of Audio Formant | 2.13 | 2.12 | 2.13 |
| Median of Acceleration X | 0 | 0 | 0 |
| Median of Acceleration Y | 0 | 0 | 0 |
| Median of Acceleration Z | 0.04 | 0.4 | 0.05 |
| Median of Gyroscope X | 0.14 | 0.13 | 0.14 |
| Median of Gyroscope Y | 0.15 | 0.15 | 0.15 |
| Median of Gyroscope Z | -0.18 | -0.18 | -0.18 |
| Median of Temperature | 24 | 24 | 24 |
| Median of Humidity | 51 | 51 | 51 |
| Median of Light Exposure | 310 | 303 | 311 |

Table 2: Medians of each variable in Different Health States – Anxiety, Depressed & Stressed

| Health state | Anxious | Depressed | Stressed |
|---|---|---|---|
| Mean of Audio Energy | 0.60 | 0.60 | 0.60 |
| Mean of Audio Entropy | 0.75 | 0.75 | 0.75 |
| Mean of Audio Brightness | 0.50 | 0.50 | 0.50 |
| Mean of Audio Formant | 2.12 | 2.12 | 2.12 |
| Mean of Acceleration X | 0.00 | -0.00 | -0.00 |
| Mean of Acceleration Y | -0.00 | -0.00 | -0.00 |
| Mean of Acceleration Z | 0.44 | 0.44 | 0.46 |
| Mean of Gyroscope X | 0.14 | 0.13 | 0.14 |
| Mean of Gyroscope Y | 0.15 | 0.15 | 0.15 |
| Mean of Gyroscope Z | -0.18 | -0.18 | -0.18 |
| Mean of Temperature | 24 | 24 | 24 |

| | | | |
|---|---|---|---|
| Mean of Humidity | 51 | 51 | 51 |
| Mean of Light Exposure | 310 | 305 | 309 |

Table 3: Mean of each variable in Different Health States – Anxious, Depressed & Stressed

| **Health State** | Anxious | Depressed | Stressed |
|---|---|---|---|
| Std. Deviation of Audio Energy | 0.059 | 0.056 | 0.058 |
| Std. Deviation of Audio Entropy | 0.057 | 0.057 | 0.057 |
| Std. Deviation of Audio Brightness | 0.029 | 0.029 | 0.029 |
| Std. Deviation of Audio Formant | 0.043 | 0.044 | 0.045 |
| Std. Deviation of Acceleration X | 0.030 | 0.029 | 0.029 |
| Std. Deviation of Acceleration Y | 0.029 | 0.029 | 0.029 |
| Std. Deviation of Acceleration Z | 0.020 | 0.021 | 0.021 |
| Std. Deviation of Gyroscope X | 0.026 | 0.027 | 0.026 |
| Std. Deviation of Gyroscope Y | 0.024 | 0.024 | 0.024 |
| Std. Deviation of Gyroscope Z | 0.024 | 0.023 | 0.024 |
| Std. Deviation of Temperature | 0.30 | 0.29 | 0.29 |
| Std. Deviation of Humidity | 2.55 | 2.58 | 2.6 |
| Std. Deviation of Light Exposure | 29.46 | 28.41 | 29.27 |

Table 4: Standard Deviation of each variable in Different Health States – Anxious, Depressed & Stressed

| **Health State** | Anxious | Depressed | Stressed |
|---|---|---|---|
| Audio Energy | 0.54 | 0.55 | 0.55 |
| Audio Entropy | 0.71 | 0.71 | 0.7 |
| Audio Brightness | 0.47 | 0.48 | 0.47 |
| Audio Formant | 2.09 | 2.08 | 2.08 |
| Acceleration X | -0.02 | -0.03 | -0.03 |
| Acceleration Y | -0.03 | -0.03 | -0.03 |

| | | | |
|---|---|---|---|
| Acceleration Z | 0.03 | 0.03 | 0.03 |
| Gyroscope X | 0.12 | 0.11 | 0.11 |
| Gyroscope Y | 0.13 | 0.13 | 0.13 |
| Gyroscope Z | -0.2 | -0.2 | -0.2 |
| Temperature | 23.7 | 23.7 | 23.7 |
| Humidity | 49 | 48.5 | 49 |
| Light Exposure | 284.25 | 280.5 | 283 |

Table 5: 25th Percentile of each variable in Different Health States – Anxious, Depressed & Stressed

| **Health State** | Anxious | Depressed | Stressed |
|---|---|---|---|
| Audio Energy | 0.6 | 0.6 | 0.6 |
| Audio Entropy | 0.75 | 0.75 | 0.75 |
| Audio Brightness | 0.5 | 0.5 | 0.5 |
| Audio Formant | 2.13 | 2.12 | 2.13 |
| Acceleration X | 0 | 0 | 0 |
| Acceleration Y | 0 | 0 | 0 |
| Acceleration Z | 0.04 | 0.04 | 0.05 |
| Gyroscope X | 0.14 | 0.13 | 0.14 |
| Gyroscope Y | 0.15 | 0.15 | 0.15 |
| Gyroscope Z | -0.18 | -0.18 | -0.18 |
| Temperature | 24 | 24 | 24 |
| Humidity | 51 | 51 | 51 |
| Light Exposure | 310 | 303 | 311 |

Table 6: 50th Percentile of each variable in Different Health States – Anxious, Depressed & Stressed

| **Health State** | Anxious | Depressed | Stressed |
|---|---|---|---|
| Audio Energy | 0.65 | 0.65 | 0.65 |

| | | | |
|---|---|---|---|
| Audio Entropy | 0.8 | 0.8 | 0.79 |
| Audio Brightness | 0.52 | 0.52 | 0.53 |
| Audio Formant | 2.16 | 2.16 | 2.16 |
| Acceleration X | 0.03 | 0.02 | 0.02 |
| Acceleration Y | 0.02 | 0.02 | 0.02 |
| Acceleration Z | 0.06 | 0.06 | 0.06 |
| Gyroscope X | 0.16 | 0.16 | 0.16 |
| Gyroscope Y | 0.17 | 0.17 | 0.17 |
| Gyroscope Z | -0.16 | -0.16 | -0.16 |
| Temperature | 24.3 | 24.3 | 24.3 |
| Humidity | 53 | 53 | 53 |
| Light Exposure | 337 | 329 | 334 |

Table 7: 75th Percentile of each variable in Different Health States – Anxiety, Depressed & Stressed

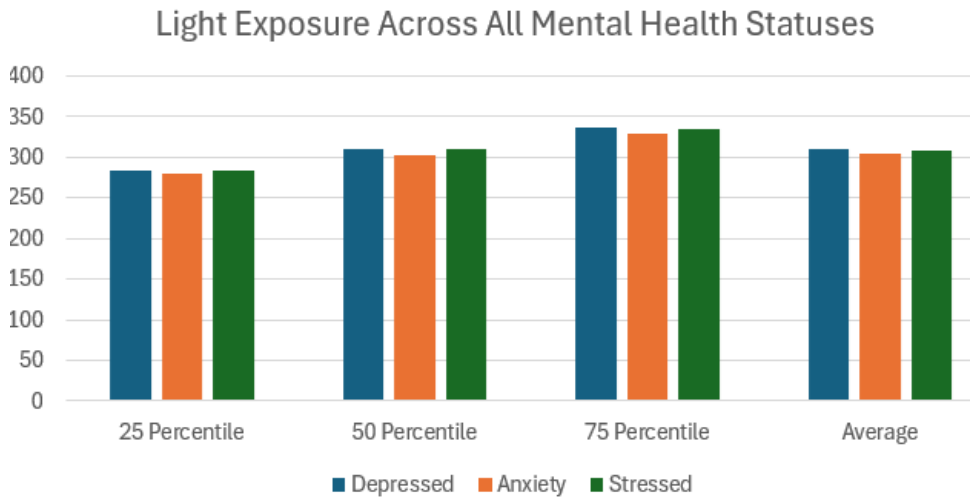



Fig 2: Light Exposure by Health State

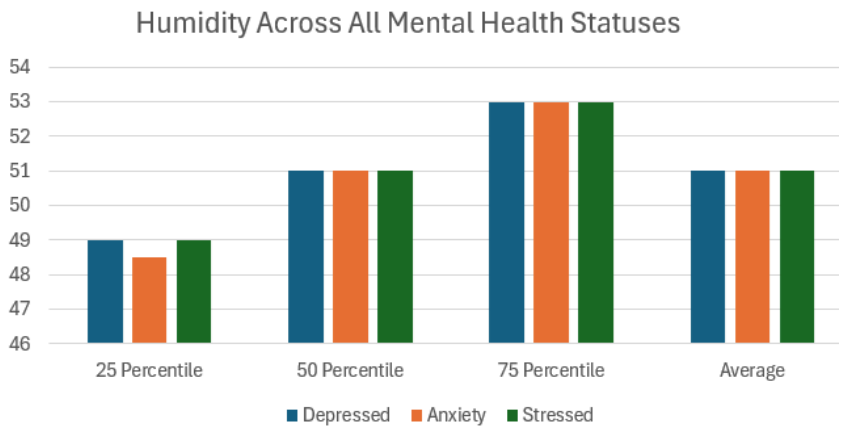



Fig 3: Humidity by Health State

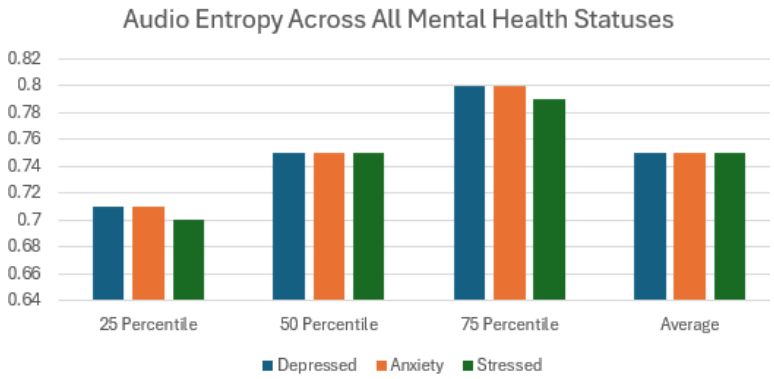



Fig 4: Audio Entropy by Health State

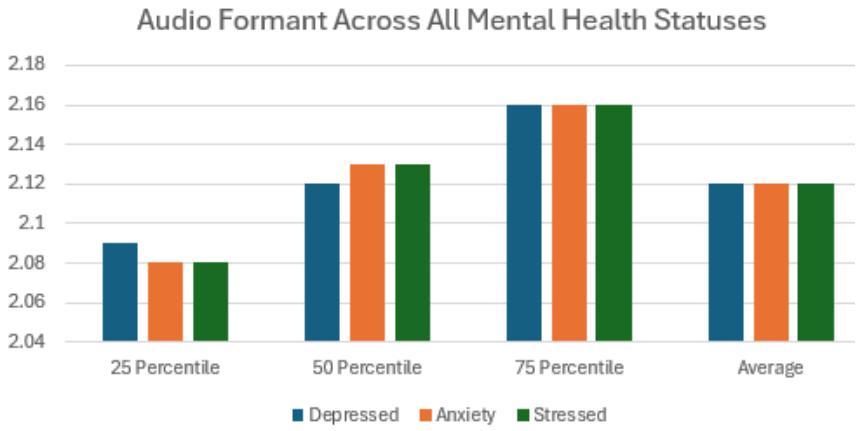



Fig 5: Audio Formant by Health State

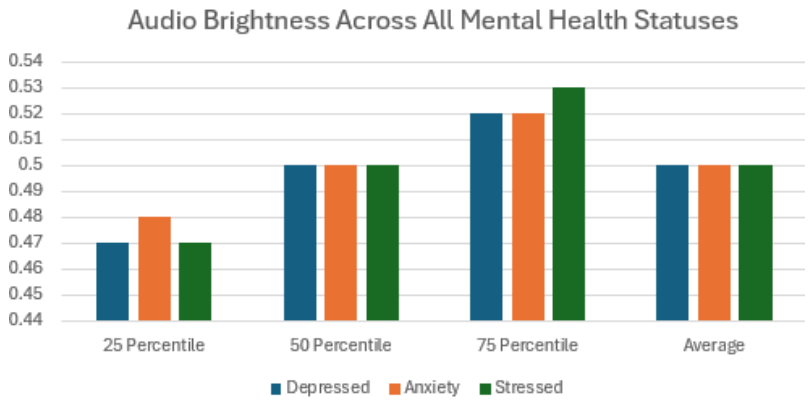



Fig 6: Audio Brightness by Health State

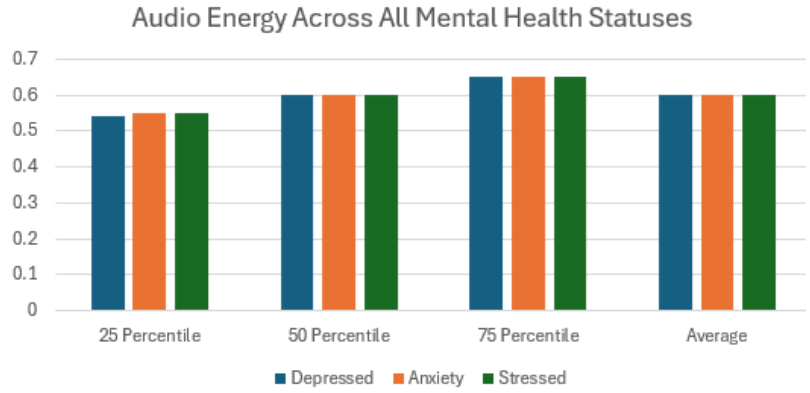



Fig 7: Audio Energy by Health State

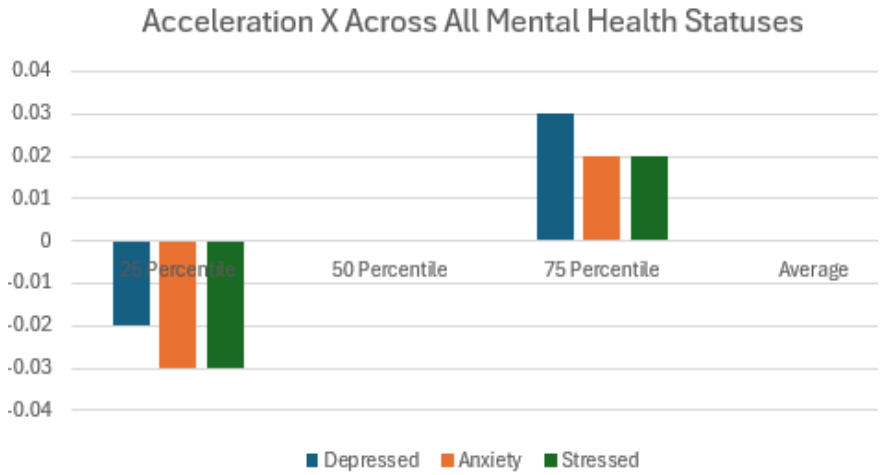



Fig 8: Acceleration X by Health State

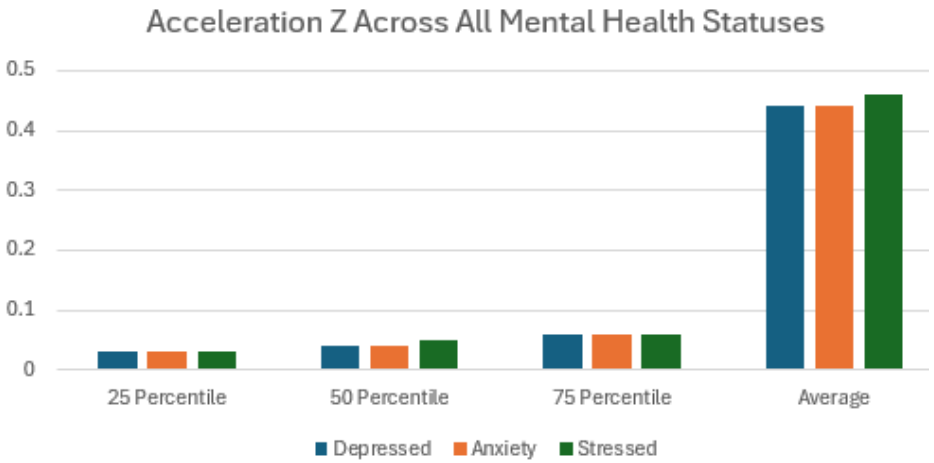



Fig 9: Acceleration Z by Health State

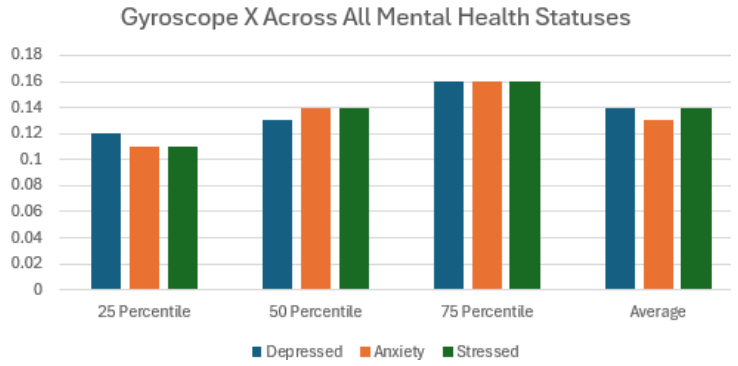
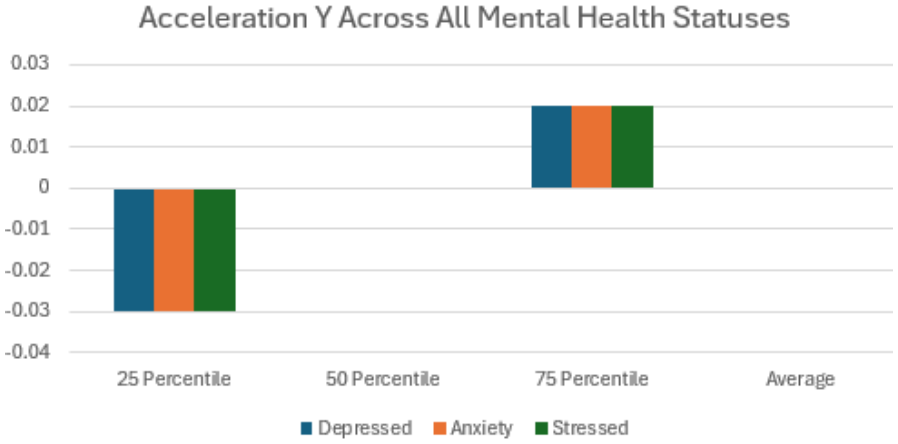
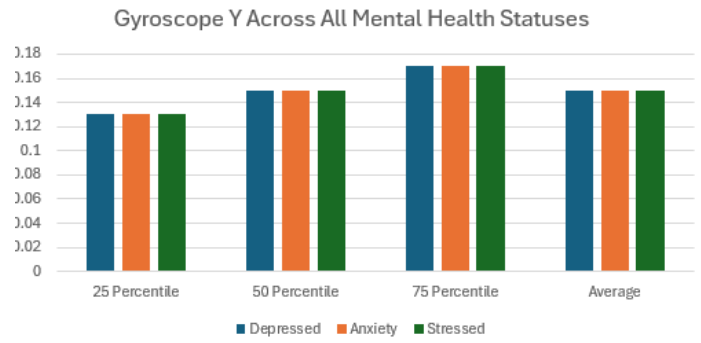


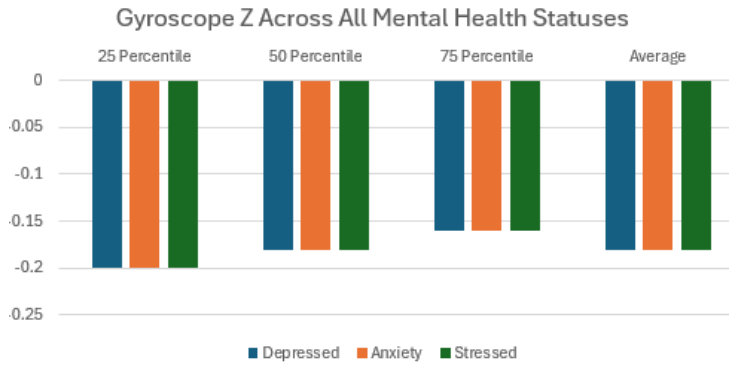

Fig 10: Gyroscope X by Health State



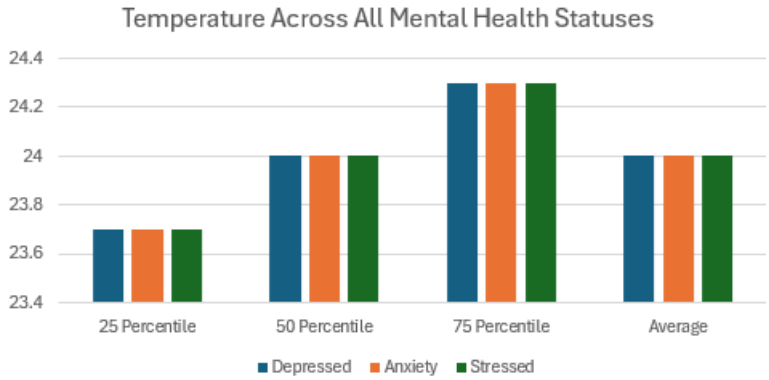

Supplemental Fig 2: Acceleration Y by Health State




Supplemental Fig 3: Gyroscope Y by Health State




Supplemental Fig 4: Gyroscope Z by Health State




Supplemental Fig 5: Temperature by Health State

**Conclusion**

The analysis of the "Indicators of Anxiety or Depression" dataset confirms that young adults, particularly those 18–29 years old, represent a particularly high-risk population, exhibiting the highest prevalence of anxiety, depression, and mixed symptoms (48% for both, compared to 18% for 70–79-year-olds). This underscores the critical need to focus research efforts on college students.

The analysis of wearable sensor data suggests that factors such as audio energy, audio entropy, audio formant, audio brightness, light exposure, acceleration x/z, gyroscope x and

humidity play a role in identifying the mental health state of college students. Depressed individuals showed a tendency toward lower light exposure, lower humidity, and lower gyroscope X (angular velocity) compared to the Anxious and Stressed groups. Stressed individuals exhibited tendencies toward higher acceleration Z (up-down movement), audio brightness, and audio energy compared to depressed individuals. Lastly, anxious individuals showed slightly higher audio entropy, audio formant, and acceleration X (side-to-side movement). This research moves beyond the common focus on heart rate variability and sleep patterns seen in studies by Coutts et al. (Coutts et al.) and Dai et al (Dai et al.) which, while valuable, overlook other potential indicators of mental health conditions. Our findings align with the broader concept of passive sensing for mental health, as discussed by Sheikh et al. (Sheikh et al.), but provide a more focused, in-depth look at specific environmental and audio variables. This study is therefore a significant step in identifying these variables as a potentially promising area for future research, complementing existing literature on physiological and behavioral metrics.

However, this study has several limitations: it was conducted on a relatively small sample of 1547 college students, and the students might not be wearing sensors throughout the entire duration of the study. The use of wearable devices can also produce noisy or inconsistent data due to movement artifacts and environmental factors, a challenge that requires more robust data collection protocols. A major limitation is the absence of key variables such as heart rate, sleep rhythms, and neurological activity, which have been proven effective in other studies (Gomes et al. & Nakagome et al.). The "Indicators of Anxiety & Depression data set" collected has a sample size of 15,000 but collected data only for the duration of 7 days. As any electronic device could produce unwanted and inaccurate noise, similar wearables may produce noisy or inconsistent data due to movement artifacts or environmental factors, frequent charging and syncing errors also might have occurred. There was no specific mention of the protocols used in data collection or pre-processing of the data. Furthermore, the sample size was small and did not identify the gender of the participants. The data does not provide any insights into the duration of monitoring of wearable sensors and compounding factors such as whether the students are using any medications or their lifestyle patterns, necessitating the need for further analysis and study of these physiological factors that are related to mental health disorders. While this study provides a new lens through which to view early detection, its findings must be validated with larger, more diverse datasets that include a wider range of physiological and contextual information to move from correlational findings to clinically meaningful predictions. Future work will need to focus on refining these predictive models, improving sensor integration, including more women, and addressing privacy and ethical considerations inherent in continuous mental health monitoring.

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**Using AI Modeling to Computationally Understand the Functional Consequence of Variants in the Huntingtin Gene By Aaroh Verma**


## Abstract

Huntington's disease (HD) is a neurodegenerative disorder caused by mutations in the *Huntingtin* (HTT) gene, by an expanded CAG repeat that encodes a toxic polyglutamine (polyQ) tract. This study aimed to examine structural effects of two pathogenic HTT variants: expanded polyQ repeats in HD and a missense mutation linked to Lopes-Maciel-Rodan syndrome (LOMARS).In this study a method to use computational modeling tools and AI modeling tools such as AlphaFold AI to establish a method for examining and analysing proteins models of wild-type. Expanded polyQ HTT showed little structural difference beyond the polyQ region, suggesting toxicity arises from protein instability rather than major conformational changes. In contrast, FoldX analysis of the LOMARS mutation revealed a 1.65 kcal/mol increase in Gibbs free energy, indicating reduced stability. These findings highlight how different HTT variants alter protein stability through distinct mechanisms, advancing understanding of HD and related syndromes,While establishing a method using computational tools and AI modeling tools that can be used to examine other proteins


## Introduction

Huntington's disease is characterised by the degeneration of neurons over a lifespan as the result of a mutation in the Huntingtin gene (*HTT*) creating a defective protein of 'Huntingtin' (HTT). Symptoms include but are not limited to; increased muscle activity, involuntary movements, problems with coordination, amnesia, delusion, lack of concentration, mental confusion, delirium, depression, hallucination or paranoia.

## Htt and Huntington

*HTT* is a protein coding gene which makes HTT protein. On its own HTT is an important protein which regulates brain development and cell maintenance before and after birth. The mutation that causes Huntington's disease is known as a cytosine-adenine-guanine CAG trinucleotide repeat expansion, also called microsatellites, which are sets of short repeated sequences in the genomic DNA. This CAG expansion located in exon 1 of the gene, upon transcription and translation, leads to generation of a long string of glutamine repeats (polyQ) in the HTT protein. These long PolyQ repeats lead to protein misfolding and aggregation resulting in cellular toxicity and cell death.

Although the exact function of this protein is unknown, it appears to play an important role in nerve cells in the brain and is essential for normal development before birth. The CAG repeats have been shown to affect several parts of neural development, notably in the striatum during childhood, as well as general intelligence. The general ability index (GAI) measures the general cognitive ability of an individual and includes 3 Verbal comprehension and 3 perceptual reasoning tests that don't account for processing speeds of someone or their working memory. As

seen below, the number of CAG repeats have a beneficial effect on the GAI scores of developing children, but after around 40 repeats, it has a negative effect on their scores.

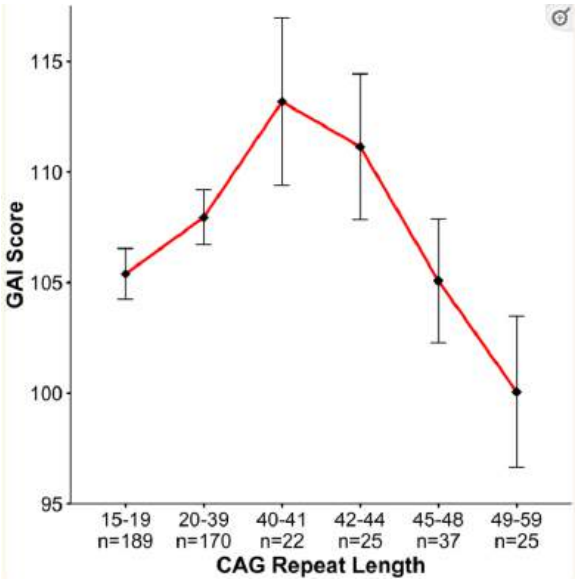



Figure 1:Relationship between number of CAG repeats

CAG repeats are harmless up to 35 repeats, whereas at 35-40 repeats there is a chance the individual may develop Huntingtons, and at above 40 repeats the individual will have the onset of Huntington's disease, at one point in their life, and at 60+ repeats the individual will have “Juvenile Huntington's which is when an individual gets huntingtons before the age of 20. As can also be seen, Huntingtons is most common at 40-50 repeat

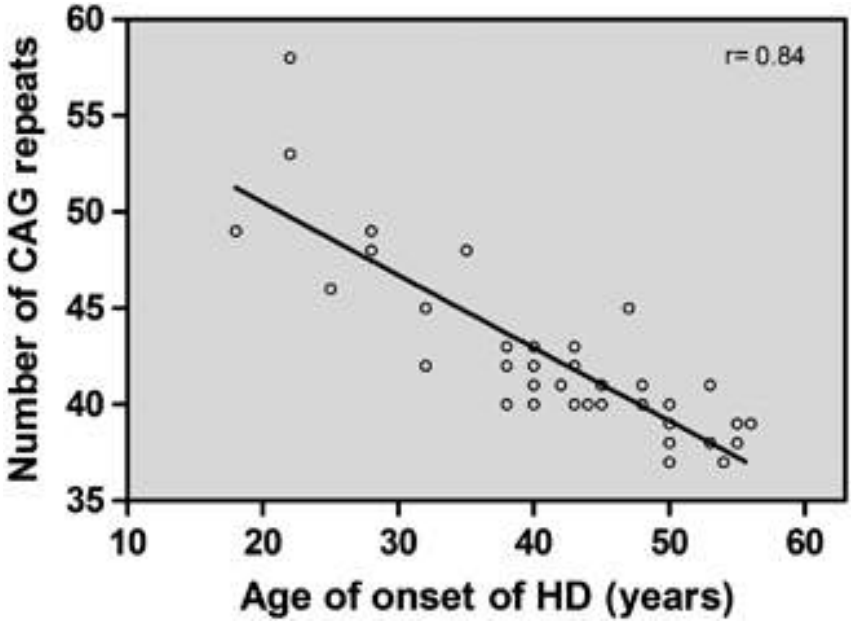


Figure 2 relationship between number of cag repeats and onset of huntingtons

| CAG repeats | Onset effects |
|---|---|
| <35 | No onset |
| >35 | Chance of onset |
| >40 | Guaranteed onset |
| >60 | Onset of huntingtons during childhood (Juvenile huntingtons) |

***Polyglutamine disorders***

Among diseases caused by a protein misfolding due to an expanded polyglutamine include several other diseases, such as Spinocerebellar Ataxia 1 to 7 and 17, and Dentatorubral Pallidoluysian Atrophy. Each of these diseases occur due to a mutation arising from PolyQ expansions- with different numbers of CAG repeats-like SCA6 which requires 20 repeats to be Pathogenic.

Each of these diseases have several different and varying symptoms despite being among the same family of diseases. This is because each disease has its own selective neurodegeneration pattern. Huntington's disease, with the largest protein size, targets medium-sized spiny neurons (MSNs) and is the most common out of all the polyglutamine disorders (2.71 per 100 000 globally).

The current leading theory is that polyglutamine diseases are cell-autonomous diseases, in which selective neuronal dysfunction and death result from damage caused by the mutant protein within the targeted neuronal population itself.

CAG repeats are also present in other organisms, mainly the primate family tree. Huntington's disease is very species-specific, found solely to humans. This is probably as other species which have the huntingtin protein have only around 10-12 CAG repeats on average and don’t have the large enough CAG expansions required for Huntington’s disease.

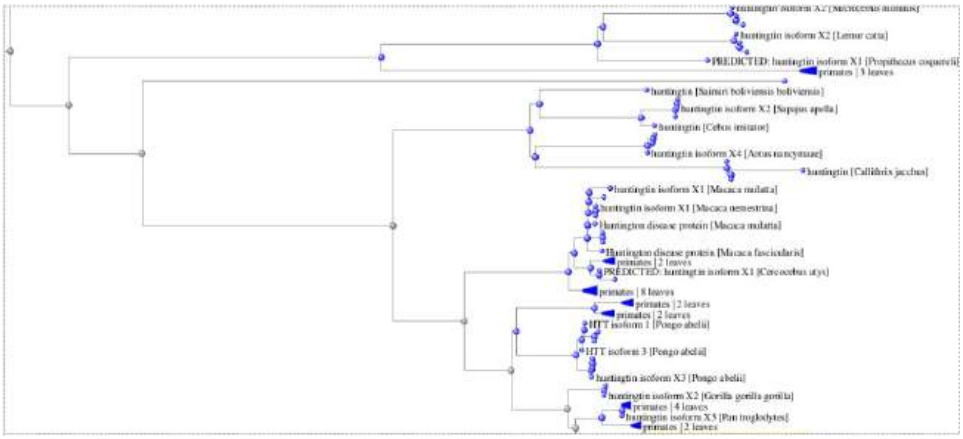



Figure 3: Branching diagram of species with further branches from the bottom are less closely related to humans

A phylogenetic examination conducted for the HTT protein on the NCBI database shows that most species containing HTT are very closely related to humans with very few exceptions. These few species with PolyQ repeats in the Huntingtin isoform X1 are plotted below by the number of their PolyQ repeats. Species in the phylogeny tree that are further away from humans do not contain the first exon as found in humans but carry an entirely different exon 1 without any the PolyQ repeats.

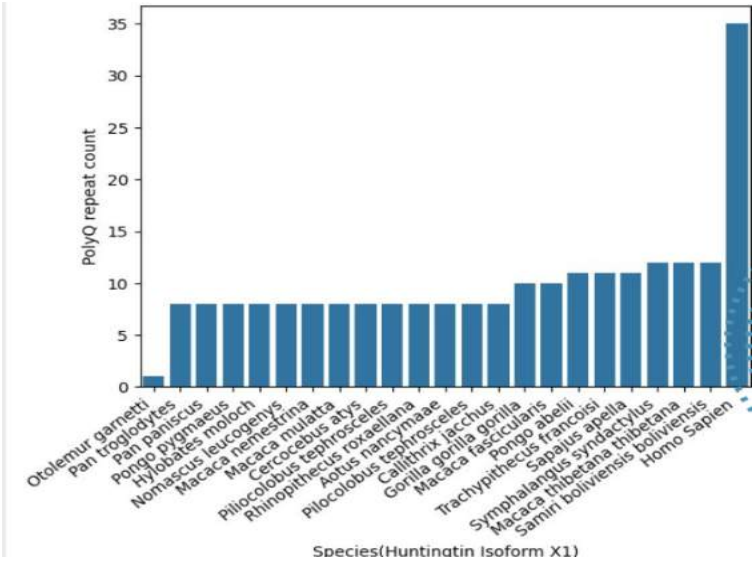



Figure 4:Bar graph of number cag repeats in the exon 1 of species closely related to humans

While PolyQ repeats are crucial for neural development, they are not a good track of organism intelligence, as despite the great apes having on average more counts of these repeats; there are several other species which have higher counts, as, if PolyQ repeats were a reliable track of intelligence, chimpanzees *(species name Pan troglodytes)* should have the second highest number of PolyQ repeats behind humans, which it does not.

These repeats may increase in counts from 21 repeats all the way to around 121 repeats, leading to an abnormally long polyQ chain which misfold the protein and create toxic insoluble inclusion clumps in the cytoplasm or nucleus of the cell as shown below;these are various cell samples of the inclusions of the misfolded huntingtin. These inclusions of toxic misfolded aggregates cause Huntington's disease, they have a toxic effect of MSNs, causing cell death.

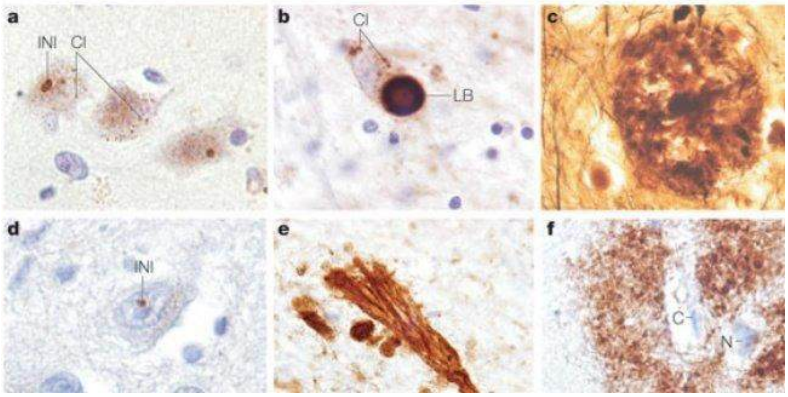



Figure 4:The red-brown markers are aggregates of misfolded huntingtin in the cell nucleus and cytoplasm,'

***Variants in Huntingtin***

Aside from the CAG expansion repeats, there are 5-7 other single nucleotide variants (SNVs) of *HTT* found to be pathogenic, according to the Clinvar database. One singular variant stands out from these, causing a disease known as LOMARS *(Lopes-Maciel-Rodan syndrome).* LOMARS is a Compound heterozygous missense Mutation of *HTT* which is extremely rare, with around 4 official recorded cases globally. It presents with symptoms similar to Rett syndromes such as delayed development, muscle weakness and seizures. Rett syndrome is caused by mutations in Methylcytosine-binding protein 2 (*MECP2*) gene. While HTT and MECP2 do not directly interact, PRPF40B, a protein that interacts with both HTT and MECP2, plays a crucial role in mediating their interaction. Mutations in PRPF40B can disrupt its interaction with MECP2, leading to weakened protein-protein interactions that are associated with LOMARS and Rett-like symptoms.

**OBJECTIVES**

Our objective was to understand the effect of the CAG repeat expansion that results in Huntington's and the SNV that results in LOMARS on the structure of the HTT protein. Protein structure and functions are closely related such that significant alterations in protein structure lead to changes in protein function as well as protein stability with varying mutations in the protein causing varying consequences. Understanding different structural consequences of variants in *HTT* is essential in order to better understand how the Huntingtin protein functionality may change, and in turn how Huntington's disease as a whole works.

Huntingtons disease was chosen because it is a monogenic disorder with a known ,well-defined genetic cause, making it ideal for studying how specific variants alter protein structure. The HTT gene uniquely contains both a common pathogenic repeat expansion (CAG/polyQ) and rare missense variants such as those causing LOMARS, allowing evaluation of different types of mutations within the same protein. This made HTT an excellent test case for developing and validating a computational method for variant analysis

Furthermore,HTT protein is large, complex, and difficult to resolve experimentally, studying it provides a meaningful context for testing whether AI-based and computational tools can overcome limitations faced by traditional structural biology methods.

**Methodology and Results**

***Introduction to Alpha fold***

Alpha fold AI is a highly accurate protein structure prediction model that takes an amino acid sequence , and a template structure as inputs, it models the protein structure using AI. It generates 5 different protein structures of ranks 1-5, with rank 1 being the most accurate prediction and rank 5 being the least accurate prediction. While Alpha fold is able to model it, Alpha fold has its own limits, as it can only model up to 1400 amino acids, so I took a small part of Huntington comprising the first exon to model through the Alpha fold AI. Which is also why 5 (Rank 1-5) different models were used for further comparisons. I generated 5 different samples of a Wildtype variant with a small and benign amount of CAG repeats which will be referred to as **"W"** and a Pathogenic variant with many CAG repeats which will be referred to as **"CAG"**.

While there exist public pdb files of the structure of Huntingtin; the techniques used to generate them such as cryoEM, were unable to resolve the exon 1 of Huntingtin which is the area of interest I require containing the PolyQ. So I computationally modelled the first 1400 amino acids of HTT using Alpha Fold.

***Checking Structural differences***

Using the Alpha fold AI, I checked if there were any Structural differences in the rest of the protein structure when there was an expanded polyglutamine repeat present in the protein, I aligned the first 1400 amino acids of two Huntingtin proteins with the RCSB pairwise alignment tool to understand any structural differences aside from the Polyglutamine chain. To account for the randomness of the Alpha fold tool, 25 individual alignments and root mean square deviation

(RMSD) calculations across the 5 different structures were made to get a larger sample size. RMSD value is the means of measurement of the deviation between 2 different placement and arrangements of atoms across the entire alignment.

pLDDT score, as seen in the bottom left, determines the confidence and accuracy level of the protein structure according to the Alpha fold AI which is seen in the sample generated. This is a Huntingtin protein structure with 80 CAG repeats and a very long chain which is distinctly abnormal in this pathogenic variant and has a high-medium confidence level. The reason parts of the protein have a very low confidence level is because of how dynamic a few parts of the proteins are, thus their exact location may vary in multiple samples.

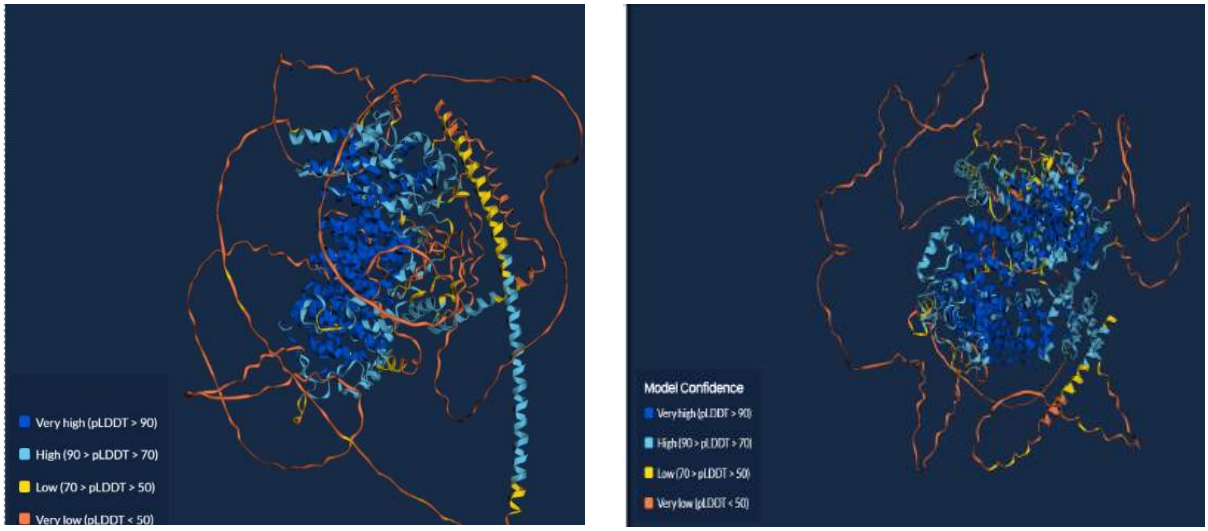



Figure 5:Pathogenic variant sample (Left) versus Wild Type variant sample (Right)

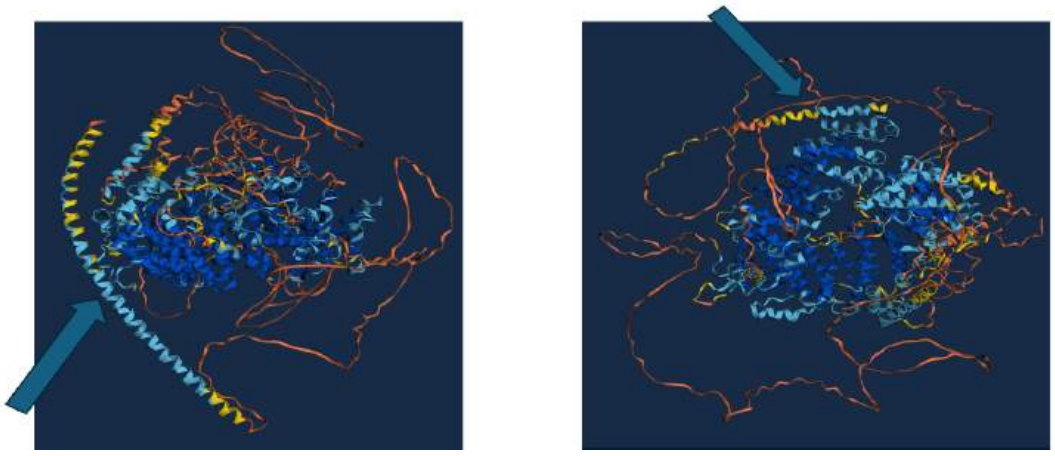


Figure 6:Visualisation of CAG repeats present in the huntingtin protein

After generating 5 samples of ***W*** and ***CAG***, I compared each sample against each other, I compared ***W/W, CAG/CAG***, and ***CAG/W.*** I compared different wild type samples against each other and different pathogenic samples against each other to find how similar each sample was to each other to determine the baseline variability of Alpha Fold AI predictions. I did this using the RMSD value of each protein structure, which gave us an accurate figure of the similarities and how different protein samples were.

***RCSB pairwise tool results***

Upon looking at each structure in the RCSB pairwise alignment tool, 1 structure is represented in orange, while the other is in blue when comparing.

As can be seen in the ***'W/W'*** comparison, the structure of the same protein would differ due to the inherent uncertainty in prediction by Alpha fold AI, as it generates each structure of the protein separately. Sometimes these structures would be slightly different with parts of the protein being out of place as seen in the overlapping of two structures of the same protein.

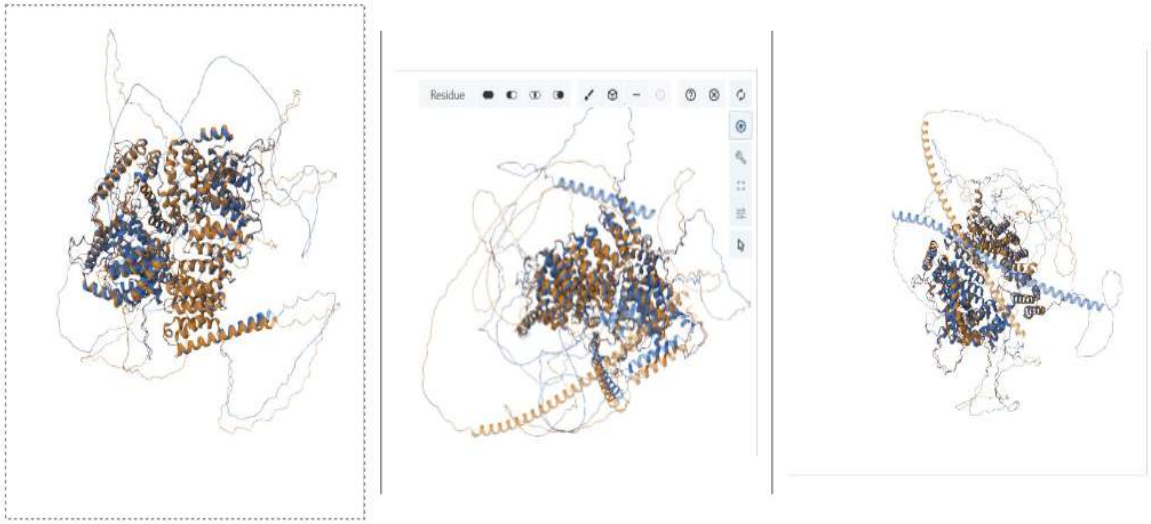



Figure 6:Protein alignment comparisons of Wildtype/Wildtype, Wildtype/Pathogenic, and Pathogenic/Pathogenic, in that order

One structural difference that was found was that with increasing CAG repeats the Alpha fold AI is increasingly unsure of the polyglutamine chain, as seen in the *'CAG/CAG'* comparison, where the polyglutamine chains had significant differences compared to the rest of the protein structure, this may be because of the instability of the protein with an increasingly big polyglutamine chain or it might be because of the Alpha fold AI unsure of the structure due to the abnormality.

Some of the limitations of this analysis include - the limited chunk of the Huntingtin protein that was used, limitations of the use of the Alpha Fold AI. For more accurate results, a

larger chunk of the protein could be used with a more accurate tool or a larger dataset can be taken in order to attain more reliable results.

After comparing all the results in the RCSB tool, I plotted the results on the graph of all the comparisons made

I got an average RMSD Value of:
3.514 for **'W/W'**
3.768 for **'W/CAG'**
3.886 for **'W/CAG'**

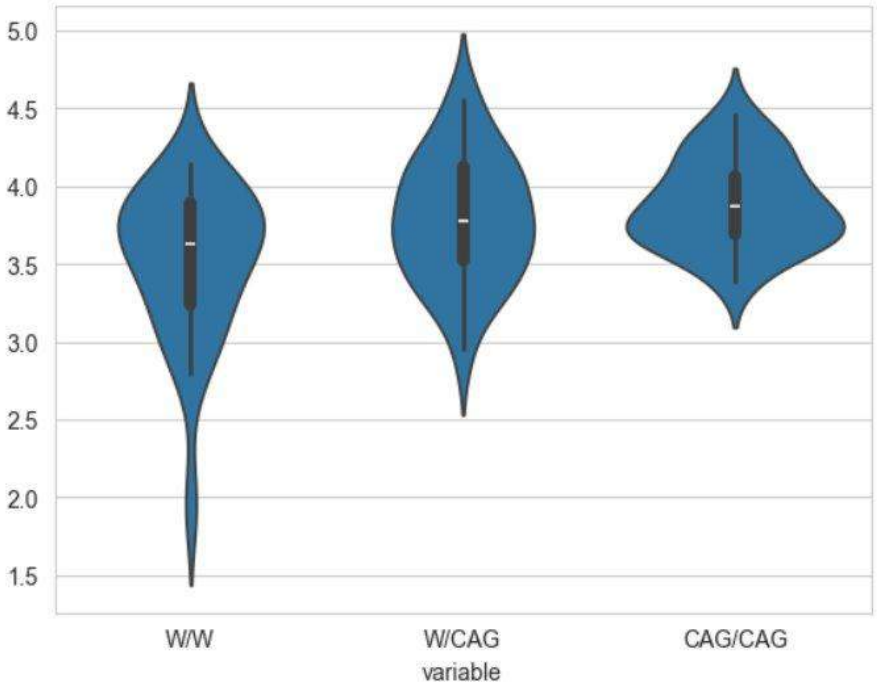



Figure 7: Mann-whitney U test results

As can be seen by the values themself, the number of CAG repeats has little difference on the structure.

***Statistical Analysis***

To statistically confirm this, I checked using 3 different tests if the samples had a normal probability distribution before further comparing their RMSD scores. I used the Shapiro-Wilk test, normal test, and the Anderson darling test and found that the samples had a skewed probability spread, so I tested it with a non parametric test,  the Mann-Whitney U test.

The Null hypothesis in this scenario was that;

**“The structures are not different because of the inherent randomness of the Alpha Fold AI”**

While the alternative hypothesis was;

**“Due to increasing the expansion of PolyQ; there is a noticeable different in the structure of the protein excluding the polyQ chain”**

I used the Mann-Whitney U test to check the probability that each sample is different. There was a 0.37 probability (p-value) when comparing the data sets of ***‘CAG’*** and ***‘W’*** that each difference in structure happened because of chance, proving that the structure remains similar and that there may not exist a significant difference between these structures (<0.05). Due to there being an extremely high chance of these structures not being different; I have to accept the Null hypothesis.

***YASARA and FoldX***

YASARA is a molecular-graphics, modelling and simulation program and FoldX is an addon for YASARA, it is a protein design algorithm that uses an empirical force field. It can determine the energetic effect of point mutations as well as the interaction energy of protein complexes which can determine changes in stability of a protein.

For our tests- I will check for the change in protein stability by measuring the Gibbs’ free energy ( $\Delta$ G) upon point mutations in FoldX. I will be changing a wild type variant of Huntingtin into a missense mutation that causes LOMARS. To do this- I will inflict a point mutation in the 703rd amino acid- changing a proline to a leucine which causes the missense mutation- causing LOMARS.

To compare the stability difference I will check the change in energy before and after inflicting the point mutation. Before checking the point mutation changes, I first had to ‘Repair’ the protein structure, this identifies residues which have bad torsion angles, or VanderWaals’ clashes, or total energy, and repairs them to attain the least energy obtainable for the given structure.

The way it operates is the following: First it looks for all Asn, Gln and His residues and flips them by 180 degrees. This is done to prevent incorrect rotamer assignment in the structure due to the fact that the electron density of Asn and Gln carboxamide groups is almost symmetrical and the correct placement can only be discerned by calculating the interactions with the surrounding atoms. The same applies to His, it does a small optimization of the side chains to eliminate small VanderWaals’ clashes. This way it will prevent moving side chains in the final step. It identify the residues that have very bad energies and I mutate them and their neighbours to themselves exploring different rotamer combinations to find a new energy minimum

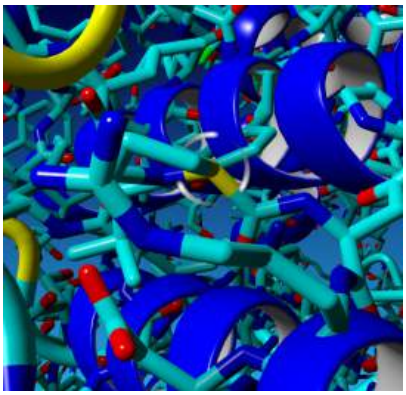


Figure 8 The highlighted amino acid is proline before the point mutation, it has been "repaired" with a significantly lower energy level, with the original Huntingtin protein having an overall energy level of around 959.5 kcal/mol.

Above is the "repaired form" with an energy stability of 638.12 kcal/mol, upon mutating the repaired structure of the protein, from the proline to the leucine,it has not changed much structurally but has an increased overall energy to 639.77 kcal/mol.

**Discussion**

Through this project, I wanted to understand and check the structural consequences in the Huntingtin protein caused due to the presence of variations that are known to be pathogenic. I tested two variants in HTT - The PolyQ repeats found in Huntington's disease and a missense SNV found in LOMARS disease. To determine the effect of PolyQ repeats on HTT protein I used Alpha Fold AI to model a pathogenic number of PolyQ repeats in HTT. I compared this Alpha Fold modelled pathogenic structure to the wildtype protein structure by aligning them using the RCSB alignment tool.

AI-based tools like AlphaFold proved useful for generating structural models and comparing broad conformational features, but they showed limitations in precision for highly disordered or abnormal regions such as long polyglutamine tracts. While the method was effective for overall structure comparison, it could not reliably detect subtle structural disruptions caused by CAG expansion.

Upon comparing the RMSD of the two structures I did not find a significant difference between them. This could be a result of limitations in Alpha Fold with regard to the maximum size of protein that can be modelled and the variability that exists in its predictions. I used Yasara and FoldX to introduce the SNV found in LOMARS in the HTT protein. I found that the protein with the SNV has a 1.65kcal/mol increase in energy; which leads to structural destability suggesting that the pathogenic mutation causing LOMARS of Huntingtin protein is less stable than the wild type.

The method of using computational and AI tools developed in this project can be applied broadly to other proteins to assess the structural consequences of genetic variants. By using AlphaFold AI  to model the wild-type and mutant protein sequences, followed by RCSB pairwise structural alignment and RMSD comparison, researchers can rapidly determine whether a given mutation produces detectable conformational changes. When deeper analysis is needed, tools like YASARA and FoldX can be used to quantify changes in thermodynamic stability (ΔG) for specific point mutations.

Compared to experimental structural biology techniques such as cryo-electron microscopy (cryo-EM), X-ray crystallography, or NMR spectroscopy.Thecomputational and AI method established in this study is significantly faster, more cost-effective, and does not require specialised laboratory equipment.,this can be used a preliminary screening tool to quickly identify which variants are likely to alter protein folding or stability. Such computational pre-analysis can guide laboratory experiments, help prioritize clinically relevant mutations, and accelerate research on rare diseases where experimental data is limited.

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**Demand Surges in the Pokémon TCG Market, and How Resellers Facilitate Bubbles**
**By Clayton Song**


## Abstract

A staple of the Pokémon franchise, Pokémon Trading Card Game (Pokémon TCG) brings together collectors and players who buy and sell Pokémon cards, which are collected at random from sealed Pokémon booster packs. Although the market is normally stable (sealed products have set retail prices by The Pokémon Company), starting in November 2024, secondary market prices have consistently risen, while sealed Pokémon TCG products in retail stores have been sold out completely. To investigate this, price and sales volume data of Elite Trainer Boxes (a type of sealed product) were extracted from graphs on one of the leading marketplaces, TCGplayer, and analyzed. From the revealed trends, it can be determined that the releases of both the mobile app *Pokémon TCG Pocket* and the expansion Prismatic Evolutions contributed greatly to the growth of demand and steady price hikes since November. Additionally, the large but decreasing supply on TCGplayer helps to identify the roles of the primary consumers in the market: scalpers (people who aggressively purchase retail products and then quickly resell for profit), collectors, and investors. Through these discoveries, it can be concluded that the increased demand for sealed Pokémon TCG products created incentives for competitive buying of retail products and resale on the market, which ultimately led to shortages, as The Pokémon Company could not keep up with the snowballing demand. By understanding the catalysts and the internal conditions of the Pokémon TCG market that facilitated these shortages, The Pokémon Company can better prepare for future demand surges.


## 1. Introduction

### *The Pokémon Franchise and Trading Card Game*

In February 1996, Satoshi Tajiri released the first *Pokémon* game, creating a fictional world of "pocket monsters" that featured iconic characters like Charizard and Pikachu, with a cast of 151 Pokémon. Fast forward to today, with over 1,000 unique characters, *Pokémon* has become the second-largest video game franchise, encompassing numerous video games, an anime series, a live-action movie, and more (1). One of the more successful ventures by the franchise has been the Pokémon Trading Card Game (Pokémon TCG), a collectible card game developed just eight months after the creation of Pokémon. As the franchise gained a global presence, Pokémon TCG saw success as a competitive game, hosting its first-ever international tournament in 2004 (2). This growth quickly made Pokémon TCG renowned for its flashy artworks and rare cards, and so the hobby of Pokémon card collecting was born.

### *The Pokémon Card Market*

Since the creation of the TCG, Pokémon card collecting has only increased in popularity, leading to the development of an extensive secondary market through platforms like eBay and

TCGplayer, as well as physical card shows. Pokémon cards are normally collected by opening booster packs, each containing a random selection of cards, making it difficult to get any one specific card (especially rarer ones). Rather than leaving it up to luck, however, these marketplaces let TCG players directly buy their favorite cards for a collection or to complete a competitive deck by facilitating sales between players.

As the TCG continued to grow, The Pokémon Company increased its card production, quickly deflating many cards' value (3). In the current market, common cards are often worth a couple of cents at most. On the other hand, more popular cards can be worth hundreds or even thousands of dollars, such as the Evolving Skies Umbreon VMAX, which sold for upwards of $1,700 in January 2025, as collectors chase after certain cards' art and popularity. The allure and potential profit of these rare cards have significantly increased demand for sealed products, leading to competitive buying of retail products by Pokémon fans and other consumers seeking a profit. On the secondary market, higher demand has driven the prices of booster packs up high above the manufacturer's suggested retail price (MSRP). While newer booster packs have an MSRP of $4.49 each, for example, they often sell for prices around $7, and any sold at MSRP are quickly sold out and resold on the secondary market at this inflated price (4).

The climbing prices of sealed Pokémon TCG products have been troublesome, as they severely limit accessibility to Pokémon TCG for casual fans. The Pokémon Company has made efforts to combat this, as they keep MSRP static, only increasing it every 2–3 years, and continuously restocking. Despite this, aggressive buying has kept retail products in short supply, even those released recently. While a demand increase would reasonably explain the price hikes, it fails to explain the visible shortage in both retail (primary) and secondary markets.

***Prevalent Trends and Hypothesis***

In a standard supply-and-demand model, two forces could increase the price of cards: increased demand or decreased supply. Pokémon card prices have generally been influenced by demand, as parallel trends in price and quantity of booster packs sold on secondary marketplaces suggest demand shifts. The consistent production of booster packs by The Pokémon Company has also kept the supply in surplus since the pandemic, keeping prices on secondary marketplaces at or below MSRP. In waves of high popularity, the increased demand usually spills over to third-party sellers, driving the price and quantity sold of booster packs up until the excitement dies down and prices stabilize. More recently, however, Pokémon card and booster pack prices have skyrocketed while The Pokémon Company fails to keep up with production. Booster packs have more than doubled or even tripled in price from a year ago, making it hard for casual fans or collectors to enjoy the hobby. This paper will explore the trends in the price and quantity sold of Pokémon booster packs and how shifts in Pokémon TCG customers have affected the supply and demand of Pokémon cards. Through analyzing prices and sales volumes of Pokémon cards and sealed products, it can be observed that increased demand from a large population of resellers and collectors has driven sealed Pokémon TCG products into shortage while facilitating price hikes.

## 2. Context

To understand the excitement that causes fans to spend hundreds of dollars on boxes of booster packs, it's important to examine how Pokémon cards work and the existing ecosystem of consumers. This section will examine what makes certain Pokémon cards (specifically "hits") valuable, while explaining historical trends in Pokémon cards that exemplify how scalping has affected the hobby in the past.

### *Pokémon Card Categorization*

Pokémon cards are first categorized into "series." Within Pokémon TCG, series are a fundamental division, primarily defining which cards are permitted in competitive play and the available card rarities (5). While series also apply to other aspects of the Pokémon franchise, like video games and the anime, this paper focuses on their role in the TCG. Within each series, Pokémon cards exist in sets known as "expansions," each featuring a unique title, chain of related products, and, most importantly, a set of cards. The most recent series and focus of the study, Scarlet & Violet, contains 16 expansions, such as Surging Sparks and Twilight Masquerade, which in turn include Pikachu ex and Latias ex (Surging Sparks) and Greninja ex and Perrin (Twilight Masquerade), to name the two most valuable cards of both. Of these expansions, three had not yet been released during the studied period, so the focus will fall on the other 13. For a player to have a chance to get a specific card, they must open a booster pack of the expansion it belongs to. This means the set of cards available in an expansion determines the demand for the booster packs from a specific expansion and the expansion's popularity overall.

### *Rarity and Value*

While there are a lot of interesting and competitively viable Pokémon cards out there, the main attraction has always been the elusive rare cards, featuring a special artwork and shiny luster. These cards are known as "hits," with the most sought-after known as "chases," accordingly worth the most (6). These chase cards are often cards of popular Pokémon or exceptional art, or in some cases both, such as Paldea Evolved's Magikarp. For Scarlet & Violet, the rarities are (in ascending order of rarity): common, uncommon, rare, double rare, ultra rare, illustration rare, special illustration rare (SIR), and hyper rare (HR). Cards with rarities of double rare or higher are considered hits (6).

Rarity is an important factor in determining the available supply of a card, with higher rarity cards existing in fewer quantities. Although this is a key characteristic, a card's market value is often more significantly influenced by its appeal to collectors. SIRs are often worth more than their HR counterparts, especially as of the Scarlet & Violet era, despite being more common. Consider the card Alolan Exeggutor ex from the Surging Sparks expansion, released on November 8, 2024.




Fig 1: Images from TCGplayer. Left: Surging Sparks Alolan Exeggutor ex (SIR), Right: Surging Sparks Alolan Exeggutor ex (HR).

The HR version of the card has consistently sold at $10–20, whereas the SIR sells for generally around $40–60, demonstrating that rarity alone doesn't determine a card's price. Similarly, Pikachu ex from the same expansion exhibits a similar trend, with the price of the SIR being worth 2–5 times more than the HR. Another point to note is that the Pikachu ex SIR has sold between $250–500, despite having the same rarity as the Alolan Exeggutor ex SIR. This is explained by the fact that Pikachu ex is a more popular card, which is to be expected when dealing with the mascot of Pokémon. Other factors can also affect the popularity of cards, such as the quality of artwork or simply nostalgia. Whatever the case, price is most directly influenced by a card's popularity.

***Card Grading***

Another option collectors have to pursue rarer and more valuable cards is grading, which Professional Sports Authenticator (PSA) defines as "assessing the quality and condition of a trading card" (7). Grading a card can quantify its quality and preserve it, increasing its value and price. This is done by examining any human-inflicted damage to the card, but also the precision of manufacturing, leaving some factors out of a collector's control. Although there exist other companies such as CGC and Beckett, PSA and its 10-point scale remain the most popular, where a single card can be graded for $25 and with a two-month wait. Despite the high cost, grading a card has the potential to increase a card's value greatly. On the market, PSA 10 cards often have a price triple that of their ungraded counterparts, equating to hundreds of dollars on high-value cards. This possibility for a nearly perfectly printed card adds another way to enhance a collection, further increasing the potential value of a booster pack.

***Printing***

Millennium Print Group (MPG), a subsidiary of The Pokémon Company, is in charge of printing all Pokémon cards from start to finish (8). MPG prints billions of Pokémon cards a year with high precision, such that severely misprinted cards can be worth thousands of dollars. Most

cards are printed in the United States, while some other language cards, like Portuguese and Japanese cards, are printed in Brazil and Japan. Cards are printed in different quantities depending on their rarity and language; they will continue to be printed until they are eventually rotated out of the printing cycle after about two years (with some exceptions). Once cards are printed, they are grouped into booster packs, which typically contain 10 cards (five for Japanese booster packs), each containing a special, higher rarity card as one of the last cards. These booster packs are what customers will finally buy.

***Distribution***

Opening booster packs is the primary way of obtaining new Pokémon cards, especially rarer, high-value cards. While some booster packs are sold in singular form, most are retailed in sets or boxes. Some examples include Booster Bundles and Display Boxes, containing six and 36 booster packs, respectively, with the latter intended to be sold to retailers where customers would then purchase individual booster packs. These sets, boxes, and individual booster packs are sent to distributors, who sell them at wholesale prices to retailers. From there, some retailers like Target and Costco choose to sell at MSRP; others sell at their own prices. These market prices are based on the cards available in a booster pack and their popularity. Booster packs from an expansion with popular cards, such as Paldean Fates, which features Mew ex and Charizard ex cards, are worth considerably more than those from an expansion like Shrouded Fable with lesser-known cards. As Pokémon continues to grow in popularity, The Pokémon Company has kept card production high, printing over 10 billion cards in 2024, beating its previous record of 9.7 billion in 2023, according to The Pokémon Company's figures reports (3).

***Elite Trainer Boxes***

One hallmark sealed Pokémon TCG product for people getting into the hobby and lifelong collectors alike is Elite Trainer Boxes (ETBs). These large, decorated boxes are visibly marketed toward new players, including card sleeves, a player's guide, and other pieces needed to play the card game (i.e., coins and damage counters).




Fig 2: Surging Sparks ETB product contents from Pokémon Center, the official Pokémon store.

The Pokémon Company only releases one or two ETBs for each expansion, though they all have an MSRP of $49.99. Carrying a bulk of the value, however, are the booster packs they contain, with each ETB containing 9 booster packs corresponding to its expansion. The booster packs on their own would only cost around $40; however, the difference is made up by the accessories within ETBs and an additional “promo” card.

***Promo cards***

Promo cards, unlike other Pokémon cards, cannot be pulled from booster packs, but are rather sold along with different products or during special events like the World Championships. These cards have unique art, making them desirable still, even though they aren’t found by chance. Promo cards come in different forms, with some similar to non-hits, and others with full arts comparable to IRs and SIRs. They also function differently in value, as their supply is dictated by The Pokémon Company, and can become extremely rare collector's items in some cases. For ETBs, each box contains one promo card specific to the box, tying the two together. The demand for a promo card is therefore related to the demand for an ETB: when a promo card becomes more popular, because buying the corresponding ETB is the only way to get new ones, the popularity or price of the promo card may further justify a purchase. The Pokémon Company also sells special ETBs on Pokémon Center, their official store. Pokémon Center ETBs include more booster packs and a special stamped promo card, making the box and promo card worth more. These are shorter in supply and harder to get, however, and normally targeted toward collectors.

***Demand***

The primary demand for Pokémon cards has always come from collectors, as they chase the fanciest and most exclusive cards. The presence of a secondary market, however, has also led to a large number of Pokémon card speculators who invest in cards, booster packs, and other related items. Speculation in the Pokémon card market has exacerbated demand trends and periods of high excitement in the Pokémon TCG scene. As Pokémon card prices trend upward over time, investors purchase copies, holding them over long periods, anticipating an increased price in the long run, especially during high demand. As a result, prices climb further, and more speculators notice these upward trends. High card prices also increase the potential profit of booster packs, attracting a third group that hopes for lucky draws and opens booster packs for money. This combination of traditional collectors, investors, and profit-seekers has contributed to a strong and steady demand for sealed Pokémon TCG products.

The Pokémon Company has historically done a good job of handling the high and growing demand for Pokémon cards, increasing printing accordingly. As a result, sealed Pokémon TCG products could be easily found and purchased by casual and potential new fans. Despite these best attempts, however, unpredictable waves of popularity can catch the Pokémon company off guard, with the last wave of excitement before 2025 occurring in 2021 (9). With a surge of new fans due to the pandemic and a series of successful Pokémon products, Pokémon as

a franchise was at an all-time high. This hype, along with global supply chain disruptions from COVID-19, was bound to cause shortages, which finally came with the release of the Evolving Skies expansion. The expansion featured the Eeveelution line, an incredibly popular set of Pokémon, alongside other well-known Pokémon, contributing to the booster pack's popularity. While the price remained stable at first, as collectors took interest in lower-tier cards in the set, the price of booster packs climbed rapidly. With such high profit margins and continuous demand for the booster pack, stores sold out quickly, with cards becoming only available on secondary marketplaces like eBay or TCGplayer. Pokémon cards were being scalped.

***Scalping***

While somewhat similar to regular investing, Pokémon card scalping involves more aggressive behavior. Scalpers buy out retail stores, rapidly depleting the stock of retail-sold Pokémon products so they can be resold at a higher price, with or without the intention of creating a shortage by withholding supply. Because consumer demand was so high at the time, these products could be sold on secondary markets at these inflated prices; The Pokémon Company does not change its prices, so scalpers pocket the difference. This resulted in a mad dash to buy booster packs and other Pokémon products, severely limiting availability (10). Investing, as opposed to scalping, involves speculation that prices will increase in the long run, not resulting in the same aggressive buying. Though it may also contribute to these supply shortages, the effect is much smaller and is generally sustainable.

Following the wave of popularity and scalping in 2021, Pokémon cooled down, with supply returning as other expansions continued to be released. Prices stayed calm until January of 2025, the release of Prismatic Evolutions, another Eeveelutions set. Interest had already been building up with the release of the Surging Sparks expansion a few months prior, but Prismatic Evolutions pushed the Pokémon community to its tipping point (10). Upon its release, Prismatic Evolutions booster packs were worth $12 or more, well over the $4.49 MSRP of Scarlet & Violet era booster packs. Scalpers were attracted to this wide profit margin, racing to registers and buying as many booster packs as they could. To make things worse, The Pokémon Company's tendency to release different products for any given expansion over time meant supply was minimal at first, causing shortages that forced stores to cancel pre-orders and place limits on purchases. People only turned to more extreme methods, however, camping outside GameStops and tracking distributors to get their hands on Prismatic Evolutions or any sealed Pokémon TCG products at all (11).

For casual fans, this was a disaster. It became nearly impossible to buy booster packs being sold at MSRP, let alone find them at all. Stores were sold out online and in person, unless they charged similar prices to those on eBay and TCGplayer. Furthermore, this effect seemed to spread, with other expansions slowly creeping up in price and becoming less available. Even the less popular sets seemed to be out of stock everywhere you looked, resulting from the overall excitement surrounding Pokémon TCG at the time. With all products being scalped, it became increasingly difficult for casual fans to collect Pokémon cards.

The Pokémon TCG market has been historically susceptible to forming bubbles like this, fueled by surges in excitement and driven by scalping, competitive buying, and investor euphoria. Despite these fragile conditions, there is little to no existing literature on the condition of this market and the Pokémon TCG consumer ecosystem. As a result, this paper will focus on primary research to determine the behavior of the consumer base.

## 3. Methods

### *Data Sourcing*

To capture shifts in supply and demand, the price and quantity sold of select ETBs and their respective promo cards were examined. If the price and quantity sold were identified to trend in opposite directions, it could be determined that there was a dominant shift in supply in the specific market. Conversely, if the price and quantity sold showed similar direction trends, then it would suggest a dominant shift in demand. To maintain a reasonable scope and focus on current trends, all 13 Scarlet & Violet era expansions as of May 2025 were selected. For each expansion, the price and quantity sold of an ETB and its promo card would be tracked. The promo card could hopefully demonstrate the strength of demand for an individual ETB, though it wouldn't be a completely accurate indicator, as other factors like the popularity of the specific Pokémon on the card would be more influential.

For the expansions with two different versions of ETBs (Base Set, Paradox Rift, and Temporal Forces), there was no significant difference in trends of price or quantity sold of either ETB version, mainly because the booster packs they contained were all the same, with the only difference in value being the promo card in each. Despite this, the pairs of ETB promo cards from these expansions were similar in price and volume, so a random one of the two ETBs and its corresponding promo card were selected for each of the three expansions, as these minute differences within expansions are irrelevant.

The next step after choosing what to track was to determine where to find it. In-person sales at card shows would be difficult to track, so looking at online marketplaces was the best option. Among the most popular online marketplaces for Pokémon cards, TCGplayer (tcgplayer.com) was chosen for certain advantages. For one, TCGplayer focuses more on the sale of individual products, rather than miscellaneous combinations of items that are frequently seen on eBay or Facebook Marketplace, giving access to more specific data. More importantly, however, TCGplayer includes graphs that show weekly price and sales volume, which can be used to identify price and quantity trends. As one of the most trusted marketplaces and pricing tools for Pokémon TCG, TCGplayer was the best choice to provide accurate and reliable data.

### *Data Collection*

While TCGplayer doesn't have publicly available formatted data, both price and volume per week could be manually recorded using WebPlotDigitizer, a tool for extracting numerical data from graphs. Data was collected for 50 weeks for all 14 ETBs and promo cards, starting on

the week of June 3, 2024, until the week of May 19, 2025. For any ETBs released after June 3, 2024, the data was collected from the week of prerelease until the same week of May 19, 2025. Additional data was also collected from Pokémon Wizard (pokemonwizard.com), which stored TCGplayer price data starting from 2020. This source didn't provide volume data, but its extended timeframe made it a valuable source for additional data for prices of cards and ETBs released early on in Scarlet & Violet's lifetime.

***Control***

TCGplayer has different options for language and quality of the different products sold. ETBs were filtered for the quality "unopened" to align with the goal of investigating resales, and also because very few opened ETBs are sold. Promo cards were filtered for the quality "near mint" for similar reasons. All the data used is from English versions of the products, which were the most popular and the most affected by the scalping wave.

***Data processing and analysis***

Price changes of ETBs were generally consistent, and trends could be easily identified. However, volumes tended to vary from week to week. To solve this, both the prices and volumes sold were put on a four-week rolling average by averaging data points over a four-week window, so trends could be determined more accurately. The prices were then plotted against the smoothed volumes and examined. These graphs were visually assessed for overall trends, and relative extrema were evaluated for whether they were turning points in the data. It was noted where price and volume diverged by identifying where the slopes of price and volume trends began to move in opposite directions. The dates of the changes were then recorded for when the divide occurred.

To reinforce the assertion of trends, the correlation between both weekly price and volume sold of each ETB was measured. To accomplish this, the direction and $R^2$ value were calculated for volume as the dependent variable and price as the independent variable. This was done for two periods: from the week starting November 4, 2024, to the point where trends were identified to have changed (which will be explained further in Results), and from the same point to the week starting May 19, 2025. November 1, 2024, was determined to be the beginning of a TCG-wide demand growth, so the closest later date was taken as a starting point for identifying trends. The week of May 19 was the most recent data point in the study period, so it would encapsulate the current persisting trend.

To analyze promo cards, weekly prices, and volumes were directly plotted against one another. Price data showed some noticeable trends, while quantity was frequently sporadic and generally inconsistent. Because they exhibited limited correlation to any ETB trends, which will be discussed later, promo cards and their associated graphs were not analyzed in depth, but rather observed to look for potential broad trends.

***Limitations***

Because raw sales data on TCGplayer was restricted, the data was extracted manually, which could lead to errors and deviations from the actual data. To mitigate this risk, random data points were compared to the reported points on TCGplayer, revealing differences of around 5% at most in both price and quantity. Additionally, the large week-to-week changes in price and quantity largely trivialize these variations, and differences were often consistent for all data points of any given ETB or promo card analyzed, making the findings of trends still significant. The visual assessment of divergence and trend direction may also limit the precision of significant dates; however, all changes occurred in a recognizable two to three-week range, and only general accuracy is needed to support the claims of the paper.

Another consideration is the focus on only the English Pokémon card market. English cards were selected because they represent the largest portion of all Pokémon cards and are generally worth more than their Japanese counterparts, though market trends and behavior may differ between the two. Ultimately, Japanese Pokémon cards and the corresponding market are beyond the scope of the research, which limits this paper's conclusions on The Pokémon Company's actions.

## 4. Results

The overall trend for ETB prices was up. Prices generally climbed slowly in the earlier months of 2024, growing much faster as the weeks neared January 2025. Most ETBs, except for already popular sets, began under the $50 MSRP line in June 2024, slowly growing towards and past MSRP during this time. Quantities sold also saw a steady increase in this initial period, growing consistently, though at different rates and amounts, across expansions.

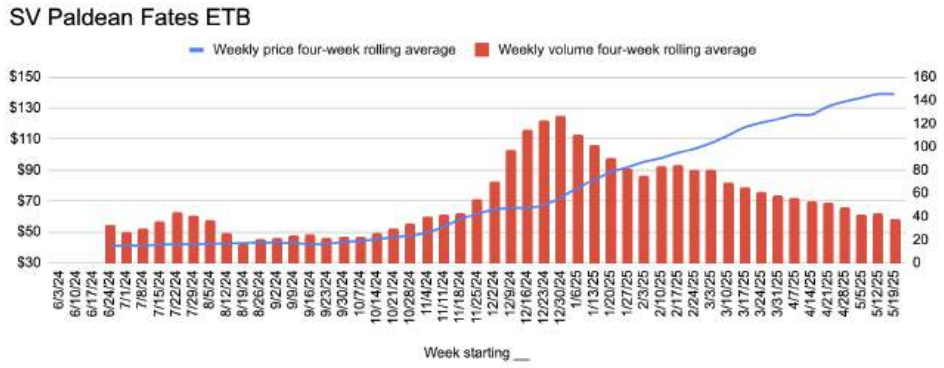



Fig 3: Scarlet & Violet Paldean Fates ETB graph. Correlation of averaged weekly price and volume sold: 11/4/24–12/30/24 (moderately strong positive correlation, $R^2$=0.79), 12/30/24–5/19/25 (strong negative correlation, $R^2$=0.95). Explanation of chosen dates and swap dates in the following section.

Supply and demand models tell us that these upward trends in both price and volume suggest an early rightward shift in demand between June 2024 and January 2025. It's worth noting that this trend is exclusive to this secondary market and is not indicative of retailers in general, especially those that sell at MSRP.

***Passing and Swap Dates***

Starting in December 2024 and January 2025, trends begin to diverge. The price consistently climbed for the next few months, until around March. Some ETBs continued to grow at steady rates, while others slowed down in growth, and some plateaued or fluctuated around a single price. Volume shows an opposite trend, however, beginning to decrease for some ETBs in the months following January. This combination of a price increase and a decrease in quantity sold suggests a more significant leftward shift, or a decrease in supply. The dates when each ETB's price transitions from being demand-driven to supply-driven, which will be referred to as "swap dates," can be determined by finding the turning point in weekly volume, with all these dates falling between January and March of 2025. Another important date to track is the first day an ETB passes MSRP, or $50 in price, which will be referred to as "passing dates," as this is when a margin would've appeared between MSRP and market prices that could be appropriated.

| Expansion | Swap Date | Passing Date |
|---|---|---|
| SV Surging Sparks | 12/16/24 | 11/11/24 |
| SV 151 | 12/30/24 | 0* |
| SV Paldean Fates | 12/30/24 | 10/28/24 |
| SV Paldea Evolved | 1/20/25 | 12/30/24 |
| SV Obsidian Flames | 1/20/25 | 12/9/24 |
| SV Temporal Forces | 1/20/25 | 1/20/25 |
| SV Prismatic Evolutions | 1/27/25 | 0** |
| SV Shrouded Fable | 2/3/25 | 2/24/25 |
| SV Base Set | 3/3/25 | 2/10/25 |
| SV Paradox Rift | 3/3/25 | 2/3/25 |
| SV Stellar Crown | 3/3/25 | 1/27/25 |
| SV Twilight Masquerade | 3/17/25 | 12/16/25 |
| SV Journey Together | 0*** | 0** |

**Table 1.** Swap and passing dates by expansion.
**The 151 ETB began over $50 at the start of the data period.*
***Prismatic Evolutions and Journey Together ETBs were released with a TCGplayer price over $50.*
****The Journey Together ETB doesn't exhibit a clear swapping point.*

For the most recent expansion as of May 2025, Journey Together, the market still hasn't had time to settle, and The Pokémon Company is still supplying ETBs in waves, making it difficult for the secondary market to stabilize into trends.

The ETBs with the earliest swap dates were Paldean Fates, Surging Sparks, and 151, which were also the first ETBs to surpass $50 (the prices of Prismatic Evolutions and Journey Together ETBs started above $50, while 151 didn't). The passing date for all ETBs that started

below $50 almost always precedes the swap date, with the only exception being Shrouded Fable, in which the passing date is three weeks after the swap date.

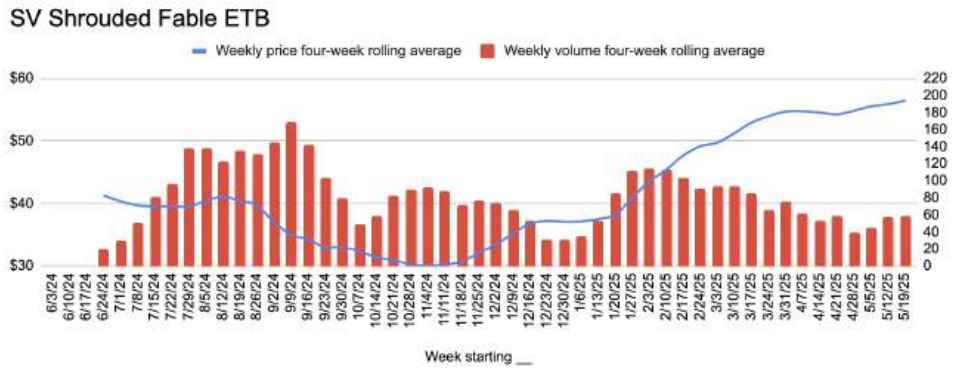


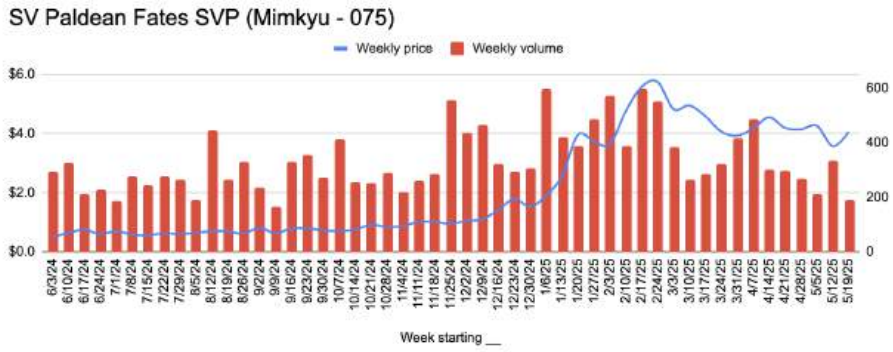

Fig 4: Scarlet & Violet Shrouded Fable ETB graph. Correlation of averaged weekly price and volume sold: 11/4/24–2/3/25 (very weak positive correlation, $R^2$=0.01), 2/3/25–5/19/25 (strong negative correlation, $R^2$=0.84). The Shrouded Fable ETB saw a decline in volume sold for some time following November 4, 2024, a unique trend among the Scarlet & Violet ETBs (aside from 151). These two represent the most and least popular expansions, and will be discussed in Sections 5.2 and 5.6.

***Promo Card Trends and Correlation to ETBs***

Promo cards, on the other hand, showed more ambiguous trends. For most promo cards, the increase in interest in Pokémon TCG in January 2025 did cause an increase in prices, though this growth usually stalled around March 2025. These price changes were somewhat reflected by volume trends, suggesting a more demand-influenced market. When comparing promo cards to their respective ETBs, the overall trends in both demand and supply couldn't confidently be matched between the two. Promo cards often exhibited dominant demand or supply shifts that weren't mirrored by their ETB counterparts.

Consider Paldean Fates's SVP, Mimikyu.

Fig 5: Scarlet & Violet Paldean Fates ETB promo card (Mimkyu, SVP 075) graph.



The card demonstrates no trend between June and November 2024, as the price stays steady and volume fluctuates. There is a subsequent price increase in November, which persists until February 2025. Although volume sold also increases, it is at a much smaller scale, which could imply a possible growth in demand. Then, following February, both price and volume sold fell, suggesting that demand decreased. Comparing this to the Paldean Fates ETB (see Figure 3), which shows a demand increase until January and a supply decrease after, there is no clear correlation between either supply or demand.

***Shrouded Fable's Results***

Shrouded Fable was an outlier on most metrics for both the ETB (see Figure 4) and the promo card, despite being released in the middle of the investigated range of expansions and a middle-ranking, albeit low, median price during the studied period. This stays true for promo card prices, as the Shrouded Fable promo card, Pecharunt, doesn't see any substantial sustained change in price, whereas other cards doubled or tripled in price, whether it be a $2 (like most cards) or $15 (Obsidian Flames Charmander) change in price.

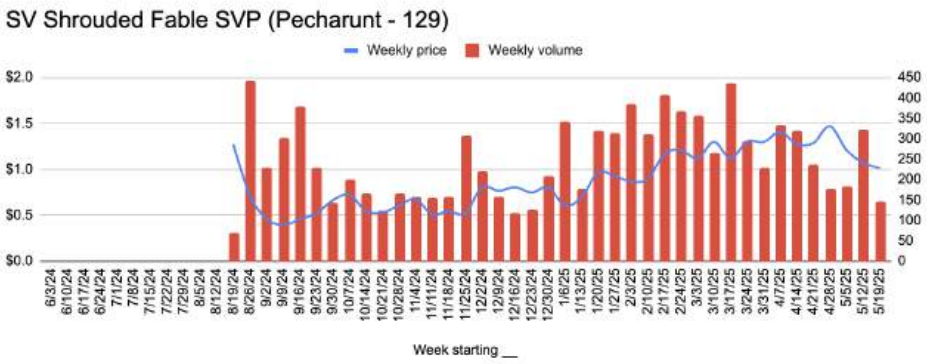



Fig 6: Scarlet & Violet Shrouded Fable ETB promo card (Pecharunt, SVP 129) graph.

The main trends identified show an initial surge in demand for ETBs on this secondary market, followed by a decrease in supply that drives down the overall quantity sold and increases prices. The dates of these swaps all occur after an ETB surpasses $50, except for the Shrouded Fable ETB. Prismatic Evolutions and Journey Together exhibit some different trends, both being released recently, and following the new wave of Pokémon card interest. Promo cards didn't exhibit as identifiable trends as ETBs, though they were generally unaffected by the supply shifts of the ETB market.

**5. Discussion**

It is challenging to pinpoint a single cause for the Pokémon card boom and subsequent price hike, as multiple factors within the Pokémon ecosystem contributed to its growth. It is

possible, however, to investigate how the different factors affected price and compounded upon each other during the period leading up to these swap dates and passing dates.

***Key Factors Increasing Demand***

An important trend in the prices of the ETBs was the accelerated increase in demand between November 2024 and January 2025, pulling prices toward and, for some, over the $50 MSRP mark. This timing directly correlates with the announcement of the Prismatic Evolutions expansion on November 1, 2024 (12). The expansion was highly anticipated and attracted interest from collectors and investors, driving the growth of demand for sealed Pokémon TCG products at the time. Another key factor was the release of *Pokémon TCG Pocket* on October 30, 2024, a mobile game that drew from aspects of the physical TCG, saw success upon release, seeing over 32 million downloads in its first month (13). This high number of downloads directly created a wave of returning and new fans for Pokémon TCG, further increasing the demand for Pokémon cards and booster packs. While there wasn't a shortage yet at this time, the combined interest generated by these two releases kicked off a major demand shock whose effect will be discussed in section 5.3. With Pokémon TCG starting to grow again, any products being sold below MSRP offered instant savings for those looking to buy, increasing demand on these secondary markets until the prices matched that of MSRP.

Although prices hadn't increased significantly yet, once this demand had grown enough and these factors drove ETB prices over $50, from that passing date, scalpers could now buy out ETBs at retail prices and resell them online for profit, effectively moving a majority of the supply of ETBs from retail, where they had static MSRP pricing, to the secondary market, where scalpers could resell at their own prices. With no supply of ETBs in retail, consumers would have to move to this market too, bringing their demand with them. The earliest ETBs to reach this point were Paldean Fates, Surging Sparks, and 151, with the passing dates of the first two being October 28 and November 11, respectively (see Table 1), and 151 being worth $63 on June 3, when the study started. These expansions each have features that make them desirable: Paldean Fates includes special "shiny" Pokémon rather than traditional arts, Surging Sparks contains the first SIR Pikachu ex in the whole Scarlet & Violet series, and 151 brought back familiar Pokémon, which will be expanded upon in the following section (14). All these features made these three expansions desirable and more popular than the others, with their ETBs passing dates occurring much earlier than the rest of the Scarlet & Violet expansions.

***The 151 Expansion as Evidence of The Pokémon Company's Capabilities***

151 was a special expansion, featuring all 151 original Pokémon from the first generation in new, modern art styles. The Pokémon Company knew this set would be a hit, as it drew upon nostalgia for the original Pokémon, which were already popular in their own right. As a result, when the set was released on September 22, 2023, demand exploded, with the price of an ETB on TCGplayer surpassing MSRP immediately (14). While this would have attracted scalpers, who then would exploit the high consumption to facilitate price hikes, The Pokémon Company

was ready, with a release schedule of products prepared to restock the underlying supply of booster packs for over a year. This strategy persisted into 2025, with the most recent Blooming Waters Premium Collection, released February 7, including 12 booster packs. As a result, 151 was never heavily scalped before mid-2024, hovering $10–20 above MSRP until around August, as seen by a majority of the ETB supply and subsequent demand arriving on the secondary market at that point (14).




Fig 7: Scarlet & Violet 151 ETB graph. Correlation of averaged weekly price and volume sold: 11/4/24–12/30/24 (weak negative correlation, $R^2$=0.39), 12/30/24–5/19/25 (strong negative correlation, $R^2$=0.85). The standardization of 11/4/24 as a starting point is inadequate here, so the pre-swap results are not indicative of trends.

The lack of scalping and the stable prices for such a long period, however, attest to The Pokémon Company's ability to anticipate the popularity of a set and plan production for over a year and a half to satisfy demand.

***The November Boom in Demand***

Aside from 151, before the Prismatic Evolutions announcement, no expansion was being sold heavily on the secondary market, and no ETB was worth more than MSRP nor being scalped (Paldean Fates passed an average price of $50 on the week of October 28, 2024, which was likely influenced by prices following November 1 but during the same week, explaining the passing date occurring before November 1). There had been a trend of small, steadily increasing demand, but it was not very significant. When Prismatic Evolutions was announced on November 1, 2024, however, the whole Pokémon market exploded. Prices suddenly took a sharp turn upwards, with more than half the ETBs worth over $50 just two months later. The growth of the most recent Pokémon video game at the time, *Pokémon Scarlet & Violet*, can be compared to the price growth of different ETBs to isolate whether it was solely the TCG that grew or some other external change. Copies sold data from Nintendo's website reveals that between the start of 2024 and May 2025, *Pokémon Scarlet & Violet* saw a small growth, an increase in total copies sold of around 1.5% per quarter (15). Compared to the TCG market, it's clear that the TCG saw special growth as opposed to overall increases. This reinforces the idea that the factors identified were the drivers of this growth, not economic or even franchise shifts.

Prismatic Evolutions was officially released on January 17 (12), accelerating prices further and drawing even more attention to Pokémon TCG. As for Prismatic Evolutions itself, an ETB traded for around $113 each upon release, making it the highest value Scarlet & Violet ETB immediately. Within two months, every Scarlet & Violet ETB was selling for more than MSRP, as observed by the passing dates, and by March, scalping proliferated across expansions, spreading the previously mentioned retail shortages and bringing a majority of demand onto the secondary market. Even Pokémon 151, which The Pokémon Company had managed to control thus far, began to see excessive scalping, with viral videos of fights breaking out at Costco over Blooming Waters Premium Collection boxes (16). Pokémon TCG had cracked under the pressure, and now things were getting out of control.

Overall, this demonstrates a strong collinearity between Prismatic Evolutions' lifecycle and the increasing demand that started around November; however, the release of *Pokémon TCG Pocket* was also around the same time and could reasonably explain such a change, potentially creating multicollinearity, which makes it difficult to pinpoint a cause. This problem will be explored in Section 5.5, which will propose a solution to identify the more significant cause.

***Supply Drives Prices as Demand Peaks***

Despite demand being intense in November, it wasn't infinite. Every ETB exhibited the same pattern, where price would continue to increase, but volume would start to fall. This indicated a tightening of supply, as even the secondary market entered a shortage. Take the Surging Sparks ETB, for example. Increasing demand was the main driving force in the market up until December 16, 2024 (Surging Sparks's swap date), when a decreasing quantity took control and pushed the price higher while volume decreased.




Fig 8: Scarlet & Violet Surging Sparks ETB graph. Correlation of averaged weekly price and volume sold: 11/4/24–12/16/24 (moderately strong positive correlation, $R^2$=0.78), 12/16/24–5/19/25 (strong negative correlation, $R^2$=0.87).

Several factors likely contributed to the decrease in supply, and it's possible to identify the reasons people would be less willing to resell their ETBs. Most prominently is because the physical amount of unopened ETBs is decreasing over this period. Almost all ETBs purchased

from a secondary market are then opened, as hobbyists and collectors still make up a majority of Pokémon consumers. This is especially true on the secondary market, as there's no value for scalpers to capture through buying an ETB and then reselling it. As a result, the number of unopened ETBs for sale drops, reducing supply. The other demographic purchasing ETBs is investors, who hope to hold onto these boxes and ultimately resell them at a higher price. While investors would resell and add back to the supply eventually, the consistently climbing prices over the studied period would incentivize them not to. Additionally, scalpers are also incentivized not to sell the ETBs they purchase from retailers, as this creates artificial scarcity, which drives prices higher and generates more profit. The combination of these behaviors culminates in a decreasing supply throughout the 50 weeks.

ETBs were being removed from the market from the beginning, but the demand-fueled price climbs were effectively sustained by The Pokémon Company's restocks. This demand would eventually hit a ceiling, as most consumers reached their maximum willingness to pay, and supply started to dwindle as shortages began. Then, around the swap dates, consumption started to outpace what The Pokémon Company could produce, accelerating the leftward shift in supply, while demand similarly slowed. Consequently, the decreasing supply became more significant than demand growth, leading to increasing prices and decreasing volumes plaguing the Pokémon market.

The trends in price and quantity of ETBs during this period shine a light on the behavioral habits of the Pokémon TCG ecosystem, demonstrating how collectors, scalpers, and The Pokémon Company interact with each other. Returning to November 1, 2024, it can also begin to offer explanations for different patterns.

### *A Comparison of Causes: Pokémon TCG Pocket and Prismatic Evolutions*

The release of *Pokémon TCG Pocket* and the announcement of Prismatic Evolutions both coincided on two consecutive days, leading to one of the biggest increases in popularity for Pokémon TCG since 2021. The problem with both dates being so close to each other, however, is that it's difficult to determine which event was the main driver. While this isn't the primary focus of the paper, it's relevant to understanding the conditions that led to the state of Pokémon TCG in May 2025. Different opinions have been expressed about whether the mobile app or the new expansion attracted more new fans to Pokémon TCG, with TCGplayer giving their take as well.

In an article published on March 19, 2025, Peter Day, an editor for TCGplayer Content, TCGplayer's hosted blog, argues that *Pokémon TCG Pocket* is the culprit and points to The Pokémon Company's handling of 151 (14). He claims that although 151 was a popular expansion, The Pokémon Company successfully predicted the demand shock and created a release schedule to satisfy it, maintaining 151 ETBs at around MSRP for over a month. Hence, if 151 didn't break the market, a similar popular set like Prismatic Evolutions shouldn't either. This conclusion relies on the assumption that The Pokémon Company could similarly predict the popularity of Prismatic Evolutions, which Day argues was less than that of 151.

A comparison of top cards and ETB prices might suggest otherwise, however. Data for Prismatic Evolutions cards is still viewable on TCGplayer, and prices for 151 cards can be found on Pokémon Wizard, as 151 was released in November 2023, and data from then is no longer available on TCGplayer. On release, a 151 ETB sold for $50.36, while a Prismatic Evolutions ETB sold for $123.82. The three most expensive cards of 151, Charizard ex, Blastoise ex, and Venusaur ex, sold for $128.57, $39.52, and $39.52 upon release, respectively, whereas Prismatic Evolutions' top three cards, Umbreon ex, Sylveon ex, and Leafeon ex, sold for $1,545.31, $598.66, and $441.95 upon release, respectively. The difference in relative prices between the two expansions is substantial. If someone were to pull the top three cards of each expansion from an ETB, 151 would yield a net profit of 312.25%, whereas Prismatic Evolutions would yield a profit of 1,988.45%. Suffice it to say, Prismatic Evolutions cards are much higher in relative value, even after factoring in the overall increased interest in Pokémon TCG following the release of *Pokémon TCG Pocket*.

This method isn't foolproof, however, as hit rates, or the chances of getting rare cards from a booster pack, differ across expansions, and the overall volume of print similarly varies, so any variations may affect the price of these cards beyond just demand. Despite this, the effect of these factors is insignificant, as the relative card-to-ETB prices across the two expansions are vastly different. Considering this, Prismatic Evolutions was likely more popular than The Pokémon Company expected, as it surpassed 151 in value and pace, and Day's claim that The Pokémon Company could have predicted and planned for its popularity is weak. The analysis suggests that Prismatic Evolutions was likely the dominant driver of the newfound excitement for Pokémon TCG, which, when combined with the wave of *Pokémon TCG Pocket* fans, grew out of control.

***Shrouded Fable as an Outlier***

All the expansions discussed already have had one trend in common: their passing dates precede their swap dates. This aligns with what's been discovered already, as these expansions have been demanded at prices higher than MSRP, according to price and volume trends. Shrouded Fable's ETB, on the other hand, swaps to being supply-driven when the price had only reached $44 (See Figure 4). The demand for Shrouded Fable after November 2024 still couldn't justify the standard ETB price, a condition unique to Shrouded Fable. The expansion was released in August 2024, so the market likely wasn't getting flooded by Shrouded Fable ETBs either, and a surplus in supply wasn't likely. This suggests that Shrouded Fable was a less popular set than others, which is supported by its roster's lack of any popular or well-known cards. These conditions have made Shrouded Fable ETBs considerably less valuable over the years.

Although Shrouded Fable was one of, if not the most, unpopular expansions to come out of Scarlet & Violet, it still fell into a shortage on February 3, as the excitement for Pokémon as a whole was likely enough to sustain scalpers' and investors' goals. This suggests that even less popular sets can experience shortages when overall market sentiment is high. Another potential

contributing factor was market manipulation by both scalpers and investors, which would be uniquely possible for a less popular expansion, such as Shrouded Fable. Influencers have historically held a strong influence over Pokémon card prices, playing a crucial role in the 2021 surge (17). This enabled influencers to promote certain investments they made, increasing demand for and prices of their holdings, ultimately benefiting them. On the other hand, scalpers may opt to withhold inventory to create artificial scarcity, similarly driving prices up. Furthermore, potential profits from a low-value expansion like Shrouded Fable would incentivize aggressive behavior, ultimately contributing to price hikes and shortages. While it's difficult to definitively assess the motives of all actors in the market, this type of market manipulation and speculation is a possibility worth considering when observing the Pokémon TCG ecosystem as a whole.

***Promo Cards***

Promo card prices and volumes were tracked to act as a benchmark for ETBs, as the two products are directly related. The only way promo cards can enter the market is if an ETB is opened, which may hint at the consumption of ETBs. Additionally, unsealed products like cards can't be scalped, as they aren't sold in retail, so trends in the demand for a card could relate to the demand for a given expansion or Pokémon TCG as a whole. As mentioned earlier, trends in promo cards were more ambiguous overall; however, promo card prices were still more often demand-driven. This is to be expected, considering that individual Pokémon cards aren't consumed in the same way products like ETBs are and can never be "opened" or removed from the market, creating a high supply of promo cards that's less influenced by the opening of ETBs.

Promo card value did somewhat influence the price of an ETB, as they are also part of the value included in an ETB. Consider Obsidian Flames, the expansion with the highest value promo card, Charmander - 044. At the beginning of March, the promo card sold for around $27.50, while the ETB sold for $94–101. By the start of May, however, the promo card sold for around $18, and the ETB sold for $90. It's important to state that the other main value driver, the booster packs within the ETB, increased from $5 to $6 during this period, demonstrating that promo cards do have the potential to drive ETB price changes. This situation is rare, however, as Obsidian Flames has the most valuable ETB promo card (having reached a peak of $27.60 over the study period, with the runner-ups not reaching even half of this and the rest worth only a few dollars), giving it unique control over the ETB value, especially with the weaker Obsidian Flames booster pack value. Additionally, the prices of both ETBs and booster packs fluctuated as the price of the promo card fell, making it difficult to substantiate a claim that any promo card could make a large impact on price. Ultimately, they still contribute to the value of an ETB, especially for the Obsidian Flames ETB's high-value promo card. In most cases, however, the value of the booster packs exceeds that of the promo card, limiting the impact that demand for promo cards has on ETBs as a whole. Overall trends found in these promo cards are also more ambiguous, and the different ways opened cards and sealed products are traded make promo cards only loosely correlated to ETB market behavior.

***Implications on The Pokémon Company***

Although bad for casual fans and consumers, the accelerated demand and scalping breakout is also bad for The Pokémon Company, if not worse. Retail presence and on-shelf visibility are important factors for any product, as just by being seen, they advertise new releases, attract new customers, and enable impulse buying. Empty shelves do little to promote the Pokémon TCG brand or encourage sales. So, although the products are technically selling out, there is much less growth, which could damage sales in the long run once demand dies down and the market stabilizes. Another important consideration for The Pokémon Company is the large surplus available on sealed Pokémon TCG products. People are paying over a hundred dollars for some ETBs, yet The Pokémon Company maintains the same low MSRP for ETBs and other products, leaving the surplus to be appropriated by scalpers. The most obvious solution would be to raise prices themselves, but this risks damaging The Pokémon Company's reputation for fixed MSRPs and also could have long-term consequences on sales and brand image.

If price is to be left alone, then The Pokémon Company must find a solution in supply. Simply printing more would increase the overall supply, shrinking the retail shortages and lowering secondary market prices, which would reduce scalping incentives. The Pokémon Company has already announced its intention to do this for Prismatic Evolutions and will likely increase production for all expansions as well (4). This was only done as a reaction, however, and it did not prevent the damage from being done. Another option The Pokémon Company has been implementing more recently is Pokémon vending machines, which dispense various sealed Pokémon TCG products. Although they existed in the U.S. as early as 2017, between March 2024 and May 2025, The Pokémon Company increased the number of Pokémon vending machines from less than 200 to over 1,400, representing a significant investment in this new technology (18). Although they were intended to help with supply issues by providing direct-to-consumer sales, vending machines also became victims of scalping and shortages. Vending machines were most often out of stock, as they operated similarly to any retailer and could be bought out and tracked for restocks.

A less reactionary solution for The Pokémon Company would be to overprint and maintain an inventory, rather than solely printing to their original projections. In doing so, it will be prepared to inject more products into retail when demand surges. These surges are unlikely, however, and The Pokémon Company would have to maintain an inventory. Yes, this would cost money, but in the long run, the potential to capitalize on demand surges and have a stronger commitment to customers would likely outweigh costs. Furthermore, additional inventory could be used for expansion restocks that The Pokémon Company frequently does, keeping turnover time low. This solution could prove to be more effective than the other options The Pokémon Company has explored, ultimately benefiting the company by insuring against future shocks.

**6. Conclusion**

This paper has established the troublesome state of Pokémon TCG, as the market continues to spiral, with prices climbing and supply dwindling. New interest from sources like

*Pokémon TCG Pocket* and Prismatic Evolutions accelerated demand, driving up prices of both cards and sealed products. Then came the scalpers, who bought out stores and marked up the prices, while the Pokémon Company failed to keep up. At the end of the day, as scalpers and investors profit off of Charizards and Pikachus, the collectors and fans are the ones who pay the price. In the community, this has manifested into frustration toward scalpers, The Pokémon Company, and just about anyone they can point a finger at, which has been expressed on platforms like Reddit and X (19). The Pokémon Company's failure lay not only in its responsibility to customers, but in the effective disappearance of sealed Pokémon TCG products in stores

Despite how bad the market may seem, Pokémon TCG went through something similar in its previous series, Sword & Shield, during the COVID-19 pandemic, and was eventually able to recover. Following the intense scalping in 2021, The Pokémon Company more than doubled Pokémon card production from 3.7 billion cards produced in 2020 to 9.1 billion cards in 2021, which has only continued to grow since then (3). The Pokémon Company can be expected to do the same again, and it has already announced its intention to increase production of future expansions and to reprint existing ones (4). With the final Scarlet & Violet expansions, Destined Rivals and Black Bolt & White Flare (Pokémon TCG's first split-set expansion), having been released, Pokémon TCG prepares to move onto its next series in September 2025 (20).

The previous two series both saw intense scalping and shortages at some point, but by applying lessons from recent and past market behavior, the new Mega Evolution Series is positioned to end the cycle. After identifying the role of both a popular eeveelution-themed expansion and a successful mobile app, it's clear that a single demand shock in the Pokémon TCG market can quickly cause shortages. The Pokémon Company should recognize the fragility of the market and its tendency to form bubbles; however, it's ultimately difficult to predict when the next wave will come. Releases within the TCG and the overall Pokémon franchise can be easily accounted for, but external factors, such as influencer presence and lifestyle shifts, can create unexpected demand that The Pokémon Company may have a delayed reaction to (17). The available 50-week data demonstrated that the recent Scarlet & Violet trends resulted from internal predictable factors, so by better anticipating the effects, the Pokémon Company can strengthen supply and reduce the risk of shortages in the future.

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**Guppy Behaviors, Heredity, and Genotype Report By May Boettcher**

## Overview

This project delves into the behavioral tendencies, genetic traits (genotypes and phenotypes), and lineage predictions of guppies—also known as *Poecillia reticulata*—as a three-part experiment.

First, it investigated the social hierarchies and interactions between male and female guppies when housed separately and together. This revealed differences in dominance structures, particularly among males, whose rankings were influenced by color, size, and behavior.

The second section of the experiment tested the accuracy of online claims about guppy genetics by identifying phenotypes and inferring genotypes through breeding pairs. This section focused on traits like body color, fin shape, and the presence of metal/pigment mutations. It confirmed inheritance patterns such as dominance, recessiveness, codominance, and also incomplete dominance.

Finally, the third part used Punnett squares and observational data (a more in-depth version of section two), to explain how hidden alleles were determined. By tracking two pairings—and an accidental third pairing—the experiment documented trait transmission and laid the foundation for future selective breeding efforts. The third section explained more about breeding lines, guppy health, and long-term goals for the project

## Introduction

Guppies are small freshwater fish known for their diverse genetics, vibrant colors, and complex semi-schooling behaviors. Due to their short lifespans, rapid breeding cycles, and vast variety of geno and phenotypes they are ideal candidates for studying behavior and inheritance in a controlled environment.

This research project explored three core aspects of guppy biology—behavioral dynamics, the relationship between phenotypes and genotypes, and whether certain alleles cause incomplete or codominance.

The first section of the experiment focused on the behavioral differences between male and female guppies. By first isolating the sexes and then later observing mixed-gender pairings, the project investigated how guppies establish hierarchies, exhibit dominance, and interact socially.

The second portion shifted to guppy genetics, evaluating whether online predictions align with real-world results. Through selective breeding and analysis, I examined how dominant, recessive, and co/incomplete dominance was inherited.

The third section used Punnett squares from the data I recorded to predict outcomes for future lineages involving the guppies. This portion also incorporated other breeding lines I've worked on in the past, and after this project, I'll be combining them and continuing.

This project.combined research, hands-on experimentation, and moral animal care, to deepen my understanding of guppy genetics while showing how even common pet store fish can provide meaningful scientific insight.

**Complete List of Materials**

- 2 Ten Gallon Fish Tanks
- 1 Set of LED Strip Lights
- Various Fish Decorations (x2 of Each)
- 2 Clumps of Pearlweed
- 2 Lifeguard 15 Gallon-Rated Filters
- 2 Tetra 10 Gallon-Rated Heaters
- Tetra Products Community Fish Food
- API Water Conditioner
- Royal Guppy Mignon Baby Fish Pellet
- API Water Testing Strips
- 2 (Unknown Brand) 1.5 Gallon Heaters with Thermometer
- Fish Nets from Various Brands

**Procedure**

This experiment was divided into three major phases.

Behavioral Observation Phase: In the first phase, I separated six male and four female guppies into two identical ten-gallon tanks to eliminate pregnancy-related variables, disease variables, and observe gender-based social behavior. Over a 16 day period, I recorded daily changes, documenting how hierarchies formed and how individual fish interacted within their groups.

Genetic Analysis Phase: In phase two, I selected and bred two final pairs based on heath, genetic diversity, and their physical traits (which were dominant traits, as the focus was to determine whether they had incomplete or codominance). I tracked their behavior during their pairings, monitored for pregnancy, and documented offspring traits once the fry were born. All data—which ranged from body color and fin shape to pigment mutations—were compared to online genetic charts from *First Edition Guppy Color Bank.* (2008) written by Shaddock, Philip. The online data acted as my basis, or control group.

Lineage Prediction: Finally, using their discovered genotypes, I created Punnett squares based on their inheritance patterns. I predicted how their traits will statistically appear in future generations.

The entire procedure was conducted humanely, with careful tank maintenance, temperature control, and overall ethical care of the fish. Fish removed after the project are kept as personal pets in an indoor pond.

**Data of Original Guppies (Part One)**

| Name | Gender | Body Color | Body Pattern | Fin Color and Pattern | Fin Shape | Metal Cell Mutations | Pigment Cell Mutations | Other | Initial Size |
|---|---|---|---|---|---|---|---|---|---|
| Sun | Male | Silver (D) | Half-Black (D) | Mosaic (R) | Delta (D) | Metal (R) | N/a | N/a | .9" |
| Calypso | Male | Silver (D) | Half-Black (D) | Black Tail (D) | Round (D) | N/a | Pink/Pingu (R) | N/a | 1.2" |
| Galaxy | Male | Silver (D) | Red Spots (D) | Blue Tail (D) | Double Swordtail (R) | N/a | N/a | N/a | 1.6" |
| Rocket | Male | Yellow (D) | Half-Black (D) | Black Tail (D) | Round (D) | N/a | N/a | N/a | 1" |
| Star | Male | White (D/R) | Solid Color (R) | White (D/R) | Roundtail (D) | N/a | Platinum (R) | N/a | 1.1" |
| Asteroid | Male | Silver (D) | Half-Black (D) | Mosaic (R) | Delta (D) | Metal (R) | N/a | N/a | 1.4" |
| Moon | Female | Beige (R) | Solid Color (R) | Yellow (D) | Round (D) | N/a | N/a | *Female* | 1" |
| Nebula | Female | Beige (R) | Half-Black (D) | Yellow (D) | Delta (D) | N/a | N/a | *Female* | 1.2" |
| Eclipse | Female | Beige (R) | Solid Color (R) | Black Tail (D) | Round (D) | N/a | N/a | *Female* | 1" |
| Asteria | Female | Yellow (D) | Solid Color (R) | Yellow (D) | Round (D) | N/a | N/a | *Female* | 1.4" |

**Data of Guppies Chosen for Final Project (Parts 2 and 3)**

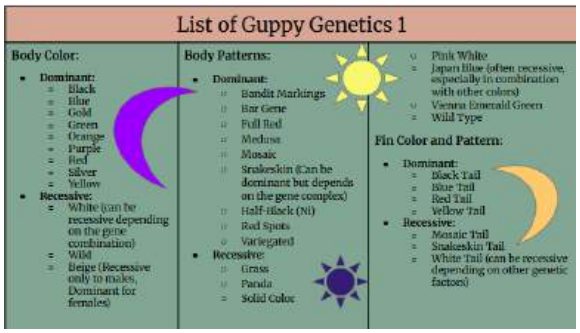
| Parents | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Name | Gender | Body Color | Body Pattern | Fin Color and Pattern | Fin Shape | Metal Cell Mutations | Pigment Cell Mutations | Other | Initial Size |
| Sun | Male | Silver (D) | Half-Black (D) | Mosaic (R) | Delta (D) | Metal (R) | N/a | N/a | 1.3" |
| Rocket | Male | Yellow (D) | Half-Black (D) | Black Tail (D) | Round (D) | N/a | N/a | N/a | 1.2" |
| Nebula | Female | Beige (R) | Half-Black (D) | Yellow (D) | Delta (D) | N/a | N/a | Female | 1.4" |
| Cassiopeia | Female | Beige (R) | Solid (R) | Red Tail (D) | Delta (D) | N/a | N/a | Female | 1.6" |
| | | | | | | | | | |

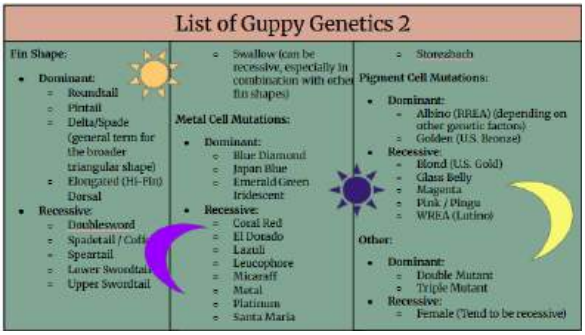
| Sun x Cassiopeia | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Name | Gender | Body Color | Body Pattern | Fin Color and Pattern | Fin Shape | Metal Cell Mutations | Pigment Cell Mutations | Other | Initial Size |
| Icari (1A) | Female | Beige (R) | Half-Black (D) | Red/Yellow Tail Mix (D) | Delta (D) | Metal (R) | N/a | Female | .7" |
| 2A | Female | Silver (D) | Solid (R) | Yellow (D) | Round (D) | N/a | N/a | Female | .6" |

| Rocket x Nebula | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Name | Gender | Body Color | Body Pattern | Fin Color and Pattern | Fin Shape | Metal Cell Mutations | Pigment Cell Mutations | Other | Initial Size |
| Danica (1) | Female | Yellow | Half-Black (D) | Yellow (D) | Delta (D) | N/a | N/a | Female | 1.1" |
| 2 | Female | Yellow | Solid (R) | Yellow (D) | Round (D) | N/a | N/a | Female | 0.9" |
| 3 | Female | Yellow | Half-Black (D) | Yellow (D) | Delta (D) | N/a | N/a | Female | 1.3" |
| 4 | Female | Yellow | Half-Black (D) | Yellow (D) | Delta (D) | N/a | N/a | Female | 1" |
| 5 | Female | Yellow | Half-Black (D) | Yellow (D) | Delta (D) | N/a | N/a | Female | 0.9" |
| 6 | Female | Yellow | Half-Black (D) | Yellow (D) | Delta (D) | N/a | N/a | Female | 0.8" |
| Juliet (7) | Female | Yellow | Half-Black (D) | Yellow (D) | Round (D) | N/a | N/a | Female | 0.9" |
| Leo (8) | Male | Yellow | Half-Black (D) | Black (D) | Delta (D) | N/a | N/a | N/a | 1" |

| Danica x Leo | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Name | Gender | Body Color | Body Pattern | Fin Color and Pattern | Fin Shape | Metal Cell Mutations | Pigment Cell Mutations | Other | Initial Size |
| Lyra | Female | Yellow | Solid (R) | Yellow (D) | Delta (D) | N/a | N/a | Female | .5" |

**Guppy Hereditary Traits**




Created from the resource: Shaddock, Philip. *First Edition Guppy Color Bank.* 2008.

**Discussion of Results**

The results this project gave provided strong support for my original hypothesis, while also revealing unexpected complexities in both guppy behavior and genetics.

In the behavioral phase, male guppies showed their hierarchies through color, ambition, and size. Males like Rocket and Sun frequently chased each other in territorial displays, while Female guppies, on the other hand, were more cooperative and less defined hierarchies. This suggests their social structures may be more influenced by size and environmental comfort than aggression.

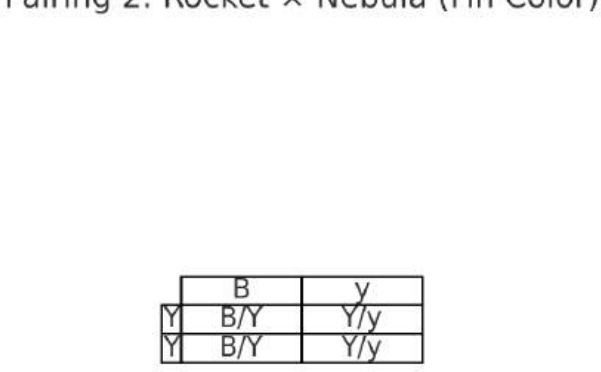
The genetic phase showed the differences between visible traits (phenotypes) and their underlying genotypes.. For example, in Pairing #1, the fry named “Icari” developed a blended red-yellow tail, which couldn’t be explained by Mendellian dominance alone. Additionally, the round tail phenotype—despite both parents having delta tails—proved that each was carrying a recessive round allele for Pairing #1. Pairing #2, while having more data points, showed a more typical Mendelian example. From the offspring phenotypes, we were unable to determine the 100% accurate genotypes, however the accuracy is estimated to be between 85-95%. Unfortunately, even starting the experiment in September 2024 only allowed 2 generations—and the second generation didn’t reveal further traits. I will be continuing this experiment to get high accuracy. Also, In Pairing #2, the dominance of yellow body color was evident—with all except one offspring showing the trait—confirming Rocket’s homozygous dominant genotype. Although, the appearance of a solid body pattern in one fry revealed hidden recessive alleles in both parents.

The third phase is interwoven with the second. It delves further into the process I used to gather the genotypes, and explains more about incomplete dominance and how that ties into lineage genetics. As said earlier, Pairing #1 shows incomplete dominance—and Pairing #2 shows typical Mandellian dominance. But what would happen with an already incomplete dominant-tailed guppy is crossed with one that isn’t? That’s why I want to continue the project over the next few years.

Overall, the experiment confirmed my suspicions that guppy genetics are far more nuanced than online charts and resources suggested. Dominance isn’t always visual, and even

simple traits can be hiding complex combinations of alleles. Long-term tracking, like this study, is essential for understanding how these traits persist or change over generations. It also reinforced how valuable it is to work with a wide variety of fish, including those from less genetically “ideal” sources—big chain pet stores (Petsmart and Petco), as they often reveal traits you wouldn’t expect—making every pairing a surprise.

**Punnet Square Examples**




**Research Conclusions Overall**

This project to evaluate guppy behavior, phenotype-genotype inheritance, and future lineage predictions across several controlled pairings. Over the course of 227 days, detailed data and information was collected through observations with careful attention to environmental variables and humane breeding outcomes. The final conclusions of this project merge all three sections into one cohesive framework, and these findings collectively enhance our understanding of guppy biology—not only through the lens of classical genetics, but also through practical, real-world behaviors.

**Research Conclusions Behavioral Hierarchy and Social Structure**

In the initial phase of the experiment, guppies were separated by gender to eliminate early pregnancies, complete quarantine, and observe baseline social behavior. My study discovered that male guppies developed defined dominance hierarchies within the first several days. I determined this through carefully observing their aggressive displays, territory guarding, and overall levels of chasing. These hierarchies were influenced not just by size, but by a combination of color intensity, swimming assertiveness, and general “ambition.” The term “ambition” I used to describe the frequency of dominance-based swimming movements like interrupting other guppies feeding. Size was not the sole factor; several smaller but more aggressive males ranked higher than larger, more passive ones. The hierarchy revised each time a fish was removed, relocated, or passed away. Notably, the loss of “Star,” a male with probable

neurological issues/swim bladder issues, led to a changing of dominance that highlights just how sensitive male hierarchy is to population change.

Female guppies, on the other hand, displayed a different behavioral structure. Unlike males, they showed less aggression and rarely established a dominance order. Instead, they tended to school, particularly when first introduced to the tank—only dispersing into individual areas after three days. While there were no aggressive or flashy displays, size appeared to be the primary indicator of the social rankings among females. In this particular project, Asteria, who was the largest female, showed early signs of becoming the "boss." She would repeatedly chase her tankmates, occasionally attempting to nip their fins. This supports existing theories that female guppies benefit from cooperation and collective defense, while males focus on territoriality and reproductive competition. However, even within this theory, some females will on occasion fight and be dominant over others. In the wild, there would be an even ratio of males to females, and it's likely to only see these behaviors in captivity.

Mating interactions caused another layer of complexity. For example in Pairing One, the female (Cassiopeia) displayed unusually dominant or forward behavior—chasing the male (Sun) instead of the reverse. This is the opposite of expected mating dynamics, and based on my research from articles like, "Beginning a Selective Breeding Program," from Selectaquatics.com, it's rare in guppies. This behavior may be influenced by Cassiopeia's large size and strong level of ambition.

Meanwhile, in Pairing Two, mating behaviors followed more traditional patterns, with the male (Rocket) constantly courting the female (Nebula). This contrast offers insight into how social dominance, personality, and size can influence mating behavior.

**Research Conclusions Environmental Impacts and Stress Responses**

Environmental conditions, particularly temperature, water clarity, and filter flow, impacted guppy behavior and reproductive success. When heaters were upgraded from undersized 5-gallon units to 50-watt models rated for 10 gallons, breeding began almost immediately. The addition of plants for added coverage also influenced the females to drop their spawn. Before this, water temperatures were dipping to 69°F at night—far below optimal for spawning behavior in a tropical species like guppies. Once the environment became more established and stable, successful breeding happened in both tanks. These findings reinforce the role that environmental optimization plays in reproductive success and support the idea that many biological flatlines during the experiment were stress-related rather than genetic or otherwise.

**Research Conclusions Phenotypic and Genotypic Trait Expression**

I explored trait inheritance using two major pairings. In Pairing One (Sun × Cassiopeia), only two fry were born, but both exhibited distinct combinations of dominant and recessive traits. One offspring, Icari, had a beige body, half-black pattern, delta tail, red-yellow fin, and metal mutation, while the other fry had a silver body, solid pattern, round tail, and no metal

mutation. This mix confirmed that both parents were heterozygous for multiple traits, even when their dominant phenotypes had suggested otherwise. The presence of a round tail, despite both parents being delta-finned, suggests a shared recessive allele for fin shape. Also, the metal mutation's 50% expression rate and the appearance of a red-yellow blended tail revealed the presence of incomplete dominance in fin coloration, a major takeaway from this pairing. This means in the future, when combining red-finned and yellow-finned guppies, it's possible to produce offspring with mixed-colored tails.

In Pairing Two (Rocket × Nebula), eight offspring and one grand-child were made. All offspring except one expressed yellow body coloration, confirming that Rocket was homozygous dominant for the yellow trait. The lack of beige coloration in any fry, despite Nebula's phenotype, suggests she was homozygous recessive, making yellow the dominant body color. However, this may not be 100% accurate because beige coloration is a sex-linked trait that's probability is increased when they were female, and the eighth fry—a male—had a black body. Most offspring exhibited the half-black pattern, though one expressed solid coloration (the black male), again confirming both parents were heterozygous carriers for a recessive trait. Fin shapes in this group followed a near 50/50 Delta to Round split, supporting the hypothesis that both parents carried one allele for each. No offspring from this group carried the metal mutation, further reinforcing that both were homozygous recessive (m/m) for that trait.

**Research Conclusions Unexpected Pairings and Limitations**

Several unexpected developments enriched the study—but also introduced variables. The unplanned pairing of Leo and Danica, who were siblings produced by Sun x Cassiopeia, produced a healthy offspring named Lyra. Despite being inbred—generally avoided due to gene compatibility producing mutations—Lyra developed an impressively strong backbone and no visible deformities. This could imply that some inbred combinations are not only survivable, but may even help correct weaknesses in previous generations, especially when preceded by careful line selection. While not conclusive, it introduced an ethical and genetic debate on the value of controlled inbreeding in guppy line improvement. Many guppy breeders, as well as breeders of other animals and plants, use inbreeding to control lines and not introduce other traits. However, in modern times this method overall appears outdated.

Additionally, the initial inclusion of store-bought guppies revealed health weaknesses. Multiple fish had visible deformities, poor immune function, or genetic instability. This prompted my creation for the "Big Box Line," a side project focused on gradually stabilizing traits through selective breeding from store-quality fish. The goal was to turn what most breeders discard into a group destined for improvement, and is being continued.

**Final Summary and Conclusions**

Overall, this project has confirmed many classical genetic expectations when compared to online resources—while also challenging others. Dominant and recessive traits in guppies *do* follow Mendelian patterns, particularly in body color, pattern, and fin shape. However,

incomplete dominance, hidden heterozygosity, and sex-influenced expression complicated the project. Behavioral data emphasized the differences between male and female guppy dynamics, with males forming aggressive hierarchies and females exhibiting schooling and less competition. Environmental stressors had measurable impacts on reproduction, reinforcing the need for ideal tank conditions in any long-term breeding study, because the fluctuation greatly impacted my timeline.

Through both planned and accidental data points (like in Pairing Three), the experiment also demonstrated that even small-scale, observation-based research can uncover meaningful, complex truths about biology.

**Conclusions (Bulleted Format)**

Male guppy hierarchy was based more on color and behavior than size alone.

➤ Rocket (not the largest) ranked highest, showing color and aggression mattered more.

Female guppies in small groups did not form a clear hierarchy.

➤ Even after 2 weeks, no dominant "boss" emerged—suggesting group size impacts dominance. Asteria came the closest (questionable whether she was "boss)."

Star, the guppy, showed signs of swim bladder and neurological issues despite no visible illness.

➤ Supports the idea that pet store guppies often carry hidden health problems.

➤Despite not having any *physical* abnormalities, because he was swimming at the top and bottom of the tank sporadically, it demonstrated neurological issues that are important to look for when ethically breeding.

Round tail shape appeared in offspring, even though both parents had delta tails.

➤ Proved that *both* parents were heterozygous (D/r), carrying the recessive round allele.

A red/yellow blended tail appeared in offspring Icari, despite neither parent having that mix.

➤ Strong evidence of incomplete dominance in fin color genetics.

Metal cell mutation appeared in only 1 of 2 fry from Sun × Cassie pairing.

➤ Suggests Sun is heterozygous (M/m) and Cassie is homozygous recessive (m/m). Metal mutations can be hidden traits.

All 8 fry in Rocket × Nebula had yellow bodies.

➤ Confirms Rocket is homozygous dominant (Y/Y) for body color.

1 fry from Rocket × Nebula had a solid body pattern, despite both parents being half-black.

➤ Reveals both parents carry the recessive solid (r) allele.

Delta and round tails appeared in a 50/50 ratio in Pairing #2.

➤ Indicates both Rocket and Nebula are D/r for fin shape—classic Mendelian inheritance.

Cassiopeia reabsorbed her first pregnancy.

➤ A relatively rare but known survival response under stress, documented firsthand.

Leo and Danica (siblings) produced a healthy fry,

➤ Lyra, showing mild inbreeding, didn't cause deformities in this case.

Lyra showed stronger spinal structure than her grandmother, Nebula.

➤ Possible sign of positive trait correction through selective breeding.

**Suggestions to Duplicate Experiment/What I'd Do Differently**

Use larger breeding groups for more reliable data.

➤ A sample size of 2–8 fry is limited; pairing multiple sets or waiting for multiple drops from the same pair could increase accuracy when identifying genotypes.

Wait until females are older before breeding.

➤ Some early-paired females either reabsorbed their fry or only had 1–2 babies. Waiting until they're more mature may result in larger and healthier drops.

Quarantine and observe fish longer before pairing.

➤ Several fish had hidden health issues (neurological, swim bladder, tumors). An even longer isolation period might help detect underlying conditions sooner.

Upgrade heaters and monitor temperature closely.

➤ Inconsistent water temperature slowed breeding. Using properly rated heaters and adding a thermometer sooner can improve spawning reliability.

Use more frequent phenotype documentation with better lighting.

➤ Fry colors and patterns can change quickly as they grow. Daily or every-other-day photos under good lighting can help track trait emergence more precisely.

Test second-generation offspring for deeper genotype analysis.

➤ Breeding the original offspring (like Icari or Juliet) could help confirm incomplete

dominance or hidden alleles passed on by the parents.

Explore co-breeding with multiple males to test sperm storage theory.

➤ Allowing females to interact with more than one male before separation may help test whether guppies can truly mix genetics in a single batch of fry.

Track behavior using video for more objective hierarchy analysis.

➤ Observing footage later could reveal subtle dominance behaviors missed in real-time.

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**Japanese Wartime Governance and the Question of Fascism, 1931-1945**
**By Darrin Shigei-Seat**


## Abstract

In terms of their involvement in World War II, Japan was one of the most misunderstood and complex nations. While the rise of fascism and communism in Europe dominate modern narratives about 1930s and 1940s politics, Japan's political shifts often go unnoticed, especially by Western historians. As a result, many label its government as fascist in the traditional sense because of its alliance with the Tripartite Pact. However, this label oversimplifies the unique political and military systems that shaped that nation. This paper examines Japan's government during the 1930s and 1940s, arguing that it was not strictly fascist but rather a distinctive combination of fascist state, an imperialist nation, and militaristic junta. To support this argument, this paper explores key events in modern Japanese history, including the Meiji Restoration, the Taisho Era, the Mukden Incident, the establishment of Manchukuo, the February 26th Incident, and the Second Sino-Japanese War. The Empire of Japan is indeed defined by these events, but on close examination, they do not align Japan with universally recognized fascist nations such as Nazi Germany, Italy, and Romania, nor do they totally fall into line with imperial powers like Britain. The paper also aims to illustrate the views of important Japanese leaders such as Emperor Hirohito, Ishiwara Kanji, Hideki Tojo, and Yosuke Matsuoka, to provide a better understanding of the ideological, political, and military forces that influenced Japan during this chaotic time.


## Introduction

"Fascism in Japan was not imported; it grew out of the contradictions of our own political and spiritual traditions. It was a 'systemless fascism'—a fascism without a unified ideology, but all the more dangerous because of its ambiguity" (Maruyama 26-33). Here, Japanese political theorist Maruyama Masao argues that Japan's "fascism" was characterized by disorganization, major power vacuums, and various groups asserting overlapping responsibility (29-38). Maruyama's observations raise the following question: if Japan's supposed fascism had so many caveats, did the country truly experience fascism?

Before addressing that question, one might examine fascism through the words of its founders, Benito Mussolini and Adolf Hitler. Mussolini believed that fascism glorifies the state and embraces war, authority, collective strength, and dedication to the cause (Nolte 1-30). Hitler defined fascism in Mein Kampf as a system to preserve racial purity, ensure obedience to the state, and maintain power within the hands of strong individuals (Hitler). Given these statements and their historical context, one can see that the core elements are a highly unified ideology with a strong and powerful leader, the expectation of putting the well-being of the state over self, ultra-nationalism, and the belief in the necessity of eradicating other races to allow for the dominance of a singular "super race" (Hitler, Mein Kampf; Mussolini, "The Doctrine of

Fascism"). Lacking some of these qualifications, can it still be argued that Japan was entirely fascist?

In the 1920s and 1930s, Japan underwent dramatic political, social, and economic shifts, from an increasingly democratic nation to a totalitarian regime under the control of the military (Maruyama 20-50). After World War I, Japan emerged as a growing power, joining the League of Nations and expanding its influence in Asia, but the prosperity of the 1920s was short-lived. The global Great Depression of 1929 hit Japan hard, devastating farmers by decreasing the value of silk, a major export, and fueling resentment among rural communities that had supplied many recruits to the military. At the same time, frustration grew with the perceived weakness and corruption of party politics during the Taishō Era (1912-1926); many believed parliamentary leaders were unable to defend Japan's interests abroad, resolve economic inequality at home, and were increasingly corrupt. Military officers and some right-wing individuals began promoting ideals of loyalty, sacrifice, and expansion, believing it was Japan's destiny to create an empire in East Asia (30-60). The economic climate, as well as the loopholes in the Meiji Constitution, would grant members of the Imperial Japanese Army the power to act independently of the civilian government, thus paving the way for an eventual takeover. By the 1930s, that takeover materialized, and the military gained dominance in government, pushing Japan toward authoritarianism, expansionism, and war (Hofmann 100-140).

When studying the classification of the Japanese government in the 1930s and 40s, historians have presented two main arguments. The argument of the vast majority of western historians and the common approach to Japanese history in the West claims that Japan was strictly fascist like Germany and Italy. Some historians base their argument on their belief that Japanese actions in China were equal to, if not more severe, than those Hitler used in the Holocaust, so the government must, therefore, be fascist (van de Ven). Others claim that Japan had a dictator in Emperor Hirohito, and that the nation's expansionist policies were predominantly motivated by the ideology of accommodating a superior race, thus making it a fascist nation ("China's Resistance During WWII Significant"). These arguments are easy to make, especially since Japan signed the Tripartite Pact and aligned itself with the Axis power; however, such a conclusion examines Imperial Japan's actions merely as part of the traditional narrative of World War II: that the conflict was strictly an ideological confrontation between Democracy and Fascism.

The other more nuanced and complicated argument was created primarily by Japanese scholars, most notably Maruyama Masao. While Masao argued Japan was fascist, he believed it did not fit the mold expressed by Hitler and Mussolini. Instead, he describes it as a system-less fascism or fascism from above. In other words, he believed that, contrary to the traditional belief that fascism is a civilian movement, Japan's government evolved from the upper echelons of the military, making it distinct from traditional fascism. The defining characteristics of Japanese fascism were the lack of responsibility on the part of military leaders and the lack of a defining leader (Hofmann 100-140). These factors were also used to explain Japanese war crimes committed throughout World War II. Despite the differences he identifies, Masao believed that

Japan's traditional worship of its emperor was inherently fascist. Maruyama also identifies some divergences from fascism in Japan's lack of a strong capable leader, its disorganized government, and its feudal system. In fact, both the liberal Maruyama and Marxist scholars believe Japan's fascist state resulted from the nation's inability to modernize: retention of feudal values and economic structure with its social hierarchy mark two strong differences from Hitler's government, which sought to eradicate classification by emphasizing community over class (Volksgemeinschaft) (Hitler Mein Kampf, Maruyama 28-42).

Yet, disagreement of opinion in classifying Japan's fascism, even among historians, remains. Some, such as Ernst Nolte, view fascism as an "extremist response to the threat of communism;" others subject it to a checklist that includes militarism, authoritarianism, anti-communism, and racism (Nolte 1-30). A number of Western historians, including Hans van de Ven, therefore, hold that Japan was indeed fundamentally fascist because of its racism (primarily against its occupied subjects) and nationalism and more similar to Germany and Italy (van de Ven). Still, some scholars, including Jeremey Yellen, focused on Japan's imperialist ambitions, claiming Japan's expansionist policies, actions, and racial beliefs, especially those in Manchuria and later in China, emulate a Western imperial model rather than a fascist one. Imperialism can be defined as an ideology that pursues the invasion of other nations and exploitation of its people for economic gain (Yellen). Others make the argument that Japan's fascist model is different from Germany's or Italy's because of the presence of a military junta, or a Gunbatsu. A military junta is defined as a type of government under the control of that nation's armed forces. The term was popular amongst more critical Japanese journalists of the time to describe their government in the 1930s and 1940s. Historian John Dower later used the term to describe Japan in his book War Without Mercy, in which he called Japan a "military-bureaucratic regime" (Dower 50-90).

Drawn from the arguments of Masao, Yellen, and Dower, my argument pushes back against the narrative that Imperial Japan can be classified as simply one of three fascist nations aligned in an Axis. It asserts that Japan's wartime government diverges from "pure" fascism, especially when the characteristics of government types utilized in Japan are more strictly delineated. This paper will argue that the Japanese Empire, rather than influenced by a singular governmental ideology, was not entirely fascist in the traditional sense of Germany's or Italy's government; instead, it is a mixture of traditional fascism, Western imperialism, and military junta. This interpretation is significant for a number of reasons.

This paper will establish how Japan fits into a world order dominated by nationalism and fascist thinking by addressing the nuances and distinctions between Japan's governmental system and those of other nations. In addition, it will present the cultural elements distinct to Japanese society and history that make its actions leading up to and into World War II more understandable. It will then quash stereotypes and categorization of historical data that ultimately creates inaccuracy. Finally, in conferring significance to a clearer picture of Japanese motivations and their roots in historical events, this interpretation will affirm an important function of history: to accurately know the past is to ensure a greater understanding of our potential future.

**The Meiji Restoration and the Pre-History of Japanese Fascism**

Japanese fascist tendencies in the 1930s and 1940s can be traced directly back to the political framework established during the late Meiji period, which began in 1868, and the economic and social upheaval of the Great Depression that began in 1927. The Meiji era created the structural loopholes and authoritarian traditions that empowered the military, while the Depression provided the spark — a crisis severe enough to convince many that only decisive, extra-constitutional action could save Japan's future (Marcon 50-60).

When the West, specifically the United States, first forced Japan to open its borders in 1853 and imposed unequal trade agreements, many low-ranking samurai in Japan felt humiliated and angered. They became convinced Japan would need to change drastically in order to survive (Gordon 150-190). Takasugi Shinsaku, a samurai from the Chōshū domain, echoed this sentiment when he wrote in 1862: "I was convinced that Japan must strengthen itself to avoid being colonized by the Western powers, or to suffer a similar fate as the Qing" (Takasugi Shinsaku Zenshu 40-60). At that time, Western powers, including Britain, France, Russia, and the United States, had spheres of influence across the Qing Empire and had forced China to sign unequal trade agreements similar to those of the Japanese (Cassel 40-75). Seeing the Tokugawa Shogunate as working with the West, the Chōshū and Satsuma domains, ruling families with their own personal armies, became hostile towards the Tokugawa Shogunate, which considered itself to be the true ruling military family of Japan. The domains backed the Meiji imperialist government, taking the first step toward independence in attempting to overthrow the Shogunate when it became vulnerable. The Meiji, with help, therefore was able to defeat the Tokugawa in the Boshin War of 1868 in the early years of its Restoration. The Meiji government then established the goal of modernizing Japan, which they saw as implementing Western ideas, government, industry, and army while maintaining Japanese culture. This sentiment was captured in the 1868 slogan Fukoku Kyōhei or "rich country, strong army" (Gordon 20-30). These goals, combined with growing interference from the United States, helped to make Japan more authoritarian, which allowed it to bear a resemblance to fascism.

**The Social and Economic Roots of Japanese Fascism**

The decline of the samurai after the Meiji Restoration played a paramount role in shaping Japanese politics in the 1930s and 1940s (Najita 100-140). Samurai of the Satsuma clan in particular were angry over Meiji's destruction of the samurai class and the current feudal order. When the samurai found themselves with no place in the modern, Western-styled Japan the Meiji government hoped to create, they attempted an uprising in 1877 known as the Satsuma Rebellion. However, they were defeated by the newly formed Imperial Japanese Army, which consisted of conscripted soldiers (Gordon 230-250). Interestingly, many former, renowned samurai or their descendants, including Tojo, Yamamoto, Yamashita, and Ishiwara, would go on to become influential military leaders within the Imperial Japanese Army, the same one that had defeated their ancestors in 1877 (Harries 50-100).

Like every industrial revolution, the one that occurred in Japan in the 1870s moved wealth and production from the countryside into major cities. Although successful for urban settings, the endeavor happened so quickly that the economy was adversely affected in rural areas (Gordon 230-250). With governmental emphasis on developing the cities, farmers struggled when the government raised their taxes based on land value. This outcome was a far cry from the period of the Tokugawa Shogunate, when taxes for the rural population had decreased. Due to exorbitant taxes, many had to become tenant farmers who cultivated silk, a valued commodity for manufacturing in the industrial revolution. However, volatility in the markets left farmers even more vulnerable to a possible economic collapse. Already on the brink of ruin, the situation for rural Japan only worsened when the Great Depression hit in the early 1930s. Rural communities were most gravely impacted because of the already high taxes, limited resources, and U.S. tariffs, which translated into less demand for silk (Louise Young 45-75). The discontent set the stage for increased military power.

In the eyes of the military, who felt a special connection to rural Japan, the incompetence and greed of the civilian government and the West had directly caused this disaster (Hillis 100-130). Colonel Ishiwara Kanji stated, "The politicians in Tokyo are blind. They care nothing for national destiny, only their own petty interests. It is our duty as soldiers to act, for they will never understand the necessities of the age" (Louise Young 145-180). Another, General Araki Sadao, said, "Japan's crisis cannot be solved by weak and selfish political parties. Only through the spirit of the sword, guided by the emperor's will, can the nation be purified and reborn" (Tansman 140-180). Still others, especially the younger, more radical officers, looked to assassinate politicians and businessmen deemed responsible. Some assassins were even lionized by the military. In one situation, naval officers assassinated Japanese Prime Minister Inukai Tsuyoshi in 1932 but received only light sentences. These actions demonstrated the lengths military leaders were willing to go to "fix" Japan through a fascist response (Hillis 280-320).

Despite the disapproval of conservative Japanese officers, the more liberal parties still dominated Japan in the 1910s and 1920s during the Taisho Era (Nishizawa). Yet, the military leaders circumvented restrictions, utilizing technicalities found in the Meiji Constitution, specifically, Article 11, which made the army answerable to the Emperor rather than the civilian government: "The emperor has the supreme command of the Army and Navy" (Constitution of the Empire of Japan). Because the Emperor was regarded as divine and therefore above political issues, he was reduced to a mere figurehead, thereby giving the military greater, more effective independence (Bix).

**Religion & State: Enhancing Fascist Ideals**

The combination of state and religion, later known as State Shinto, would become the most obvious and "clear-cut" aspect of Japanese fascism, unique because of its basis in the worship of its Emperor. During the Meiji Restoration, many scholars sought to merge state and religion to preserve Japanese culture and values from Western influence, create a national identity, and legitimize the rule of the emperor (Hardacre). Yokoi Shōnan summarized these

feelings in his 1860 treatise, Kokuze Sanron: “Although Japan had Buddhism, Shinto, and Confucianism, it lacked a true national religion in the manner of western nations” (Yokoi 156-86). This lack was seen as disadvantageous for the Japanese. Focusing worship on the Emperor would address that problem. The Meiji government believed a national religion had allowed the West to be united morally, thus making it easier for the West to justify the creation of empires on an ethical level. An example of this justification would be the White Man’s Burden, which was tied to Christian religious ideology. As a result, the Meiji Constitution Articles 1 and 3 declared the Emperor to be a divine being who will forever govern Japan: “The Empire of Japan shall be reigned over and governed by a line of Emperors unbroken for ages eternal” (Constitution of the Empire of Japan).

This perspective formed a basis for Japan to combine both the divinity of the emperor and Shintoism (with its belief that the Emperor derives from the Sun God) with Japanese culture and state, reinforcing the Emperor’s position. The 1906 Shrine Consolidation Policy began to integrate shrines into politics, which was done by cutting funding to less-obedient shrines to force them to join larger, more compliant ones, thus making them easier to control. Additionally, schools and media taught the importance of giving one’s life to protect the Emperor’s divinity. An example was the Imperial Rescript on Education (the Japanese Pledge of Allegiance) which stated: “Always respect the Constitution and observe the laws; should emergency arise, offer yourselves courageously to the State; and thus guard and maintain the prosperity of Our Imperial Throne coeval with heaven and earth” (“Imperial Rescript on Education” 673). The concept of the Emperor as the head of religious principle and state authority was further entrenched in the minds of Japan’s younger generation (Hardacre 150-220). Japanese generals were idolized for their religiosity: for example, Nogi Maresuke committed Seppuku, or traditional suicide, when Emperor Meiji died to follow the samurai ritual of junshi in following his master into death. The result was a young generation filled with ultra-nationalism and traditional religious belief, which would later be seen in the banzai charge and kamikaze strikes in World War II (Storry 350-420).

This aspect of Japanese culture was similar to traits of German fascism. The Nazi party also used religion to expand its influence and promote a willingness to give one’s life for the greater good of the state. While the Nazi takeover of Christian churches was much more forceful, the motives remained the same: to ensure the loyalty of the population. In Germany, the idea of Fuhrerprinzip stated that the will of a nation’s leader, in this case Hitler, was the will of the nation and authority to him was unquestionable (Bergen 114-128). Similarly, the Japanese were taught that they must protect the emperor’s divine and eternal rule, and that the emperor's will was the will of Japan (Hardacre 600-650). Japan’s fanaticism was similar to Germany’s as members of the Waffen-SS were described by Heinz Guderian as having “fought with an almost fanatical determination” (Guderian). Still, Japan’s ultra-nationalism and culture was one of the only aspects of its government that was truly fascist.

**Manchukuo: Imperialism and Military Junta**

The South Manchurian Railway, or Mantetsu, established in 1906 by the Japanese government to manage the railway lines Japan had seized from Russia, became the agent and purveyor of industrialization and urban development, as well as a catalyst for spreading Japanese culture and political influence (Myers and Peattie 95-105). It was a tool of expansion to entrench Japanese interests across and beyond Manchuria. Its role might appear to mirror the fascist ideal of Germany's Lebensraum, but in reality, it bears an even closer resemblance to the functioning of the British East India Company (EIC). For context, Lebensraum, a defining idea of Nazi expansion, was a "living space" for the Aryan "super race" to expand. As a fascist ideal, it required Germany to invade its neighbors and purge undesirables to create more space (Mazower 20-40). While the Holocaust and the Barbarossa Decree were fascist, Japan's expansion into Manchukuo was more about seizure of resources and had little to do with ethnic cleansing (310-340).

In invading Manchuria, Japan was not trying to expand the Japanese race while eradicating other inferior ones; rather, its goal was to expand the economic interests of the semi-private, semi-government owned Mantetsu company (Mazower 30-40; Matsusaka 120-140). Both the EIC and Mantetsu focused on commerce and empire-building, reshaping local economies to serve the mother country. For Britain, the focus involved opium and spices. For Mantetsu, the goal was to expand agriculture and gain steel, oil, and other resources vital for the continued growth of Japan's economy (Louise Young 60-100). Mantetsu established numerous subsidiary companies and transformed Xinjing, along with Manchuria's economy, to serve Japan, much like the EIC had built Calcutta to become a centerpiece of British interests in India (Lawson 100-140). Yet, while the EIC was independent of the governmental military, Mantetsu, with prominent generals on its board, was intertwined with the Japanese military from the start. Those roots deepened with the creation of the Kwantung Army, a government army that served to protect the interests of the Mantetsu (Myers and Peattie 100-150). Thus, the EIC and Mantetsu differed in their relationship to the military, since Mantetsu had aspects of an imperialistic corporation and military junta, which complicated its ability to be defined as a strictly fascist government.

Despite the army's purpose in protecting the railway, Mantetsu did not maintain control of the army; instead, radical officers began overstepping their authority, and by 1931, the Kwantung Army had effectively taken charge of Mantetsu itself. This merger of military ambition, corporate interests, and weak civilian oversight became a model for Japan's unique type of fascism (Louise Young 130-160). The South Manchuria Railway, the Japanese invasion of Manchuria, and the function of Manchukuo as a puppet state indicate that imperialism and a military junta must be considered as aspects of Japan's government, in addition to its form of fascism.

**Military Autonomy as a Marker of Japanese "Fascism"**

The year 1931 marked a decisive turning point. Japan was reeling from a crushing economic depression. Hunger and joblessness had gripped the nation, especially in rural areas, and the civilian government seemed powerless to respond. Adding to these domestic crises were international humiliations: the Washington Naval Treaty had capped Japan's naval power below that of Britain and the U.S., while the Treaty of Versailles had brushed aside Japan's proposed racial equality clause (Burkman 50-90). Many within the Kwantung Army, convinced that Western ideas and actions had weakened Japan and stripped it of its honor, decided to take action. Colonel Ishiwara Kanji stated, "By creating opportunities through stratagem, it is by no means impossible for the military to take the lead and push the state forward forcibly" (Peattie 130-140).

The so-called Mukden Incident on September 18, 1931, triggered Japan's full-scale invasion of Manchuria. Ishiwara and Itagaki Seishiro, another colonel, orchestrated a plot to justify the invasion of Manchuria by staging an explosion on a section of the Japanese-controlled Mantetsu. For the first time, Japanese armies abroad had launched a war on their own initiative while defying direct orders from Tokyo to halt operations. Since the army reported to the emperor rather than the civilian government, the officers involved were not punished (Louise Young 150-185). This precedent of military autonomy eroded civilian authority and laid the groundwork for Japan's subsequent wars in China and the Pacific. Some historians mark the incident as the beginning of Japanese fascism, comparable to the Italian fascist invasion of Ethiopia, as they were both actions against weaker nations to expand their power. However, this precedent also effectively illustrates the start of a military junta, since the army had gone rogue, against the wishes of the civilian government (Myers and Peattie 130-160). The Italian invasion was more of a first step in Mussolini's fascist mission to restore the Roman Empire and restore Italy's former glory. Another comparison could be to Anschluss, Germany's 1938 annexation of Austria; however, this action was also not due to economic reasons, but rather to reunite the German people and to create a stepping stone for a "Greater German Reich." In comparison, the Japanese invasion of Manchuria was out of desperation due to an increasingly dire economic situation in Japan, rather than a step toward elevating the Japanese race.

**The "Fascist" Puppet State of Manchukuo: A Colonial Tactic**

As a military junta with fascist ideals, the Kwantung Army embarked on an ambitious program to modernize Manchukuo and promote Japanese culture. Though nominally independent, Manchukuo schools drilled loyalty to the Japanese emperor (Louise Young 100-130). The Kwantung Army envisioned this indoctrination as a proving ground for the society it hoped to build across all of Japan. This fascist vision was influenced by General Erich Ludendorff's Der Totale Krieg, which argued that the interests of an entire nation must be subordinated to military objectives (Marwick et al.).

However, despite these militarist and ultra-nationalist currents, viewing the Japanese puppet state of Manchukuo as "fascist" in the European sense of the word risks

oversimplification (Louise Young 274-296). Similar to Nazi models in Vichy, France, Manchukuo did indeed maintain the illusion of sovereignty while in reality functioning as a puppet state. It was also similar to the Reichskommissariat in Ukraine (one of Germany's occupied territories), in the sense that its resources were plundered to support the controlling country's needs and tied to the military (Mazower 310-340). Yet Manchukuo predated both of them, following, in part, the imperialist model used by the British in India. Similar to the EIC, Japan invaded Manchuria to bolster their economy (though it would be later used to support the military). In exploiting the colony's natural resources, using private companies to expand their influence, claiming that the colony was independent, and using propaganda to justify their control over the colony, Japan seemed to copy the West with some fascist tendencies (Matsusaka 300-400).

Ultimately, Japan's imperial project in Manchukuo reveals a complexity that is belied by the term "fascist state." The Kwantung Army's seizure of near-total autonomy in defiance of Japan's civilian leadership resulted in the takeover of Manchukuo and its preparedness for war; however, for Japan, even within the military, there was no centralized leadership as exists in fascism. Rather than a single plan, there were massive power struggles between rival generals who disagreed on how Japan should be run (Louise Young 120-160). The Army's refusal to obey the directives of the civilian government was not necessarily fascist in nature, but, instead, characteristic of a military junta (120-160). In fact, Japan's invasion of Manchuria was a defiant response to the economic and military constraints created by the West and an assertion of Japanese ultra-nationalism. However, while Japan's governance and actions bear some resemblance to those of Italy and Germany, the differences reveal the Japanese Empire to be a much more complex system (280-320). It would eventually embrace militarism and the logic of total war, yet these elements stemmed from Western imperialist ideas similar to those of Britain, France, or any other colonial power (Osterhammel 151).

**Japan's Unique Form of Fascism**

Following the Mukden Incident and the Japanese takeover of Manchuria, the Imperial military seized increasingly greater control over civilian government. Although some might view those events as evidence of greater fascism, the February 26th Incident demonstrates that Japan's fascism was quite untraditional. The incident was an attempted coup by young Japanese officers and cadets of the imperial Way Faction (Kōdōha) that was originally meant to target officers of the rival, more moderate Control Faction (Tōseiha). The former wanted revenge for the latter's forced retirement of one of their leaders, General Araki. Like the Imperial Way Faction, The Control Faction also strongly disapproved of the civilian government, but it believed the military should work within the existing political system. The Imperial Way Faction, on the other hand, wanted to destroy the system and create a fascist state with the emperor at its head, to eliminate Western influences and corruption. The coup, led by Lt. Colonel Nishida Mitsugi, had three main goals: assassinate prominent cabinet members, assassinate Control Faction leaders, and capture the Imperial Palace to empower the Emperor, who, rather than actually having absolute power,

was a figurehead. However, when the coup failed, officers of the February 26th Incident were tried and executed behind closed doors (Shillony 120-125).

This incident has been cited to support the claim that Hirohito had power and allowed Japanese generals to be blamed for his decisions during World War II (Kawamura 10-80). Yet, unlike a true fascist government in the sense that Germany and Italy would define, the military did not respond because Hirohito spoke out against the plotters. Rather they were already moving against the plotters before Hirohito spoke out, thus indicating the army was actually acting in its own interests. In other words, even if Hirohito did agree with the plot to restore greater power to the Emperor, the army would have most likely compelled him to condemn the rebels or at the very least stay quiet. This very situation nearly played out in 1945 at the end of World War II, when extremist members of the Japanese Army, almost succeeded in destroying Hirohito's surrender broadcast and compelling him to continue to fight, but failed due to a lack of support from senior generals. Ultimately, the February 26th Incident was a convenient excuse for the Tosei-ha to eliminate political rivals, while weakening the civilian government. The plot heightened the military's power by giving it the opportunity to pass an edict that only current generals could serve as Ministers of the Navy and War. The military was thereby able to control the prime minister, because, if a minister resigned, the cabinet could not convene unless a replacement was named. Thus, the military controlled the prime minister and, by extension, the country. Even Emperor Hirohito was powerless as, by using the same techniques, the military was able to force him to name multiple army commanders as Japan's Prime Minister in the 1940s. Fascism in Japan, therefore, appeared to take the shape of a civilian government, but in practice its policies and authority would be dictated by the military (Bix 414-416, 518-520).

**Power Dynamic: Japanese vs. Fascist Governments**

Japan's dynamic of centralized power in the hands of the military also differed from that of Germany and Italy, whose fascist governments were run by civilian political parties, albeit ones that were extremely militarized. Japan's system is most akin to Legionary Romania, with a military dictator (Ion Antonescu) leading a civilian government controlled by the fascist party with a monarch as a figurehead. Yet, even there, an important difference emerged in Japan's lack of a singular ruler. Military leadership was split between the army and navy, whose fierce rivalry nearly erupted in violence. Within these two branches, multiple smaller factions argued over tactics, doctrines, and politics (Harries 220-225). The leadership was much different than that of a fascist leader like Antonescu, who ran both the Romanian government and military with an iron fist. Additionally, the leaders of all fascist governments maintained power until their removal by force or death (Deletant 3-10, 45-52; Mazower 112-115). Japan, on the other hand, saw multiple prime ministers throughout the period it was considered fascist. Finally, the military never officially allied themselves with the Japanese fascist party, known as the Tōhōkai (Society of the East) and was a small and insignificant faction in Japanese politics. These characteristics ultimately indicate that, rather than a fascist state, the Japanese government was a military junta,

or Gunbatsu, that is, a government controlled by the military, resulting from a political takeover (Drea 250-260).

**Fascist Treatment of Enemies Compared to Japanese Tenkō**

During the time period that nationalism was on the rise, fascist governments ruthlessly rooted out political enemies, particularly communists. Throughout the rise of the Nazi party, communists were killed or sent to concentration camps; treated with disdain, they were not even regarded as Germans (Paxton 75-80). On the other hand, the Japanese used tenkō (literally, reorientation), which refers to coerced ideological-conversion, to handle communists following the 1925 passing of the Peace Preservation Law (chian iji hō). This law was supposedly designed to protect the national polity (kokutai) and private property, but, in reality, it outlawed communism. Yet, communists were not executed or sent to camps. Tenko was based on the belief that the Japanese people were one family, and Japanese communists were simply misled members, rather than outsiders or traitors (Maruyama 102-110). The treatment of communists in the two scenarios shows a major cultural difference in Japan that separates it from other fascist nations.

**Hitler and Hirohito: Fascist Power vs. Ineffective Figurehead**

The contrast between Hirohito and Hitler is glaring. Unlike Hitler who wielded absolute power, Hirohito only held respect. For example, his condemnation of the military fell on deaf ears when he voiced his disapproval of the Marco Polo Bridge Incident, which initiated the Second Sino-Japanese War (Bix 96-98). In July of 1937, Japanese troops stationed near Beijing (Beiping, at the time) did a live fire exercise near Chinese troops defending the city. Unaware of the exercise, Chinese troops feared an attack and open fire, resulting in the second war between Japan and China. According to Koichi Kido, Lord Keeper of the Privy Seal, following the war in 1946, Hirohito recounted, “The Army's behavior has disgusted me from the start. Both at Liu-t’iao-kou in starting the Manchurian Incident, and at Marco Polo Bridge in starting this last China Incident, men at the front defied orders from central headquarters to employ despicable methods that disgrace Our imperial armed forces” (qtd. in Wakabayashi 85). This quote could be interpreted as showing that the army took action, despite the Emperor’s supposed disgust; if so, the wording might also point to the emperor’s ineffectuality. Moving forward, the military continued to act against his desires, provoking even another conflict after the China Incident, this time with the Soviet Union, with the Battle of Khalkhin Gol (Bix 115-120). He might have been worshiped as the embodiment of the nation, but his opinion did not matter to military leaders. In the case of Hitler, many generals thought he was tactically incompetent and too controlling; others looked down on his non-German ethnicity, nicknaming him the “Bavarian Corporal.” Yet all obeyed him without question, even when it led to disaster (von Manstein 250-260). Therefore, while Hirohito, with a few stern words, could make a prime minister resign out of embarrassment, such action did not show his power, since the choice of a new prime minister would still be in the hands of the military.

Additionally, Hirohito was described as being a reserved leader by historians such as Herbert Bix and some Japanese court officials. Reasons as to why he chose not to wield the power traditionally assigned to him are speculative, since there are no official commentary or primary sources on the matter. To uphold his divine status, he only made ceremonial appearances and was otherwise removed from the Japanese public. The distance he maintained from his people and the hands-off approach he took with his own leaders is clearly demonstrated in the fact that the first time many Japanese heard his voice was in his surrender broadcast (the Jewel Voice Broadcast) in 1945, nineteen years into his reign: even then, his speech required an interpreter, since many could not understand the classical Japanese he used to address the nation (Bix 393-400). This cloud of secrecy obscures the extent of his political power and his actual stance on issues. It can only be assumed from his few quotes after the war that he disagreed with many of the military's actions in China, but lacked the power to stop the military agenda, a fact that only further separates him from fascist leaders like Mussolini, Hitler, and Antonescu (Bix 40-50).

**The Second Sino-Japanese War: Definitional Differences in Fascism**

Many historians consider the atrocities in the China Theatre of World War II to be as brutal as those of Germany. However, in reality, the Second Sino-Japanese War highlights the differences between Japanese "fascism" and that of its contemporaries, Germany and Italy (Frank 150-155). These differences include the reasoning behind the atrocities, the manner in which they were carried out, and even the politics and propaganda behind the war.

In starting the Second Sino-Japanese War, on July 7, 1937, Japan's Battle of Beijing-Tianjin was actually a response to the Marco Polo Bridge Incident. Unlike Germany's motives in Operation Barbarossa, the Japanese never officially recognized the fact that they were at war with China, instead calling it the Shina Jihen, which translates to China Incident or China Affair. Additionally, the Japanese viewed themselves as the heroes who would rescue China from the corrupting influence of the West and Communism as well as reunify it under one banner (Paine115-120). The sentiment behind the move was echoed by Japanese foreign minister Hirota Kōki, who claimed that the Japanese war with China was a "heroic surgery" to get rid of the "festering sore deep down in the bosom of Eastern Asia," a term that referred to communism rather than to an ethnicity ("Hirota Sangensoku"). Additionally, the more tacit reason for war among the Japanese stemmed from a need to gain more raw material to support the Japanese economy and military (Paine 125-130). Unlike the Germans on the Eastern Front or the Italians in the Mediterranean, the Japanese did not view their conflict as a war of annihilation or a war purely for racial dominance; its purpose was not exclusively to rally nationalistic spirit, but rather to conquer more resources that would raise the status of its own nation. This perspective of the conflict, even as late as 1937, demonstrates that the Japanese were not on a fascist crusade based on ethnic cleansing or even racial superiority, per se, as Nazi Germany later embarked on (Stahel 220-225; Paine 135-140).

**War Crimes: Divergence from Fascism**

Citing Japanese fascism, some argue that the nation's atrocities in China are comparable to those of the Holocaust in Europe. These historians believe both were racially motivated and ordered by high ranking commanders, thus confirming Japan as a strictly fascist state. Hans van de Ven remarked that "Japan's invasion of China was carried out by a fascist regime that believed in racial superiority and pursued brutal military aggression…akin to those perpetrated by Nazi Germany, reflecting fascist ideology in both motive and method" ("China's Resistance during WWII"). He supports this idea by stating that Japanese military ideology was rooted in racism, that war crimes were premeditated and deliberate, and that they were ordered by generals in mop-up operations (van de Ven). However, while there was racism within the Japanese military, the direct orders from Japanese generals facilitating war crimes were more often the result of taking extreme measures to defeat their enemy (Frank 100-155). One difference was seen in Germany's proactively ordering the deaths of civilians, while the Japanese generals simply ignored whether the casualties would be military or civilian.

The most notable example of these orders was the "three alls" policy. The "three alls" policy, otherwise known as Jinmetsu Sakusen or Order Number 575, called for the death of all Chinese suspected communist rebels, the destruction of property and crops to give Chinese rebels fewer places to hide and eat, and the construction of fortifications in Japanese-occupied China. The order resulted in the deaths of an estimated 2.7 million Chinese and the destruction of many Chinese villages (Mitter 136–140; Paine 320–340). While many argue that these figures indicate racial motivation, the mass casualties can also be viewed as an extreme response to the 100-regiment offensive launched by Communist China that damaged Japanese infrastructure, thus hurting the Japanese war effort. Certainly racism was at work in every nation's actions, but for the Japanese, the callousness still differed from Nazi war crimes such as the creation of Einsatzgruppen (mobile death groups that followed the army to kill all "undesirables" and those labeled subhuman by the Nazi regime). Nazis specifically targeted civilians in an attempt to wipe out a race; Japanese showed complete disregard for civilian life in favor of winning the war at all costs (Rees 85-110; Mitter 120-140). So, while the "three alls" policy was extreme, it was not rooted in racism and served a strategic, yet brutal, purpose, making it an illegitimate argument for Japanese fascism.

Additionally, the majority of well-known Japanese war crimes resulted from a combination of a lack of discipline by commanders and the unchecked emotions of individual soldiers. Ishikawa Tatsuzō's Soldiers Alive, a historical novel based on his experiences with the Shanghai Expeditionary Force, illustrates this distinction between Japanese conduct and that of other fascist powers. The novel illustrates the descent of ordinary soldiers during the Battles of Shanghai and Nanjing, showing how violence escalated from executing suspected spies and camp followers to killing surrendering soldiers, and finally to murdering civilians without cause, all the while Japanese commanders remained complacent. It becomes clear that Japanese soldiers were increasingly frustrated with Chinese resistance; the Japanese believed they were the "good guys," helping a Chinese population that was unappreciative of this supposed salvation. This is

supported by a quote from the book Soldiers Alive, which states, “Already dozens of army civilians employees … bustled about its streets carrying out their postwar tasks: to build a cheerful North China, to make its inhabitants understand the justice of the Japanese cause, to grant them sanctuary for the pursue their peaceful lives” (Ishikawa 65). In earnest, these words convey the Japanese perception of what their actions meant for China, despite the opposite being the case. Additionally, Japanese soldiers in the book were more emotional and rash after the death of a comrade, whom they regarded as family, resulting in a need for retribution and blood (54-75). This is shown when examining the army priest, who does not pray for the Chinese dead because he grew to hate them when he thought of them as his comrades’ enemies (110-120). By looking at Japanese atrocities through these lenses, it is clear that over-emotionality and lack of discipline played a larger role in Japanese atrocities, while Hitler’s fascists were cold, calculated, and deliberate (Ishikawa 54-75; Mazower 120-150). In fact, the German government established multiple initiatives, such as the Wannsee Conference to plan the Holocaust. When German commanders ordered German soldiers to execute undesirables, it was done with deliberation and calculation. In fact, many SS officers after the war claimed they had no emotion when executing Jews en masse. One soldier, Hans Fredriech, said in an interview that he “felt nothing. My only thought was: aim carefully so you will hit them” (Auschwitz: Inside the Nazi State). Should emotionality be taken into account in defining fascism or the lack thereof? It can be argued that the extremism characteristic of fascism is tied to its uncompromising nature. The additional motivations for Japanese atrocities, including anger toward the Chinese and loss of brother-soldiers, cloud the pure definition of fascism as demonstrated by the Germans. This difference in the mentality, evidenced in how the two nations dealt with executing enemies, is, therefore, further evidence that Japan’s type of fascism differed from that of other nations.

**Final Ideological Differences**

Further evidence of disparate definitions of fascism can be seen in comparing the Greater East Asia Co-Prosperity Sphere with Lebensraum and the White Man’s Burden. Some historians believe the Co-Prosperity Sphere was merely a Japanese version of Lebensraum, aligning Japanese fascism more closely with Germany’s. However, Japan’s expression of the ideology is actually closer to the White Man’s Burden. Lebensraum asserts that the Aryan race needed to expand in order to survive; it feared “contamination” of its race if confined or exposed to other races. This belief system resulted in atrocities like the Holocaust, an all-out attack on perceived enemies that is compatible with fascism (Mazower 50-56). On the other hand, the White Man’s Burden was a Western idea, rooted in economic profit as much as in racist ideology, used to justify European colonization and civilizing missions, especially in Africa. It claimed that less technologically-developed, less educated, less religiously-affiliated peoples were “savages” who needed to be “civilized.” In reality, colonial powers only built infrastructure that helped support their colonial ambitions and eliminated attempts at independence with brute force, as was demonstrated during the Boer Wars (Osterhammel 32-36). Ideas rooted in racism therefore became a justification for the ruthless takeovers that disregarded native populations.

In terms of Japan, the propaganda associated with the Greater East Asia Co-Prosperity Sphere was nothing more than a modified version of the philosophy behind the White Man's Burden: it claimed that the Japanese had to civilize, modernize, and unite all of Asia to fight Western colonial oppressors (Paine 120-130). As in the White Man's Burden, racism was the justification for economic imperialism, rather than a call for eradication of the entire race, as was the case with the Nazis. Matsuoka Yōsuke articulated this goal in 1940, when he said, "The concept of the Greater East Asia Co-Prosperity Sphere promulgates the belief that Asia was meant for Asians…It envisions a unified East Asia free of Western colonial subjugation, with economic viability and self-sufficiency under Japanese leadership" ("First Announcement of the Greater East Asia Co-Prosperity Sphere"). In other words, despite the high numbers of Chinese who were ruthlessly killed by Japan, annihilation was never the goal. The real objective was to establish Asian hegemony under Japanese dominance and supremacy. Therefore, in reality, Japan's actions took the form of the brutal extraction of natural resources as well as exploitation of humans in conquered territories.

This mandate indicates why books like Soldiers Alive were banned: the Japanese hoped to portray themselves as saviors, rather than oppressors, in the Western tradition of conquest. In reality, Japan provoked a war with and later invaded China because China had the necessary resources to support Japan's economic growth. Also, as a disorganized state with multiple warlords and a communist insurgency, China was seen as ripe for a killing blow that would secure Japan's spot as the sole Asian superpower (Boyle 130-200). These reasons aligned with the expansionist goals of the Zaibatsu (large Japanese corporations) and the military. The manner in which the Japanese proceeded is not unlike how the West used the White Man's Burden to justify the scramble for Africa and Asia that bolstered economies at the expense of the local population (Osterhammel 32-36).

The Greater East Asia Co-Prosperity Sphere also justified war with the West, specifically the attack on Pearl Harbor. Rather than a power grab, Japan saw its war with the West as a war of survival. When the US demanded the Japanese leave China or face an oil embargo, the Japanese military felt both angered and scared. In 1940, since 80% of its oil came from the US, Japan could not support its economy and its war machine could not function without the oil. The Japanese pointed out what they saw as hypocrisy for being condemned for doing in China what the West had done in Africa and Asia (Paine 100-150). This sentiment was expressed by Prime Minister Hideki Tojo, who told the Diet, in 1941, "The United States' actions in freezing our assets and cutting off vital materials leave Japan no choice but to defend herself. The nation's very survival depends on securing the resources necessary to live and maintain sovereignty" ("Address to the Imperial Diet"). Matsuoka reiterated the sentiment when he said in a meeting, "If Japan accedes to the demands of the United States, she will surrender her independence and cease to exist as a sovereign nation. The embargoes and pressures leave us no alternative but to act decisively" (United States Department of State; Mazower 100–156; Osterhammel 50–100).

In contrast, Germany's Lebensraum and the Eastern Front was a war of annihilation: Hitler intended to exterminate minorities and political enemies, especially communists. Even

Mussolini's desire to reunite the Roman Empire was much more of a race war. These differences indicate that Japan's behavior was less fascist in nature and more akin to Western justifications for expansionism (Osterhammel 50-100). In conclusion, the Japanese saw its war with the West as a fight for its very survival and its war with China as a conquest for resources, while ignoring and actively denying the atrocities carried out by its soldiers in China using similar concepts as Imperialist powers (Yellen). Whether this was an accurate assessment or one used hypocritically in imitation of the White Man's Burden will remain a contentious subject for historians. Yet, in the case of its war with China, Japan's actions fit the mold of the imperialist White Man's Burden more than it does the fascist Lebensraum.

**Conclusion**

History is always presented through the lens of winners and losers. From the American perspective, wartime Japan was a fascist state, due to its authoritarian leadership, its ties to Germany and Italy in World War II, its "feudal" social structure, its expansionist policies, and its racial superiority complex. However, as fascism dominated world events, it became too easy to classify Imperial Japan as fascist. Given its alliance with Germany and Italy, it was too easy to dismiss its complex and disorganized political structure, as well as its varied and sometimes internally antagonistic motivations and goals.

What must be considered historically is the Japanese point of view: the motivations of its soldiers and leaders, the ideology behind actions and atrocities, and Japanese perspectives on survival and subjugation; these elements provide invaluable insight because, at its core, history is always nuanced. This was especially true for the Imperial Japanese government. The goal of this paper was to highlight some of the nuances that confirm Japan's fascism as distinct from that of Germany and Italy, allowing for greater precision by taking multiple perspectives into account.

The Japanese Empire was a complex entity that should not be labeled as practicing the type of fascism that Western nations adhered to. While it had some fascist elements, such as the elevation of the state above self and family and the near godlike worship of its leader (in this case the Emperor), it also differed in many ways. The Japanese conquests were largely economically, rather than strictly racially, motivated. The atrocities that Japanese soldiers committed were callous but not conducted to exterminate an entire race, as Hitler sought to do to the Jews. Rather, they were the result of rash, emotionally-fueled actions of soldiers and an extreme indifference to the value of human lives on the part of the Japanese Army High Command. Even their supposed version of Lebensraum through the Greater East Asia Co-Prosperity Sphere is more similar to the White Man's Burden and its definition of racism than it is to its Nazi counterpart, with its rejection of an entire race. Furthermore, the structure of the Japanese government resembled more of a military junta than a fascist dictatorship since the Emperor had little power. As a result, Japan practiced fascism under a different umbrella, combining Western colonization tactics, traditional aspects of fascism, a military junta-styled government, and imperialist ambitions.

Understanding why Japan is not entirely a fascist nation is crucial for two major reasons. One, by overusing the term “fascist,” clarity is lost: it degenerates into a term for any authoritarian state that is not communist, rather than its own unique political phenomenon. Additionally, a more nuanced definition enhances our understanding of World War II, specifically that of the Asian theatres, as not simply a conflict pitting democracy against fascism, but a result of conflicting imperial interests, differing visions for the future, and a massive resource struggle.

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**Exploratory Analysis and Machine Learning Prediction of Shark Attack Fatalities**
**By Prisha Tarar**

**Keywords** shark attacks, global, fatality rate, exploratory data analysis, machine learning, feature importance analysis

## Introduction

Shark attacks are a topic of interest for both researchers and the public, particularly in coastal areas where human activity intersects with marine life. Although relatively rare, these incidents can have serious outcomes. Understanding when, where, and how they occur can improve safety for people who spend time in the ocean (ISAF, 2024).

Studying the shark species involved in attacks can help identify patterns and potential risk factors. Some species, such as Great Whites (*Carcharodon carcharias*) and Bull Sharks (*Carcharhinus leucas*), appear more often in reports, while others are rarely identified (Neff & Hueter, 2013). Knowing which species are more likely to be involved can support local safety planning, such as monitoring specific areas or times of year more closely. It can also help individuals make more informed choices about when and where to enter the water.

This topic is also important for public understanding and marine conservation. Sharks play a critical role in ocean ecosystems, and most species are not dangerous to humans. Clear data about shark attacks can help reduce fear and prevent the spread of misinformation (Simpfendorfer et al., 2011). Accurate reporting and analysis support both public safety and the protection of marine wildlife.

Using a global shark attack database, this research explores how different factors affect when and where shark attacks happen. It looks at the time of day and season to see if attacks are more likely during certain parts of the day or year. The location of attacks is also important, as some areas—like certain coastlines or popular beaches—may have higher numbers of incidents. The type of shark involved is another key factor, since some species are more aggressive or more commonly involved in attacks. What the person was doing at the time also matters, whether they were swimming, surfing, diving, or fishing. The study also includes information about the people who were attacked, such as their age and gender. By looking at all of these details, it is crucial to better understand the patterns behind shark attacks and how to reduce the risk for people in the water.

Some studies have used machine learning to predict how dangerous a shark attack might be. Lim et al., (2019) tested two types of models—Support Vector Machines (SVMs) and Bayes Point Machines (BPMs)—on a dataset of more than 6,000 shark attack cases. Their goal was to predict whether an attack would be fatal. The Bayes Point Machine performed the best, with an accuracy of about 84.8%, while the Support Vector Machine reached 83.1% accuracy. Although these results were promising, the study was still limited by missing or inconsistent data, which affected the overall reliability of the predictions.

Another study, *Mortality and Management of 96 Shark Attacks*, focused on detailed medical records from 96 real shark attack victims. It found that around **8.3%** of these cases were fatal and developed a severity scoring system to help classify the outcomes. However, the study only included a small portion of all known attacks, since most records didn't have enough medical detail, which made it harder to generalize the findings.

Earlier research also struggled with similar challenges, such as incomplete or missing data, a lack of environmental context like weather conditions or shark behavior, and the absence of a standard global dataset. Some studies didn't deeply explore global trends or patterns over time. Others used models that weren't very accurate, especially when the species of shark involved was unknown or unconfirmed. In our study, we aim to address these limitations by improving data quality and model performance to support more reliable and meaningful research.

Past studies about shark attacks have shown that the data needs to be better. But there are some big problems with the information they use: (1) many records are incomplete, have missing details, or there isn't one global dataset everyone uses; (2) there isn't enough information about other important factors that could affect shark attacks; (3) they don't explore global trends and patterns; and (4) the models they use aren't as predictable or reliable due to the aforementioned data issues.

In this study, we aim to (1) pre-process, curate and standardize global shark attack dataset, (2) conduct exploratory data analysis to identify the trends, patterns, and correlations related to shark attacks, (3) build a simple yet effective machine learning model to predict the risk of fatality from the shark attack. First, we will pre-process and organize the shark attack dataset to improve its quality and consistency for analysis. This includes handling missing data, standardizing entries, and simplifying categories where appropriate. Second, we will conduct exploratory data analysis to identify trends and relationships in the data. We will look at how different variables—such as species, victim age, location, and activity, correlate with the outcome of the attack. Third, we will build a machine learning model to predict the risk or severity of shark attacks. The goal is not to predict when attacks will happen, but to assess the relative risk of fatality under different conditions, based on historical patterns.

**Dataset**

The dataset that was used in this study documents shark attacks that have occurred from the 1900s to the present. It includes around 5,000 different attacks from all over the world. Each row in the dataset represents a single shark attack and includes basic details about the location, time, type of attack, victim, and shark species involved.

The location data include the country, area, and specific site of each attack. Time-related columns capture the date and time of day when the incident occurred. Additional columns record the victim's age and gender. The dataset also contains columns describing the type of attack, the activity the victim was engaged in at the time, and the shark species involved. An important field, the "Fatal" column, indicates whether the attack was deadly ("Y") or not ("N"). Although a

few reports are missing information, overall the dataset provides enough detail to help identify patterns and trends.

## Methodology

### *Data Pre-Processing*

Shark attack type columns originally included over 10 different categories. To make the data easier to understand, it was simplified and grouped into five main sections, such as unprovoked, provoked, sea disaster, boating, and unknown attack types. These new groupings help organize similar type of attacks and make information clearer for analysis.

The Activity column included many specific activities as shown in Figure 1 the victim was engaged in at the time of shark attack. To make the data more organized, we grouped them in broader categories such as surfing, swimming, fishing, diving, boating and other. This helped us better understand what people were doing when shark attacks occurred and made it easier to spot patterns. By simplifying the data, it also became easier to compare activities across different types of attacks.

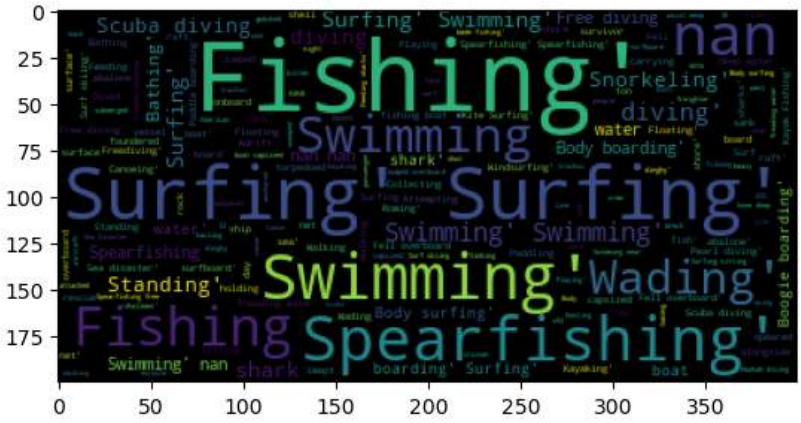



**Figure 1**. Wordcloud of the activities the victims were engaged in at the time of shark attack

The Shark Species column was cleaned and simplified by grouping similar entries into clear, recognizable categories. For example, all types of white sharks were grouped as Great White, while common species like Bull Shark, Tiger Shark, Blacktip Shark, and Hammerhead Shark were listed separately. Rare or unclear cases, including unknown or unconfirmed species, were grouped as Unknown or Other. This made it easier to spot patterns and see which shark types are most often linked to attacks.

The Countries column was used to create a new column called Hemisphere. Each country was classified as either in the Northern or Southern Hemisphere based on its location on the globe. This helped simplify the data, making it easier to compare shark attacks across larger regions without having to look at each individual country. It also allowed us to see broader geographic patterns in the data.

A new column called Ocean was created using information from the Countries column. Each country was matched with the ocean it borders, like the Atlantic, Pacific, Indian, Arctic, Southern oceans. If a country does not have access to an ocean, it was assigned a “No Ocean” category. This allowed us to group shark attacks by ocean, making it easier to see where most attacks are happening across the world’s waters. It also helped highlight which regions may have higher shark activity.

The Time of Day column was also simplified. Originally, it included exact times or a wide range of specific hours. To make the data easier to work with and to help identify general patterns, the times were grouped into four main categories: "Morning," "Afternoon," "Evening," and "Night." This made it easier to see when shark attacks were most likely to happen during the day.

The Date column was converted to show whether each shark attack happened on a Weekday or a Weekend. This change made it easier to study if attacks are more common when more people are likely to be in the ocean, like on weekends compared to weekdays. It helped reveal patterns related to human activity and ocean use.

***Exploratory Data Analysis***

This section presents an overview of shark attack patterns based on factors such as victim age, activity at the time of the attack, shark species, location, and time. The analysis focuses on identifying trends in both fatal and non-fatal incidents across the globe. By examining how attacks vary by season, time of day, geographic region, and type of activity, we aim to better understand the conditions under which shark attacks are more likely to be fatal. These patterns help provide context for the data and support further analysis of possible risk factors.

Figure 2 shows the number of shark attacks reported each year from 1840 to the present, separated by fatal and non-fatal outcomes. The total number of attacks rises steadily over time, especially from the mid-1900s onward. In the earlier years more fatal attacks occurred more frequently than the non-fatal, with fatality rates at 40–45% in the early 1900s. This could be a result of not as developed technologies of the time to capture and record all attacks. Non-fatal attacks consistently occur more often than fatal ones across the entire timeline. The proportion of fatal attacks remains fairly steady in recent decades, typically below 20%, with no large changes or spikes. This suggests that although more attacks have been reported in recent decades, the chance that an attack results in death has not increased significantly.

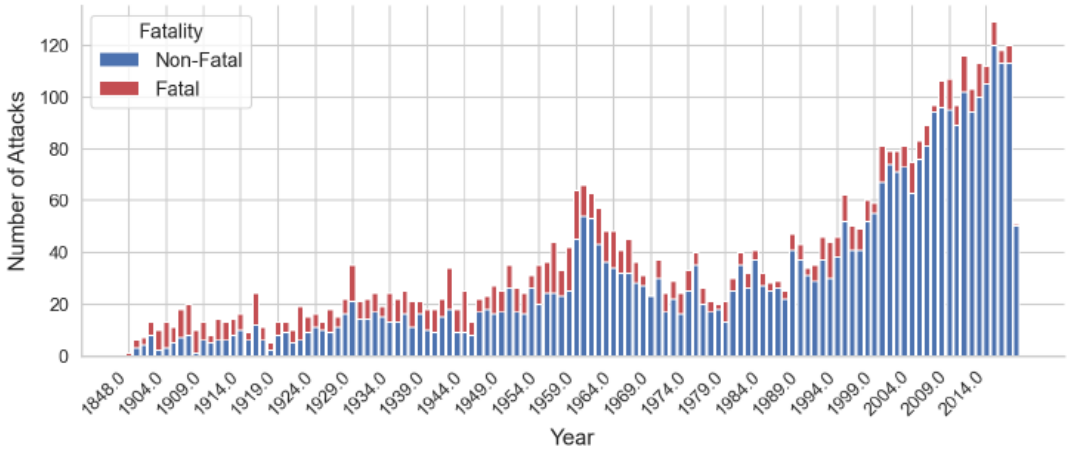



**Figure 2.** Number of shark attacks per year, showing fatal (red) and non-fatal (blue) cases from 1840 to present.

Figure 3 breaks down shark attacks by age, separating fatal from non-fatal cases. Most attacks happen to people aged 10–20, with those 20–30 coming in second. Across every group, non-fatal attacks are more common, but the chance of fatality isn't the same for all ages. The 10–20 group faces a fatality rate between about 13% and 20%, which is pretty significant given how many attacks happen in that bracket. Kids under 10 usually have lower fatality rates, though a few outliers probably come from having fewer cases overall. The 20–30 group's fatality rates look very similar to the 10–20 group. So, while teenagers and young adults get attacked the most, their risk of fatality stays relatively high compared to younger kids, which is a crucial point for how we think about prevention and safety.

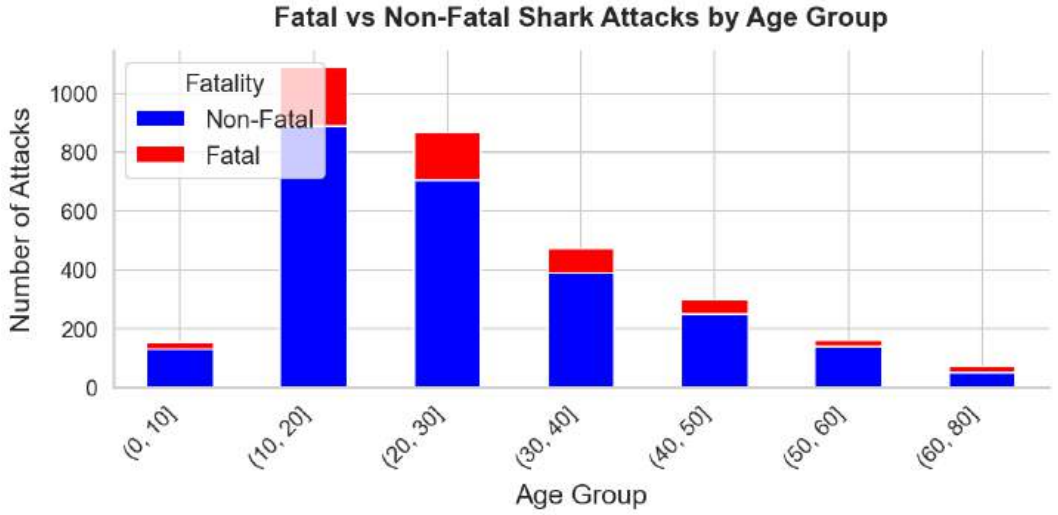



**Figure 3.** Number of shark attacks by age group colored by fatality

Figure 4 shows the number of shark attacks based on the gender of the victim, divided into fatal and non-fatal outcomes. The majority of recorded attacks involve male victims, with non-fatal cases being more common for both genders. Male victims have a slightly higher fatality rate (about 20.6%) compared to female victims (about 17.1%). Female victims account for a smaller share of total attacks, which may reflect over different circumstances.

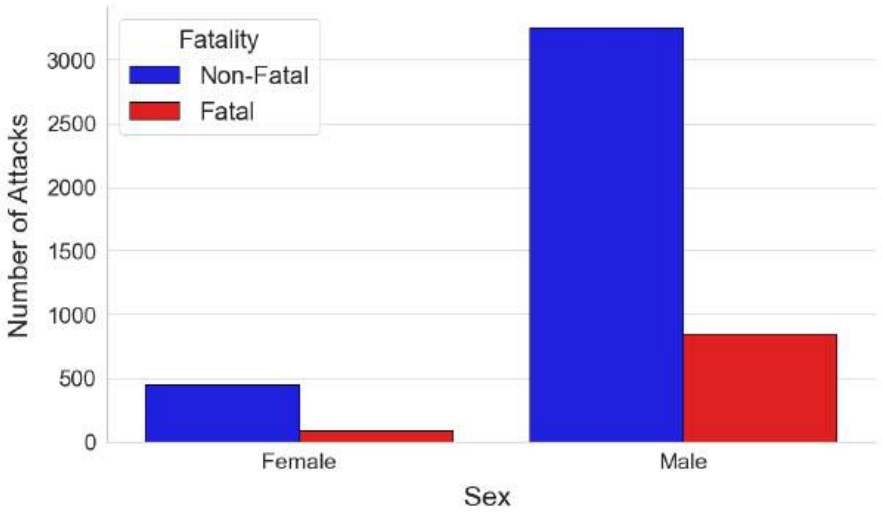



**Figure 4.** Shark attacks by victim gender colored by fatality

Figure 5 categorizes shark attacks by type: unprovoked, provoked, sea disaster, boating. Provoked attacks—where the shark was engaged or disturbed by the victim—are less common. Sea disasters and boating-related attacks are relatively rare and have a 0% fatality rate. Unprovoked attacks have the highest fatality rate of approximately 27%. This figure helps clarify how shark attacks are classified and which types are most frequently reported.

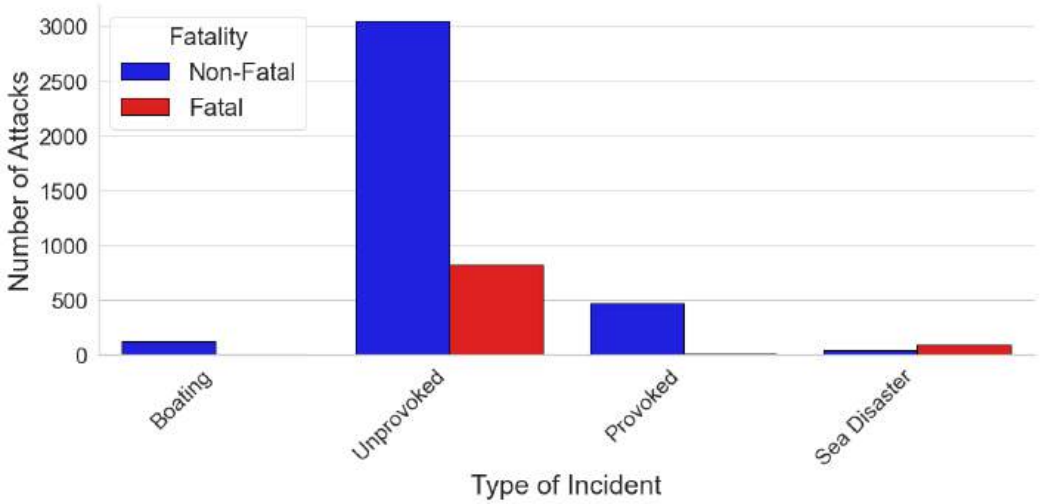



**Figure 5.** Shark attacks by type of incident colored by fatality

Figure 6 shows fatality rates for the top activities victims were engaged in during shark attacks. Swimming has the highest fatality rate at approximately 35%, followed by boarding at 29%, diving and other activities both at around 24%, and fishing at 15%. Surfing has the lowest fatality rate at just 6%. The variation in fatality rates suggests that the type of activity is linked to differences in the severity of shark attacks. A pattern that emerges is that the more physically immersed or active a person is in the water, the higher the fatality rate tends to be. This figure highlights how the risk of fatality differs among activities during shark attacks.

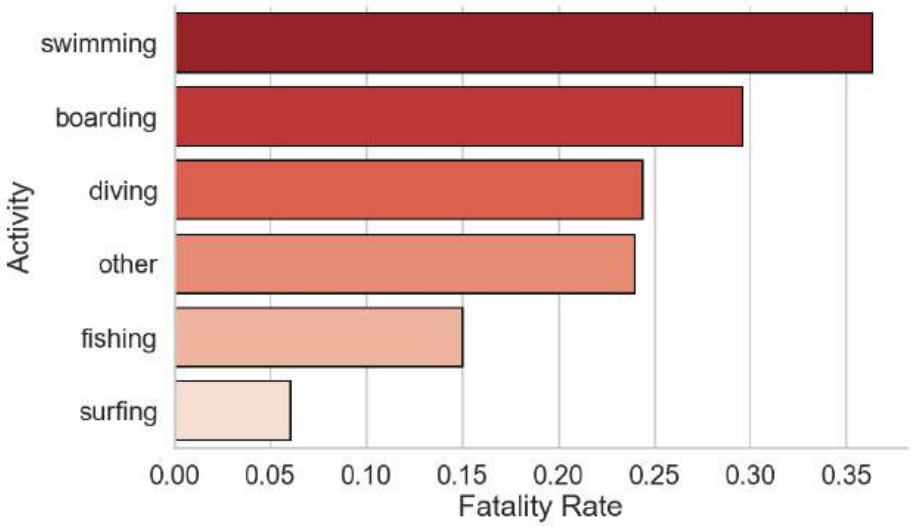



**Figure 6.** Fatality rate of shark attacks by activity, showing the percentage of attacks resulting in death.

Figure 7 is a pie chart showing the share of shark attacks by species. The White and Bull Sharks account for the largest portions, indicating they are the species most often identified in attack reports. A significant part of the chart is labeled as “Other,” which includes cases where the shark species was not identified or was rare. This shows that in many attacks, the species involved cannot be confirmed. Among identified species, Whites lead in frequency. The figure provides a clear overview of which shark species are most commonly linked to attacks and the amount of missing or unclear data on species.

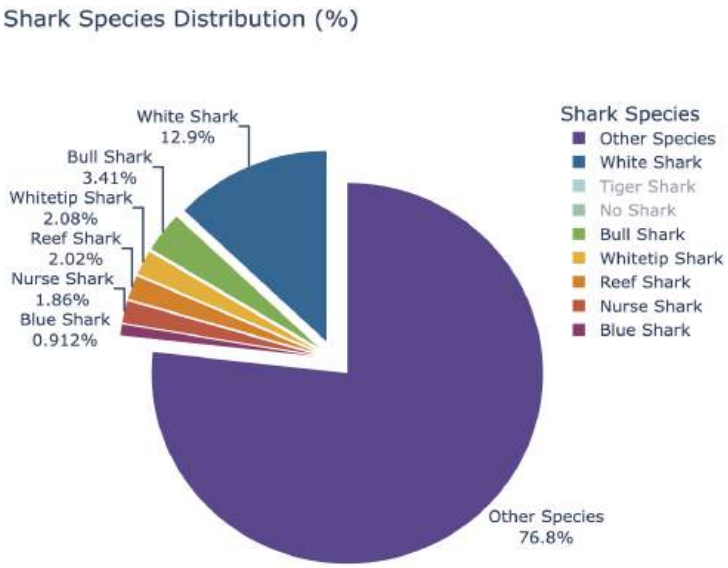



**Figure 7.** Distribution of shark attacks by species, with "Unknown/Other" representing unconfirmed or rare cases.

Figure 8 illustrates shark attack counts distributed across four time categories: morning, afternoon, evening, and night, separated by fatal and non-fatal outcomes. The highest number of attacks occur in the afternoon, followed by morning and evening, with the fewest at night. Non-fatal attacks exceed fatal ones in all time categories. The data indicates a clear time-of-day pattern in attack frequency, with an overall fatality rate of approximately 21%, reflecting a notable proportion of fatal outcomes across all time periods.

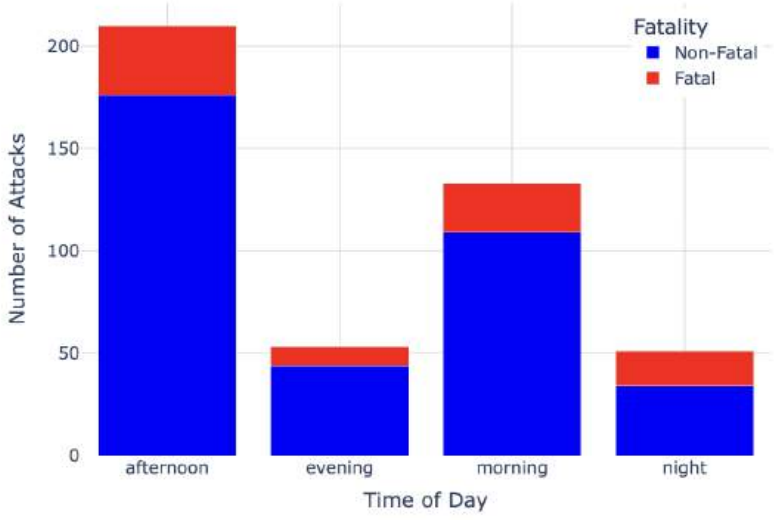



**Figure 8.** Shark attacks by time of day colored by fatality

Figure 9 shows the total number of shark attacks by season, split into fatal and non-fatal cases. Summer has the most non-fatal attacks, followed by winter and fall, with spring seeing the fewest. In all seasons, non-fatal attacks are more common than fatal ones. The fatality rate is the highest at close to 16.5% in the summer, which suggests that while the number of attacks changes with the seasons, the chances of one being fatal don't vary much. The figure makes it clear that attack frequency shifts with the seasons, but the severity doesn't.

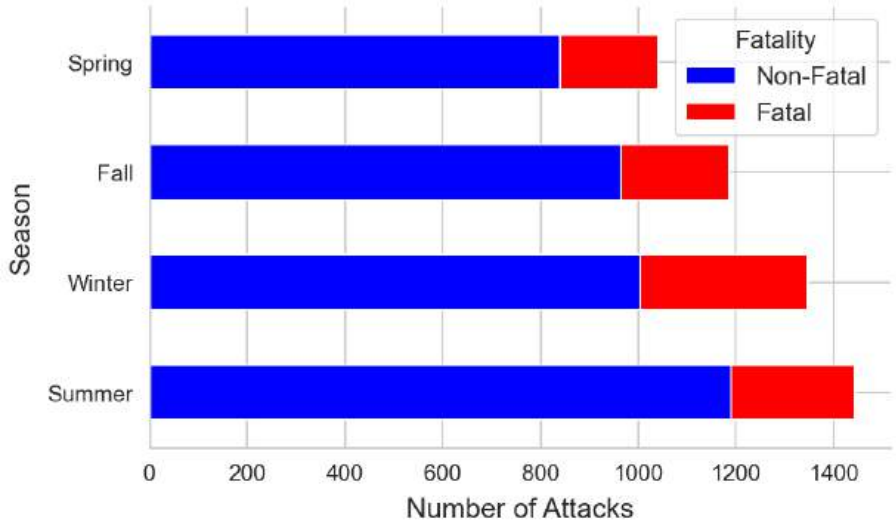



**Figure 9.** Number of shark attacks by season colored by fatality

Figure 10 compares shark attacks in the Northern and Southern Hemispheres, separating fatal and non-fatal outcomes. The Northern Hemisphere reports a higher total number of attacks than the Southern Hemisphere, which may be related to greater coastal population density or more widespread ocean use in the north. In both hemispheres, non-fatal attacks occur more frequently than fatal attacks. However, the Southern Hemisphere shows a slightly higher proportion of fatal attacks relative to total attacks compared to the Northern Hemisphere, with estimated fatality rates around 22–24% in the south versus 20–22% in the north. This could suggest differences in species, attack circumstances, or reporting practices between hemispheres. The figure summarizes geographic differences in shark attack frequency and severity, offering insight into global patterns based on hemisphere.

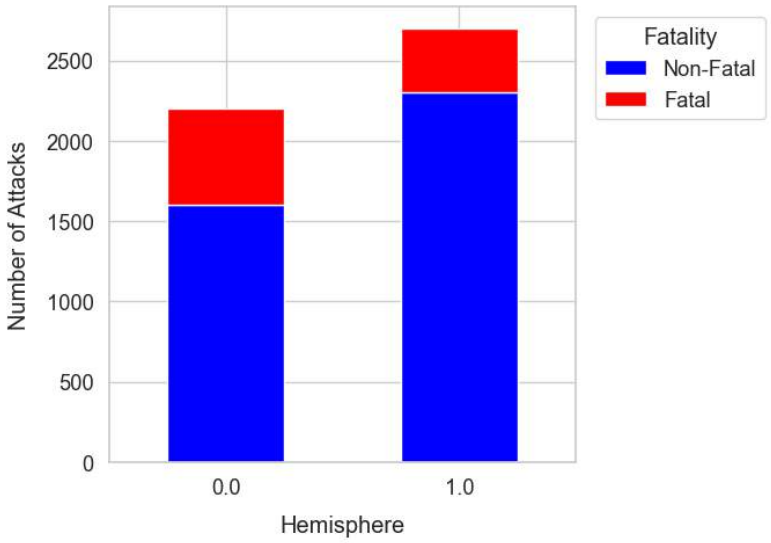



**Figure 10.** Shark attacks by hemisphere in Northern (North = 1.0) and Southern (South = 0.0) Hemispheres colored by fatality

Figure 11 displays the number of shark attacks by season for the Northern and Southern Hemispheres. In the Southern Hemisphere, summer shows the highest fatality rate at approximately 27%, followed by fall and winter, each with rates around 25%, and spring slightly lower at about 23%. In contrast, the Northern Hemisphere shows less seasonal variation, with all seasons—summer, spring, and fall—showing similar fatality rates around 14%, and winter slightly higher at approximately 25%. This figure highlights how fatality rates vary based on both season and hemisphere, focusing on the percentage of attacks that are fatal rather than the total number of incidents.

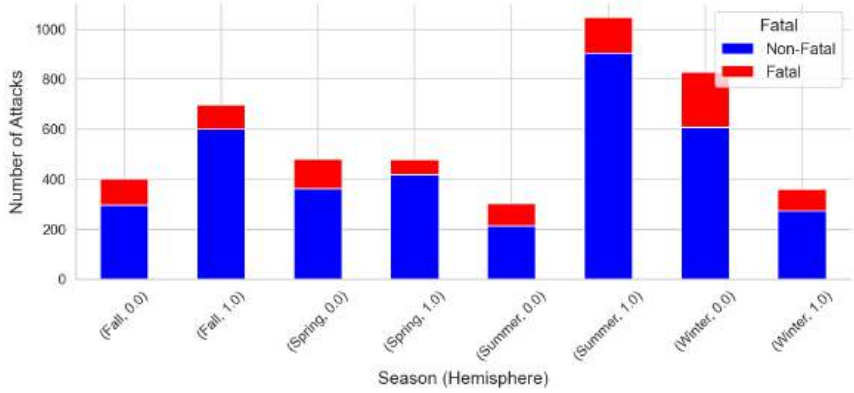



**Figure 11.** Shark attacks by season in Northern (North = 1.0) and Southern (South = 0.0) Hemispheres colored by fatality

Figure 12 shows the total number of shark attacks in the top 10 countries with the highest numbers of incidents. The United States records the most non-fatal attacks, followed by Australia with the second most. In most countries shown, non-fatal attacks are more frequent

than fatal ones, though the proportion of fatal attacks varies. The countries by the Atlantic Ocean region have the highest fatality rate at about 36.4%, followed by Australia with approximately 20.5%. Other locations like the Bahamas have much lower fatality rates, near 0%. This figure provides a geographic comparison of attack frequencies and outcomes, highlighting which countries and regions have the greatest reported incidents and how fatality rates differ across them.

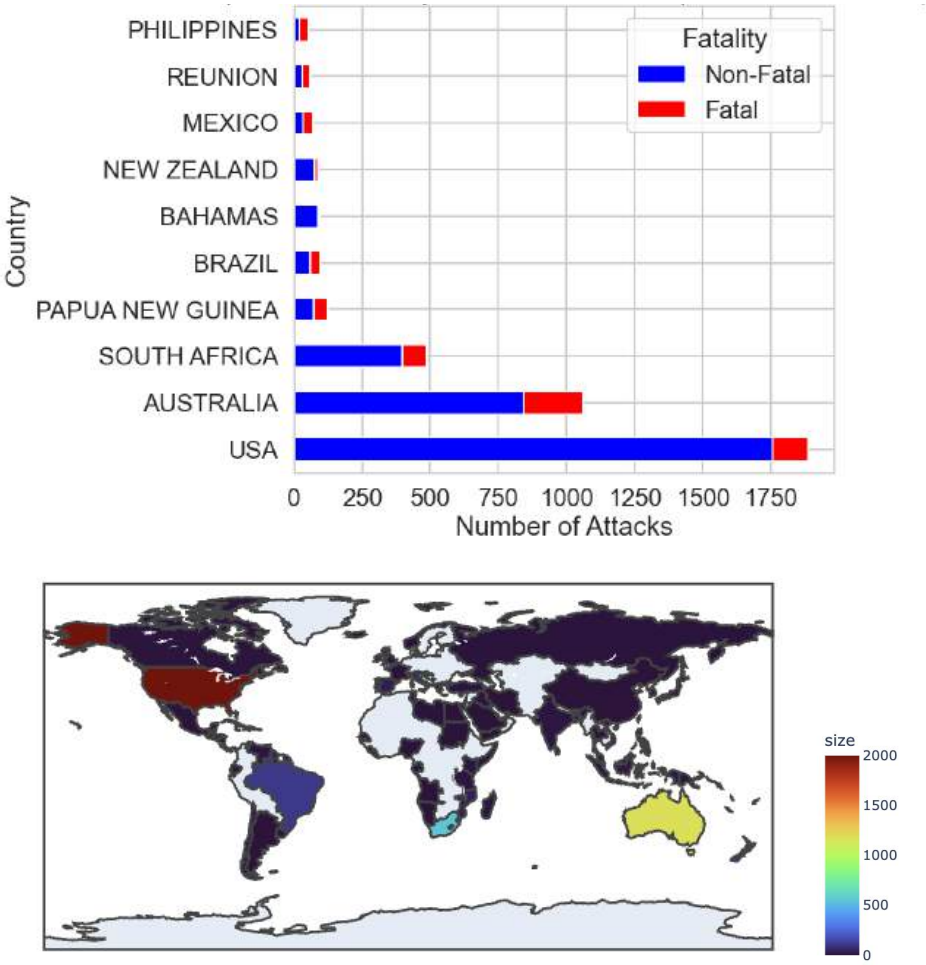



**Figure 12.** (top) Shark attacks in the 10 countries with the most incidents colored by fatality, (bottom) Data from countries around the world, with color showing how big the value is (darker = more, up to 2000).

Figure 13 displays shark attacks grouped by the ocean nearest to the location of each incident. The Pacific Ocean accounts for the largest number of attacks, followed by the Atlantic and Indian Oceans. The Southern and Arctic Oceans show no recorded incidents, while a notable number of attacks occurred in locations not directly connected to an ocean, categorized as “No Ocean.” Across all ocean regions, non-fatal attacks are more common than fatal ones. However,

the fatality rate varies significantly: the Atlantic Ocean has the highest fatality rate at approximately 29.4%, followed by the Pacific at 22.6%, the Indian Ocean at 21.1%, and the "No Ocean" category at 9.8%. This chart helps identify where shark activity is most frequently reported in relation to global ocean regions.

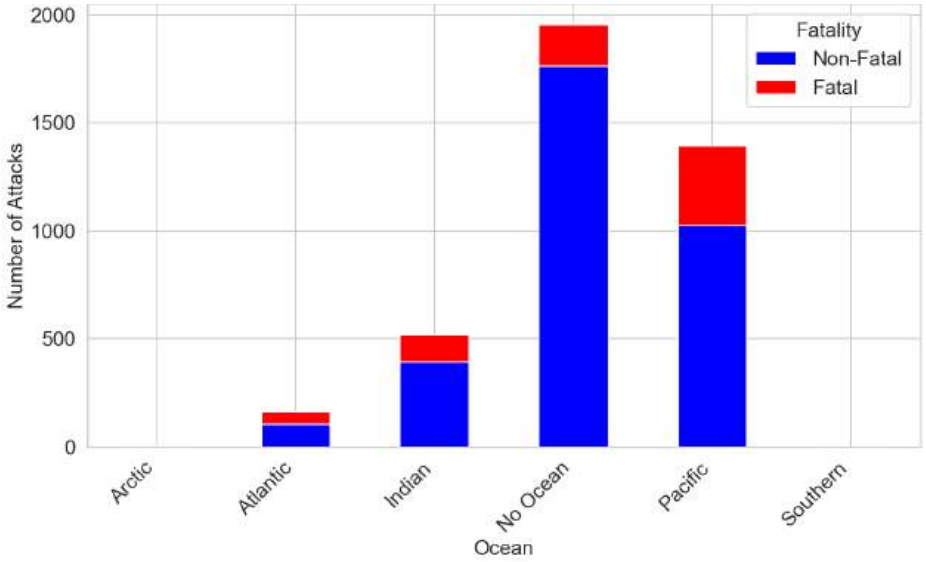



**Figure 13.** Shark attacks by Ocean colored by fatality

***Models and Evaluation Metrics***

After completing the exploratory data analysis and data preprocessing, the final input features (X) include the key variables that were found to have meaningful relationships with shark attack fatality outcomes. These features consist of the victim's age, gender, activity at the time of the attack, shark species involved, type of attack, hemisphere, ocean, season, and time of day. Each of these factors was encoded and standardized to ensure consistency across the dataset. The output variable (y) represents whether the shark attack was fatal or non-fatal, encoded as a binary classification label where 1 indicates a fatal attack and 0 indicates a non-fatal one. To prepare the data for model training, the dataset was split into training and testing subsets using an 80–20 ratio. A stratified split was applied to maintain the same proportion of fatal and non-fatal cases in both subsets, ensuring that the class distribution remained balanced for accurate model evaluation.

In this study, we used six different machine learning models to help us predict outcomes related to shark attack fatality risk. Logistic regression is a simple model that uses mathematical relationships between input variables to estimate the probability of an event occurring (Pedregosa et al., 2011). It looks at all the features we give it and calculates a probability for each outcome. K-Nearest Neighbors (KNN) works by comparing a new example to previously observed examples and predicting the outcome based on the majority class of its nearest neighbors (Cover & Hart, 1967). It is intuitive but sensitive to the choice of the number of neighbors.

Random Forest is composed of multiple decision trees, each trained on different parts of the data; it aggregates their results to make a final prediction (Breiman, 2001). Extra Trees is similar, but introduces additional randomness when splitting nodes, improving variance reduction and computational efficiency (Geurts et al., 2006). Both models are effective at handling nonlinear and complex data patterns, which is valuable when analyzing multifactorial environmental and biological phenomena such as shark attacks (Midway et al., 2019).

We also used two boosting models, XGBoost and LightGBM. XGBoost builds trees sequentially so that each tree attempts to correct the errors of the previous one (Chen & Guestrin, 2016). LightGBM operates similarly but uses a leaf-wise growth strategy that allows faster computation and better handling of large datasets (Ke et al., 2017). Such models can be especially useful when dealing with heterogeneous ecological or behavioral data, as seen in global shark attack trends (Midway et al., 2019).

We evaluated model performance using precision, recall, F1-score, and precision-recall AUC (Saito & Rehmsmeier, 2015). Precision measures how many of the predicted positives were correct, recall measures how many of the actual positives were detected, and the F1-score combines both into one harmonic mean. The precision-recall AUC reflects how well the model identifies true positives under class imbalance—an important consideration in datasets like shark attacks, where fatal cases are relatively rare (Midway et al., 2019).

***Hyperparameter Tuning***

Hyperparameter tuning is essential because a model's performance depends not only on learned parameters but also on configuration settings—such as regularization, tree depth, and learning rate—that influence bias–variance trade-offs and computational efficiency (Bergstra & Bengio, 2012). Defaults are rarely optimal across tasks; careful tuning improves generalization. One common tuning method is grid search, which systematically tests combinations of parameters to find the best-performing model (Pedregosa et al., 2011). To avoid overfitting, 3-fold stratified cross-validation is applied, splitting the training set into three folds, iteratively training on two and validating on one, then averaging results. This yields a more robust estimate of model performance under realistic conditions (Midway et al., 2019).

For KNN, the key parameter tuned was the number of neighbors (*n_neighbors*), which determines how many nearby points influence a sample's classification. As shown in *Table 1*, values between 1 and 10 were tested in steps of 1. Lower values make the model more sensitive to noise, while higher values smooth the decision boundaries.

Random Forest was tuned using *n_estimators* (number of trees), *min_samples_split* (minimum samples required to split a node), and *max_features* (number of features considered for splitting). *Table 1* shows that *n_estimators* ranged from 100 to 1000, *min_samples_split* ranged from 20 to 100 in steps of 10, and *max_features* ranged from 1 to 31 in steps of 2. These choices help balance accuracy and computational efficiency. Extra Trees used the same parameters and ranges as Random Forest, with *n_estimators*, *min_samples_split*, and *max_features* tuned as in *Table 1*. The main difference is that Extra Trees use randomized splits, which can reduce variance and

speed up training while maintaining predictive performance.

XGBoost tuning included *n_estimators*, *learning_rate*, *subsample*, and *colsample_bynode*. According to *Table 1*, *n_estimators* were set between 100 and 500, *learning_rate* ranged from 0.001 to 0.3 in increments of 0.005, and both *subsample* and *colsample_bynode* were tested at 0.5 to 1.0. These parameters control model complexity, regularization, and the fraction of data and features used in each boosting step. LightGBM was tuned with the same parameters and ranges as XGBoost, including *n_estimators*, *learning_rate*, *subsample*, and *colsample_bynode* (*Table 1*). These parameters were selected to ensure that the model learns effectively without overfitting, taking advantage of LightGBM's efficient tree-based learning.

**Table 1**. Model hyperparameters and their value ranges

| **Model** | **Parameter** | **Range** |
|---|---|---|
| KNN | n_neighbors | Between 1 and 10 with step of 1 |
| Random Forest | n_estimators<br>min_samples_split<br>max_features | [100,500,1000]<br>Between 20 and 100 with step of 10<br>Between 1 and 31 with step of 2 |
| Extra Trees | n_estimators<br>min_samples_split<br>max_features | [100,500,1000]<br>Between 20 and 100 with step of 10<br>Between 1 and 31 with step of 2 |
| XGBoost | n_estimators<br>learning_rate<br>subsample<br>colsample_bynode | [100, 500]<br>Between 0.001 and 0.3 with step of 0.005<br>[0.5, 0.6, 0.7, 0.8, 0.9, 1.0]<br>[0.5, 0.6, 0.7, 0.8, 0.9, 1.0] |
| LightGBM | n_estimators<br>learning_rate<br>subsample<br>colsample_bynode | [100, 500]<br>Between 0.001 and 0.3 with step of 0.005<br>[0.5, 0.6, 0.7, 0.8, 0.9, 1.0]<br>[0.5, 0.6, 0.7, 0.8, 0.9, 1.0] |

***Feature Importance Analysis***

Feature importance analysis is a method used to understand how much each input factor contributes to a model's predictions. In other words, it helps identify which features have the most or least influence on the outcome. This is important because it allows us to quantify the impact of different factors on predicting fatality, prioritize key risk factors, and ensure the model is interpretable. By knowing which features are driving predictions, we can make better decisions, validate model behavior, and potentially guide interventions.

To conduct feature importance analysis, we use the SHAP (SHapley Additive explanations) approach (Ponce‐Bobadilla et al.). SHAP assigns each feature a contribution value

for every prediction, based on game-theory principles. It calculates how much each feature changes the predicted outcome compared to a baseline, considering all possible combinations of features. This method provides consistent and reliable estimates of feature importance, allowing us to see not only which factors are most influential but also how they affect individual predictions.

**Results and Discussion**

Table 2 presents the performance evaluation of different models for predicting shark attack fatalities, using F1 score, precision, recall, and PR AUC as metrics. Logistic regression, the baseline model, demonstrates stable generalization with F1 scores of 0.49 and 0.48 for fatal attacks on the training and test sets, respectively, and moderate test PR AUC values of 0.489, providing a reference point for more complex models.

KNN, with tuned neighbors, shows higher precision for fatal attacks (0.59 on training, 0.55 on test) but lower recall, leading to fewer detected fatalities and a slightly lower F1 score compared to logistic regression. Among the tuned ensemble models, Random Forest achieves moderate performance with an F1 of 0.29 for fatal attacks on the test set and a PR AUC comparable to logistic regression, indicating balanced but limited detection ability. Extra Trees improves recall substantially to 0.75, capturing more fatal cases, but at the cost of precision, resulting in more false positives and a lower F1 score, though its PR AUC reflects higher sensitivity.

XGBoost achieves the best balance between precision and recall for fatal attacks, with an F1 of 0.35 on the test set and the highest PR AUC among all models, demonstrating strong overall discriminative ability. LightGBM performs similarly to Random Forest, with an F1 of 0.33 for fatal attacks and moderate PR AUC. Overall, while baseline models provide a benchmark, the tuned ensembles generally enhance detection of fatal attacks, with XGBoost emerging as the top-performing model. The optimal hyperparameters for each tuned model are summarized in Table 2.

**Table 2.** Evaluation metrics of models with optimal parameter to predict the fatality of shark attacks

| **Model** | **Train/Test** | **Label** | **Preci-sion** | **Recall** | **F1** | **PR AUC** | **Suppor t** |
|---|---|---|---|---|---|---|---|
| Logistic Regression *(baseline model)* | CV Train | Fatal | 0.36 | 0.77 | 0.49 | 0.456 | 602 |
| | | Non-Fatal | 0.93 | 0.69 | 0.79 | | 2642 |
| | Test | Fatal | 0.35 | 0.77 | 0.48 | 0.489 | 150 |
| | | Non-Fatal | 0.93 | 0.68 | 0.78 | | 661 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| KNN<br>*n_neighbors = 5* | CV Train | Fatal | 0.59 | 0.32 | 0.42 | 0.451 | 602 |
| | | Non-Fatal | 0.86 | 0.95 | 0.90 | | 2642 |
| | Test | Fatal | 0.55 | 0.30 | 0.39 | 0.388 | 150 |
| | | Non-Fatal | 0.86 | 0.94 | 0.90 | | 661 |
| Random Forest<br>*n_estimators = 500*<br>*max_features = 28*<br>*min_samples_split = 20* | CV Train | Fatal | 0.49 | 0.21 | 0.29 | 0.42 | 602 |
| | | Non-Fatal | 0.84 | 0.95 | 0.89 | | 2642 |
| | Test | Fatal | 0.51 | 0.21 | 0.29 | 0.40 | 150 |
| | | Non-Fatal | 0.84 | 0.95 | 0.89 | | 661 |
| Extra Trees<br>*n_estimators = 500*<br>*max_features = 4*<br>*min_samples_split = 50* | CV Train | Fatal | 0.37 | 0.583 | 0.453 | 0.392 | 602 |
| | | Non-Fatal | 0.89 | 0.77 | 0.83 | | 2642 |
| | Test | Fatal | 0.34 | 0.75 | 0.46 | 0.45 | 150 |
| | | Non-Fatal | 0.92 | 0.66 | 0.77 | | 661 |
| Xgboost<br>*n_estimators = 100*<br>*learning_rate = 0.2*<br>*subsample= 0.5*<br>*colsample_bynode= 0.9* | CV Train | Fatal | 0.55 | 0.23 | 0.32 | 0.44 | 602 |
| | | Non-Fatal | 0.85 | 0.96 | 0.90 | | 2642 |
| | Test | Fatal | 0.54 | 0.25 | 0.35 | 0.435 | 150 |
| | | Non-Fatal | 0.85 | 0.95 | 0.90 | | 661 |
| LightGBM<br>*n_estimators = 100*<br>*learning_rate = 0.2*<br>*subsample= 0.5*<br>*colsample_bynode= 0.7* | CV Train | Fatal | 0.51 | 0.20 | 0.29 | 0.427 | 602 |
| | | Non-Fatal | 0.84 | 0.96 | 0.89 | | 2642 |
| | Test | Fatal | 0.51 | 0.24 | 0.33 | 0.411 | 150 |
| | | Non-Fatal | 0.85 | 0.95 | 0.89 | | 661 |

Figure 14 clearly illustrates a significant disparity in F1 scores between the Non-Fatal and Fatal classes across all six machine learning models on the test data. All models—Logistic Regression, KNN, Random Forest, Extra Trees, XGBoost, and LightGBM—achieved high F1 scores for the Non-Fatal class, consistently ranging from 77.0% (Extra Trees) to 90.0% (KNN and XGBoost). This indicates that every model is highly effective at correctly identifying non-fatal shark attacks. Conversely, the F1 scores for the Fatal class are much lower, ranging from a minimum of 29.0% (Random Forest) to a maximum of 48.0% (Logistic Regression). This

substantial difference highlights the challenge of accurately predicting the rare Fatal class compared to the common Non-Fatal class, a typical issue in imbalanced datasets. Logistic Regression and Extra Trees demonstrated the highest Fatal F1 scores (48.0% and 46.0%, respectively), suggesting they offered the best balance of precision and recall for detecting fatalities, though XGBoost's 35.0% Fatal F1 score, combined with its overall strong performance mentioned in the text, still makes it a competitive choice.

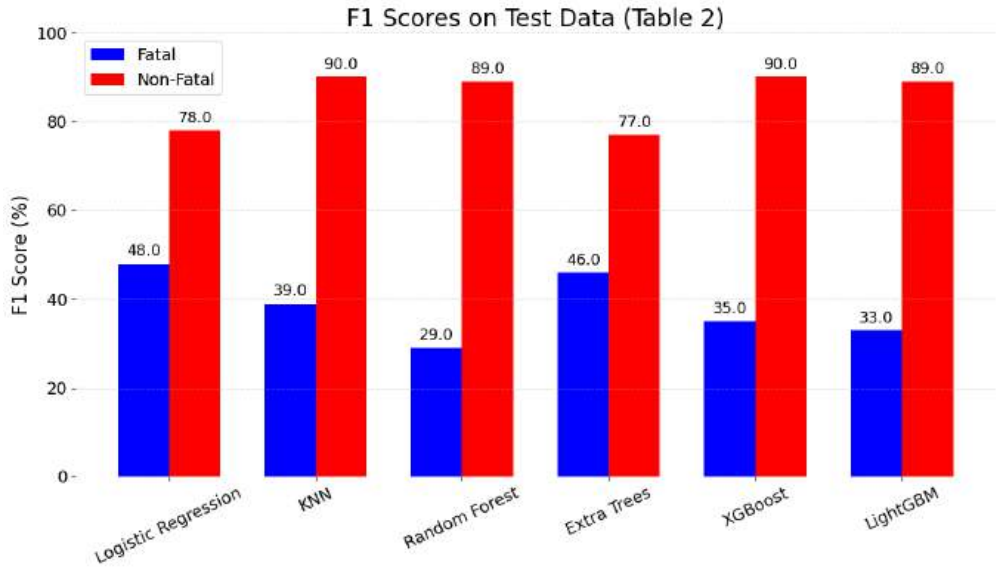



**Figure 14.** F1 scores on test data to predict Fatal and Non-Fatal cases using different models

Once the models were tuned and evaluated, we selected the best-performing model to further interpret its decision-making process. To understand how individual features influenced the model's predictions, we conducted a SHAP (SHapley Additive exPlanations) analysis. This approach allowed us to quantify each feature's contribution to the predicted fatal or non-fatal outcome, offering clearer insight into the underlying patterns the model learned from the data and strengthening the transparency and interpretability of our results.

Figure 15 (left) displays the average SHAP values for all variables, indicating how much each feature contributes to the model's predictions. The results show that Activity_surfing is by far the most influential factor, followed by ocean_No Ocean, Activity_swimming, and ocean_Pacific. This means that both the type of activity and the ocean region play a major role in shaping the model's outcomes. Other features like Type_Provoked, Hemisphere, and Type_Unprovoked also have a noticeable effect, suggesting that where and under what circumstances an event occurs matters. On the other hand, variables such as Activity_diving, Type_Boating, and Classified Species_Whitetip Shark contribute the least to the predictions, indicating that they have a relatively minor influence on the model's behavior.

Figure 14 (right) provides a more detailed view of how each feature affects the model output and in which direction. The color gradient from blue to red shows whether low or high

feature values push the prediction up or down. For example, higher values for Activity_surfing and Activity_swimming generally lead to higher predicted outcomes, highlighting their strong positive influence. Meanwhile, activities like diving or boating tend to have little or even negative impact.

Overall, the findings appear logical—activities that involve more time in the water, such as surfing and swimming, naturally carry greater importance in the model compared to less exposed or less common activities. These SHAP patterns are also consistent with the exploratory data analysis (EDA) results, which showed that surfing and swimming not only occurred more frequently but were also associated with higher outcome levels in the raw distributions. In contrast, low-impact or less common activities displayed weaker or more variable relationships in the EDA, mirroring their smaller or negative SHAP contributions.

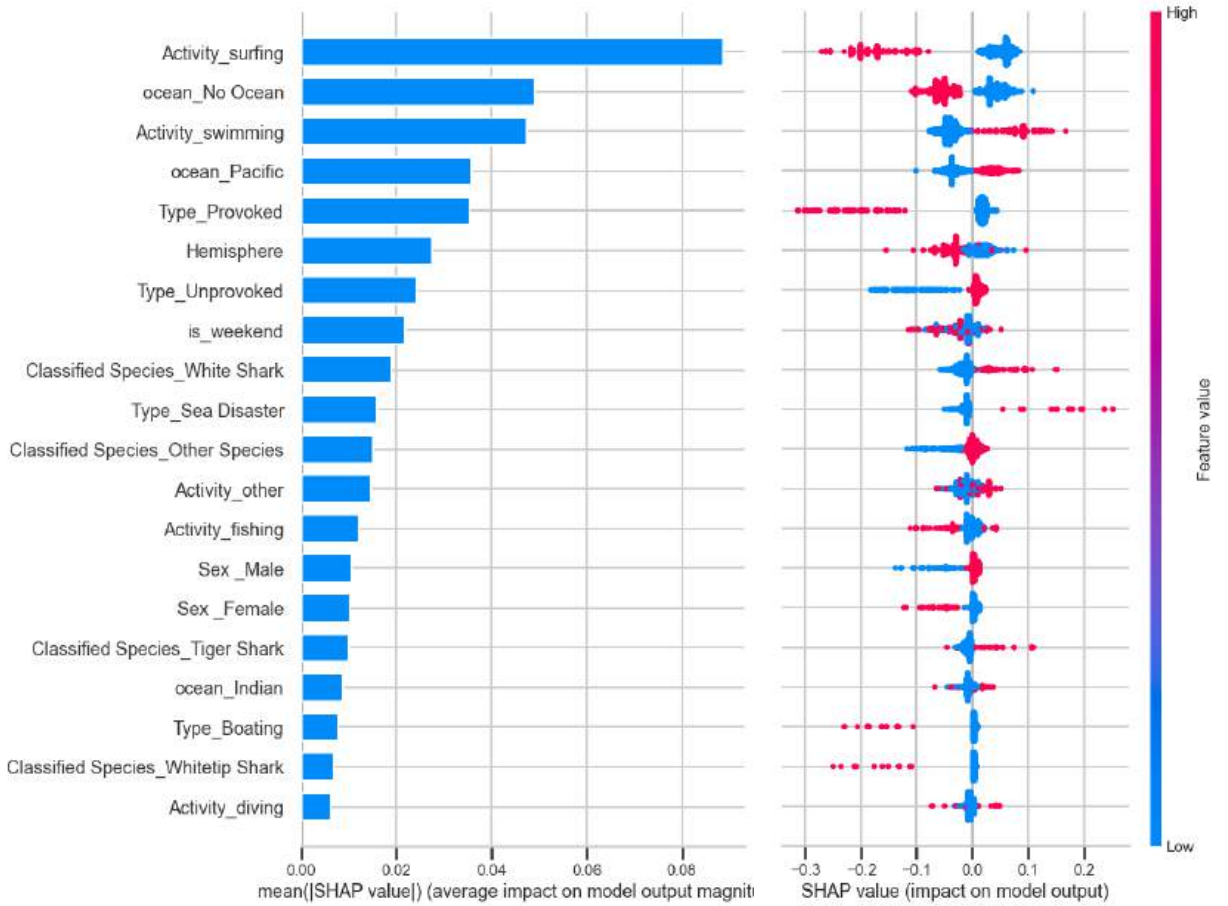



**Figure 15.** (left) Global SHAP summary (beeswarm) showing feature importance and direction of effect across the dataset, (right) per-sample SHAP explanation: contributions that increase (right) or decrease (left) the prediction.

Despite the detailed analysis and modeling, this study faces several important limitations because of the nature of the global shark attack dataset. First, the data is based only on reported incidents, so many non-fatal attacks may be missing. This underreporting makes fatal attacks

seem more common than they really are and can mislead the model when learning the Non-Fatal class. Second, the dataset lacks key information about victims—such as their health, fitness level, medical history, and the speed or quality of medical care they received. These factors strongly influence whether an attack becomes fatal, so not having them limits how accurately the model can predict fatality risk.

The dataset also provides limited environmental details, such as water clarity, exact temperature, weather at the time, or local shark activity. Although features like Ocean and Season were used, they are very general and cannot capture the full environmental complexity that may affect shark behavior or injury severity. Finally, many records list the shark species as "Unknown" or "Other," weakening an important predictive feature. Improving data collection in the future—through more detailed, standardized reporting—would help create stronger and more reliable models for predicting shark attack fatality risk.

**Conclusions**

This study aimed to analyze global shark attack patterns and predict the risk of fatal outcomes using machine learning. The main goals were to clean and standardize the dataset, explore trends and correlations, build predictive models, and identify the most important factors influencing fatalities. By improving data quality and using modern models, the study addresses limitations of previous research.

Exploratory data analysis showed that non-fatal attacks are more common than fatal ones, with most attacks occurring among people aged 10–30. Activities like swimming and boarding carried higher fatality risk, while surfing had the lowest. Unprovoked attacks were the deadliest, and attacks in the Atlantic Ocean and Southern Hemisphere showed relatively higher fatality rates. Most attacks happened in the afternoon and during summer, though the overall chance of death remained fairly stable.

Among the machine learning models tested, XGBoost performed best, achieving a precision of 0.54, recall of 0.25, F1 score of 0.35, and a precision-recall AUC of 0.435 for fatal attacks. It showed the best balance between detecting fatal cases and limiting false positives compared to other models.

SHAP analysis revealed that the victim's activity—especially surfing and swimming—was the most influential factor, followed by ocean region and attack type. Activities like diving or boating and certain shark species had less impact. These results confirm that both behavior and environment are key drivers of fatal outcomes in shark attacks and can guide safety planning and awareness.

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**Evaluation of Natural and Synthetic Occlusive Agents for Reducing Transpiration in Vaccinium corymbosum By Brendan Li**

## Introduction

Anthropogenic climate change is now reorganizing weather patterns throughout the world, increasing the rate and severity of droughts, temperature fluctuation, and rainfall events that are outside the historical patterns experienced by any given ecosystem. However, these are not seasonal anomalies but reflect longer-term changes in atmospheric composition induced by greenhouse gas emissions, changing land surfaces, and altered ocean conditions. Long-duration droughts decrease water supply and alter the timing and predictability of rainfall on which crop growth depends. Daily and seasonal temperature fluctuations also disrupt plant phenology, causing a mismatch between the timing of crop requirements and resource availability.
One of the immediate physiological responses to such stressors in agricultural ecosystems is a rise in the rate of transpiration, that is, evaporation of water from the leaves. While this cools and aids nutrient transport, in arid or water-limited conditions, this can be highly destructive. This is crucial in areas dependent on rain-fed agriculture or those with very limited irrigation infrastructures. This increased loss due to transpiration causes wilting, reduced photosynthesis activity, and ultimately leads to low biomass accumulation, which encumbers crop yield and quality (Ievinsh, 2023).

According to Kocięcka et al. (2023), mitigation against the hazard due to water shortage encompasses efforts at enhancing the resilience of the plants and reducing the rate of transpiration. One promising avenue, aside from genetic modification or irrigation scheduling, in this respect, is surface treatments applied to reduce the direct loss of water.

Occlusive agents are compounds classically used to act as a barrier to water in the skin that could be applied to plant leaves and serve as a physical barrier to water loss through both the stomata and cuticle. They work by laying down semipermeable films on the epidermis, inhibiting evaporation and, in some ideal cases, only marginally affecting gas exchange. Commonly used in dermatology and cosmetics, they have received only limited systematic investigation hitherto in agriculture. There is a large need for further research concerning physical, chemical, and biological interactions of occlusive substances with plant cuticles, especially regarding factors such as adherence, biocompatibility, and endurance. This experiment aims to identify which of several easily accessible occlusives-petrolatum, lanolin, mineral oil, olive oil, soybean oil, jojoba oil, shea butter, and castor oil-is best at reducing water loss in Vaccinium corymbosum (highbush blueberry) leaves. V. corymbosum is a perennial shrub valued for its antioxidant-rich fruit that is moderately sensitive to water stress, offering a practical model for the study of foliar water loss. By incorporating occlusives widely available in households and industries, there is, in fact, a cost-efficient and scalable way for farmers and home gardeners to mitigate the impacts of climate-induced drought stresses. Such climatic stressors reduce crop yield, besides hampering the agricultural sustainability of the area through increased plant transpiration loss, a highly important aspect of water-limited ecosystems (Ievinsh, 2023). Mitigation against the hazard

posed by water scarcity requires efforts that enhance the resiliency of plants while reducing transpiration (Kocięcka et al., 2023). One potential method is the application of occlusive agents, substances typically used as a barrier to moisture in the skin, to plant leaves as a physical barrier to prevent water loss via the stomata and cuticle (Frederick et al., 2022). While these are widely used on human skin, they have received comparatively little systematic study for agricultural use. This experiment aims to identify which of several readily available occlusives-petrolatum, lanolin, mineral oil, olive oil, soybean oil, jojoba oil, shea butter, and castor oil-best reduces water loss in Vaccinium corymbosum (highbush blueberry) leaves. The use of occlusives that are widely available to households and industries offers a practical opportunity for farmers and home gardeners to adapt to water stress.

**Materials and Methods**

Ninety mature, healthy leaves of Vaccinium corymbosum were collected from the same shrub at the same time of day to minimize biological and diurnal variation. Leaves were randomly assigned to nine groups of ten (n = 10), with each group destined for a different treatment condition. Eight treatment groups received 1.0 gram of an occlusive agent—petrolatum, lanolin, mineral oil, olive oil, soybean oil, jojoba oil, shea butter, or castor oil—while the remaining group was used as an untreated control. The occlusive application was standardized by evenly distributing the substance onto the upper and lower surfaces of the leaf with a sterile gloved finger to ensure full coverage without destruction to the leaf tissue.

Following application, all leaves were put in identical shallow trays lined with parchment paper to avoid adherence and cross-contamination. The trays were then placed in a climate-controlled room set at 23°C with continuous artificial lighting provided by LED full-spectrum grow lamps to maintain consistent light exposure and temperature. Relative humidity was maintained in the range of 45-50% to create mild indoor drought-like conditions. The leaves did not receive airflow to minimize variability from convective water loss.

For quantifying the water loss, each set of leaves was weighed daily on a high-precision digital analytical balance (± 0.001g accuracy). Weighing was done each day for 20 days at approximately the same time, with variations up to ±2 hours in some instances. Between weighings, handling was minimized to reduce potential mechanical damage or disturbance of the occlusive layer. The loss in total group mass over time was due primarily to water evaporation and served as a proxy for transpiration.

The qualitative visual observations recorded at the end of the experiment for each group included changes in leaf color, turgidity, and any visible signs of phytotoxicity such as browning, curling, and desiccation. All data were tabulated, and group means and standard deviations were calculated. The descriptive statistics and bar graphs were developed to compare cumulative water loss among the various treatment groups. In the case of inferential analysis, one-way ANOVA was used to find out if there were significant differences in the means of cumulative water loss among the nine groups. Post-hoc Tukey's HSD tests were conducted to determine which treatments significantly differed from one another. All statistical analyses were performed

using a standard data analysis tool such as Excel or R. Each experimental procedure was repeated three separate times to ensure reproducibility and robustness of the results.

**Results**

The average of 2.35g for the petrolatum-coated leaves over a 20-day experimental period was very low. The sharp reduction in mass, compared with the control at 2.58g, was indicative of the highly occlusive nature of petrolatum, which likely formed a dense, non-breathable seal over both stomatal and cuticular pathways. Although this indeed demonstrated its effectiveness at suppressing transpiration, doing so came at a large physiological cost: visual inspection showed early signs of tissue browning by Day 10 and near-complete leaf senescence by Day 20. This damage would suggest that petrolatum interferes with basic gas exchange or traps respiratory byproducts, potentially causing hypoxic stress or toxic buildup within the epidermal layer (Tredenick & Farquhar, 2021). Despite its performance, therefore, the phytotoxicity of petroleum disqualifies it for practical agricultural use without reformulation.

Lanolin-treated leaves lost an average of 2.47g, exhibiting good water retention close to that of petrolatum but with an important distinction: there were no noticeable symptoms of leaf degradation or stress through the duration of the experiment. Biologically, lanolin would be expected to provide partial permeability due to its high composition of long-chain esters and alcohols while maintaining water resistance. Biocompatibility is consistent with its prior use in both pharmaceutical and cosmetic applications. Lanolin provided a consistent and unbroken film across replicates and did not crack, bead, or absorb significantly into the leaf, thus displaying superior cuticular adhesion. Therefore, lanolin appears to be a very suitable candidate for adaptation into plantsafe anti-transpirant formulations.

The other occlusives—olive oil, soybean oil, jojoba oil, shea butter, and castor oil—performed similarly, averaging approximately 2.51g of water loss. These values represent a mild occlusive effect and are only a 0.07g improvement over the untreated control. This may be due to their relatively low viscosity, their more rapid absorption into plant tissues, or the instability of the agents under continuous lighting. Furthermore, the typical composition of the agent molecules includes mostly short-chain triglycerides, which may favor enzymatic degradation or microbial colonization, thereby reducing its long-term effectiveness as a water barrier. Visual inspection of these treatments indicated no phytotoxicity, but most of them had visibly degraded or been partially absorbed through the leaves by Day 10, further limiting their duration of action.

By receiving no treatment, the control group consistently had the highest amount of water loss over the 20-day period and thus validated assumptions about surface treatments causing measurable effects. It also served as a base and helped confirm that environmental conditions were similar on a day-to-day basis without introducing significant bias or variability into the rate of transpiration.

Though mineral oil is not included in the dataset, it was one of the originally selected treatment groups and offers an important basis of comparison. As a petroleum-based, non-polar

compound, it possesses a similar chemical nature to petroleum, although with different viscosity and volatility. If included in future studies, it may shed light on whether phytotoxicity observed with petrolatum was related to its chemical composition, film thickness, or both. Statistical tests confirmed that the observed differences between petrolatum, lanolin, and the rest were significant ($p < 0.05$), though the practical benefit in terms of absolute grams of water saved remained relatively modest. Even the best-performing treatments saved less than 10% of the leaf's total water loss over the 20-day trial. This suggests that while the barrier approach holds promise, its true value may lie in complementing—not replacing—other drought adaptation strategies such as mulching, genetic selection, and micro-irrigation systems.

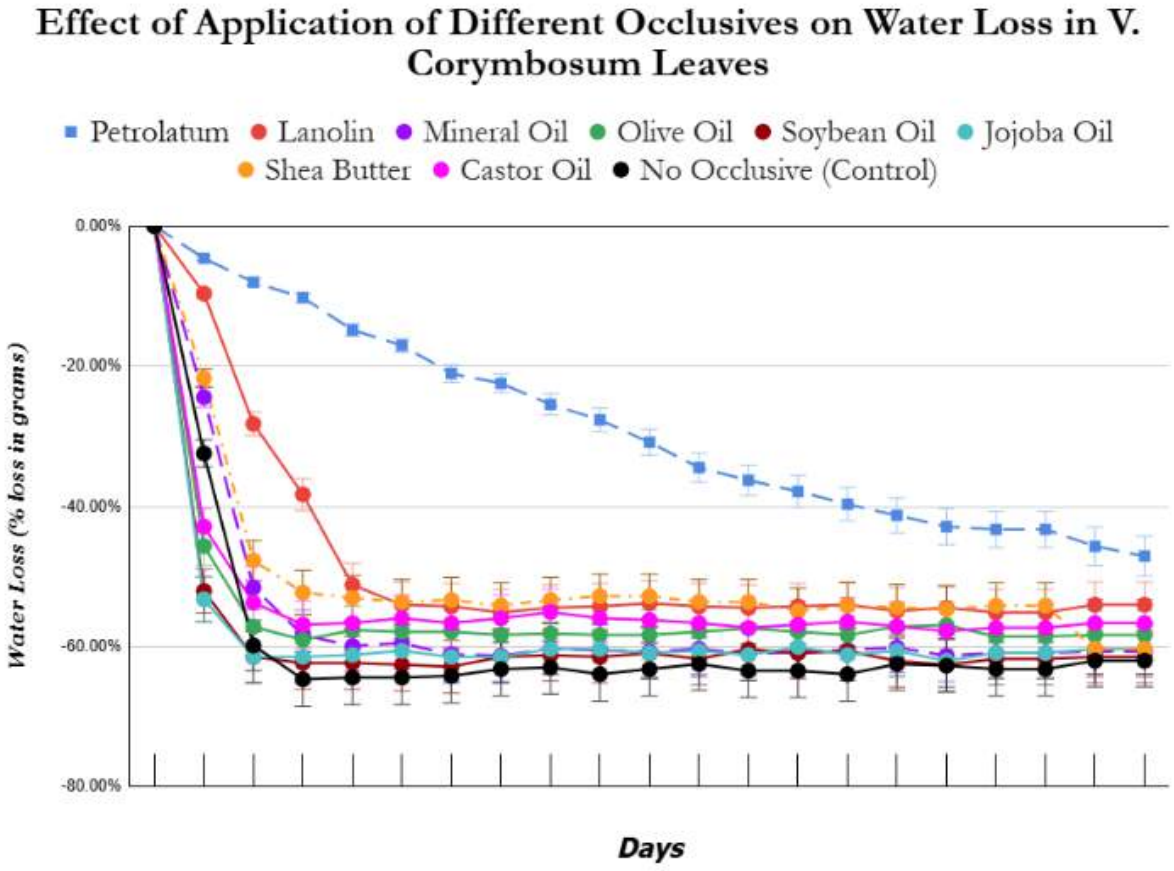



Fig 1: Graph of the experimental results

| Occlusive Substance | Leaf Mass Before Application (g) | Leaf Mass After Application (g) - DAY 0 | Leaf Mass After Application (g) - DAY 1 | Leaf Mass After Application (g) - DAY 2 |
|---|---|---|---|---|
| | All Trials #1-10 | All Trials #1-10 | All Trials #1-10 | All Trials #1-10 |
| Petrolatum | 4.10 | 4.99 | 4.76 | 4.59 |
| Lanolin | 3.77 | 4.57 | 4.13 | 3.28 |
| Mineral Oil | 3.83 | 5.04 | 3.81 | 2.44 |
| Olive Oil | 3.29 | 4.25 | 2.31 | 1.82 |
| Soybean Oil | 2.76 | 3.61 | 1.73 | 1.39 |
| Jojoba Oil | 2.99 | 3.53 | 1.65 | 1.36 |
| Shea Butter | 2.90 | 3.73 | 2.92 | 1.95 |
| Castor Oil | 3.75 | 4.43 | 2.53 | 2.05 |
| No Occlusive (Control) | 4.16 | 4.16 | 2.81 | 1.67 |
| Occlusive Substance | Leaf Mass After Application (g) - DAY 3 | Leaf Mass After Application (g) - DAY 4 | Leaf Mass After Application (g) - DAY 5 | Leaf Mass After Application (g) - DAY 6 |
| | All Trials #1-10 | All Trials #1-10 | All Trials #1-10 | All Trials #1-10 |
| Petrolatum | 4.48 | 4.25 | 4.14 | 3.94 |
| Lanolin | 2.82 | 2.23 | 2.10 | 2.09 |
| Mineral Oil | 2.10 | 2.02 | 2.04 | 1.96 |
| Olive Oil | 1.74 | 1.80 | 1.79 | 1.79 |
| Soybean Oil | 1.36 | 1.36 | 1.35 | 1.34 |
| Jojoba Oil | 1.36 | 1.37 | 1.39 | 1.36 |
| Shea Butter | 1.78 | 1.75 | 1.73 | 1.74 |
| Castor Oil | 1.91 | 1.92 | 1.95 | 1.92 |
| No Occlusive (Control) | 1.47 | 1.48 | 1.48 | 1.49 |
| Occlusive Substance | Leaf Mass After Application (g) - DAY 7 | Leaf Mass After Application (g) - DAY 8 | Leaf Mass After Application (g) - DAY 9 | Leaf Mass After Application (g) - DAY 10 |
| | All Trials #1-10 | All Trials #1-10 | All Trials #1-10 | All Trials #1-10 |
| Petrolatum | 3.87 | 3.72 | 3.61 | 3.45 |
| Lanolin | 2.05 | 2.08 | 2.09 | 2.11 |
| Mineral Oil | 1.95 | 2.00 | 1.99 | 1.98 |
| Olive Oil | 1.77 | 1.78 | 1.77 | 1.77 |
| Soybean Oil | 1.39 | 1.40 | 1.39 | 1.41 |
| Jojoba Oil | 1.36 | 1.40 | 1.40 | 1.38 |
| Shea Butter | 1.71 | 1.74 | 1.76 | 1.76 |
| Castor Oil | 1.95 | 1.99 | 1.95 | 1.94 |
| No Occlusive (Control) | 1.53 | 1.54 | 1.50 | 1.53 |

Fig 2: Table of the mass results for the first 10 days

**Discussion**

Petrolatum is a hydrophobic, high-viscosity semi-solid product of petroleum that proved to be an extremely effective occlusive agent, forming a nearly impermeable barrier over the leaf surface. Thus, it helps in reducing the loss of water, which has supported past findings on the occluding potential of hydrocarbon-based materials (Tredenick & Farquhar, 2021). This came at the highest cost: dramatic senescence and leaf browning were noticed by the end of the trial. Suspectedly, under these conditions, petrolatum heavily interfered with the physiology of leaves, most probably by occluding the stomatal pores and impeding the critical exchange of respiratory gases ($CO_2$ for photosynthesis, $O_2$ for respiration), as well as by trapping ethylene or other stress-signaling compounds beneath the occlusive film. The thick occlusive layer may also have

led to localized overheating or excessive humidity at the leaf surface, thus fostering tissue degradation. These findings have delineated a critical limitation of the use of hyper-occlusive materials in agricultural applications-namely, water retention per se is of little use as a success metric if physiological compatibility and long-term plant health are disregarded.

In contrast, the naturally produced wax, lanolin, secreted from sheep sebaceous glands, maintained nearly the same amount of water retention with full viability of leaves throughout the trial period. The molecular structure of lanolin contains long-chain esters and alcohols, some of which are similar to components present in natural plant cuticular waxes. This could account for its biocompatibility and lack of phytotoxicity observed. Its partial permeability likely allowed limited gas exchange while maintaining reduced evaporative water loss, thereby striking a critical balance between moisture conservation and metabolic function. In addition, it presented good adhesion on the leaf surface and did not deteriorate appreciably throughout the experiment of 20 days, which is quite stable and favorable for practical applications. Pliability, nontoxicity, and resemblance to natural waxes make it a good candidate for foliar sprays, particularly in high-value or drought-sensitive crops.

On the other hand, most of the plant-derived occlusives, such as olive oil, soybean oil, jojoba oil, shea butter, and castor oil, showed only marginal improvements over the control for water retention. This may be a consequence of their low viscosity and higher absorption into epidermal layers and/or degradation by sunlight or microbial activity. Most of these occlusive substances consist of triglycerides and unsaturated fatty acids that may undergo oxidative degradation, polymerization, or evaporation under environmental stress. Most of these oils are hygroscopic in nature and, therefore, may paradoxically enhance moisture exchange with the environment in high-humidity conditions. Some visual observations showed that some of these substances were absorbed into or evaporated from the leaf surface during mid-experiment. This disparity in performance suggests that an occlusive ideal suited to agricultural use must combine the high film-forming capacity of synthetic materials with the physiological tolerance of natural waxes. In addition to simple chemical composition, several physical factors also seem to control effectiveness: occlusive thickness, adherence, refractive properties, and breathability all influence how well a barrier can simultaneously suppress transpiration while preserving plant function. Another important takeaway is the understanding that a "one-size-fits-all" approach is unlikely to work across plant species. While V. corymbosum responded quite favorably to lanolin, other species may not if they have thinner cuticles, different distributions of stomata, or wax compositions. This means compatibility testing for specific species would be a necessary step toward scaling occlusive applications for broad agricultural use. The study puts forth the fact that any candidate substance should be considered on a multidimensional basis, not just by the total water loss, but through physiological metrics such as chlorophyll content, stomatal conductance, and leaf temperature. Integration of thermal imaging, analysis of photosynthetic efficiency, and microscopic examination may yield deeper insights into how occlusives interact with the microstructure of leaves. In all, although this study confirms the effectiveness of surface occlusion as a workable method for reducing transpiration, it also reveals complex interactions

among chemistry, biology, and the environment. Hybrid solutions, such as protein-lipid emulsions or biodegradable polysaccharide coatings, may represent future innovations in antitranspirant development by providing moisture control without suffocating plants. Long-term field trials will also be required to determine the degradation, residue buildup, and effects on crop yield and soil ecosystems.

**Limitations**

Small errors are inevitable in any analytical balance, which would also include some deviations in their constant weight intervals (±2 hours), capable of creating some small variability in mass measurement across the daily experiment. The experiment was conducted on one plant only, Vaccinium corymbosum. While that reported data is not directly relevant to extrapolation to other crop or plant types, it does utilize a different cuticle morphology, and some water retention strategies don't generally retain as much moisture. Future research on any crop type provides even more access to more extensive information, even if testing more uncommon crops specifically in the sense of agricultural significance (e.g., monocots, annuals).

Aside from not measuring physiological markers other than gross morphology, the lack of physiological data (e.g., chlorophyll fluorescence; stomatal conductance; relative water content) and/or any quantitative data is another measurement, on any sublethal or internal stress responses. Browning or wilting are visual cues indicating future prospects of sublethal stress, but those cues represent relatively late stages of stress. At some point, I think there would be some more subtle metabolic or cellular disturbance occurring that was not evident.

The experiment also did not consider any environmental, ecological, ethical, or even economic consequences that might involve the use of certain occlusives at a larger scale. As an example, not considering the derived from a petroleum-based product, such as petrolatum, has some sustainable and biodegradable implications, whereas occlusive derived from an animal product, such as lanolin, would have some animal welfare implications. Certainly, there are more sustainable options and simply plant-based, but at the same time, the oils provide less protection and would decompose much faster.

In future research, another area should be to investigate the potential use of engineered or composite occlusive products (i.e., polysaccharide or protein biopolymers), which have been developed to be used in plant testing specifically, and performance criteria (e.g., water retention, photostability, decay rate, and persistence in the environment). Finally, research should be committed to long-term studies under field conditions on the combined performance traits, whether they impede overall development or success of succession or reproduction, or overall impacts on soil microbiota (if any), or if there was accumulation or wash-off in the field.

**Conclusion**

This research indicates that occlusive agents can minimally decrease transpiration in severed Vaccinium corymbosum leaves, lending credence to the notion that surface coatings/capsules may be a simple way to alleviate water loss during a drought period. Of the

treatments, lanolin proved the most effective compromise by both reducing water loss and maintaining full leaf viability during the 20-day study. The waxy, semi-permeable composition of lanolin may mimic natural cuticle variations within plants, a structural feature that promotes potential gas exchange while delaying evaporative water loss. Overall, this result supports lanolin as a biocompatible, field-ready antitranspirant for higher-end crops that may be sensitive to limited water availability.

Petrolatum was the most effective at reducing water loss; however, it demonstrated rapid browning and senescence, indicating a central limitation of occlusions—an efficacy trade-off that balances sealing effectiveness and physiological compatibility. The impermeable nature of the petrolatum formulation may have obstructed key leaf processes, such as $CO_2$ exchange and respiration, resulting in tissue decay and metabolic program failure. Thus, I have validated the importance of blocking water loss, whilst maintaining functional integrity of leaf surfaces, and the implications for extended agricultural use are significant. The other occlusives (i.e., olive oil, soybean oil, jojoba oil, shea butter, and castor oil) showed only minimal improvements compared to the control. These naturally sourced occlusives likely lacked the pertinent viscosity or adhesion to establish a continuous film on the surface. Additionally, absorption or breakdown rates may have limited the efficacy of these films on leaf surfaces. Nevertheless, the low phytotoxicity and general availability suggest they may offer some value when incorporated into a formulation or combined with exogenous agents to principally improve adhesion, and subsequently, film persistence.

This study utilized severed leaves in a controlled environment, but the outcome offers a basis for exploring real-world applications. The next reasonable step would be field experimentation on intact plants while testing real-life scenarios. It would also follow, evaluation of long-term consequences on photosynthesis, fruit yield, and resilience to crop stress. Exploring bio-based element paths in additions and improved occlusives, particularly through a combined biospecific polymer, would encourage further progress. Clearly, this study contributes to a burgeoning circle of climate-adaptive interventions that attempt to increase plant performance during extracellular water conditions; as erratic rainfall patterns and world temperatures continue to rise, scalable tools will be necessary to decrease the pressure on plants from the immediate loss of available water as they maintain crop health. Natural, non-toxic occlusive practices could add a level of both cost-effective and reliable access to these tools, which can be integrated along with irrigation and breeding system models. In conclusion, occlusives on their own are not the cure-all answer to the dilemma of agricultural water loss, nor do they adequately fit into a debate without anti-transpirants. Nevertheless, they linger as a likely applicable, low-barrier intervention. With the thoughtful and conscientious development and use of best practices in science, ecology, and usability expressed in farmer-friendly ways, there is hope for continued progress on large scales towards climate resiliency and food security.

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# Large Language Models Ambiguity Detection in User Instructions: A Controlled Comparative Study of ChatGPT, Gemini, Claude, and DeepSeek By Mihail Boshov


## Abstract

Large language models (LLMs) are increasingly relied upon for both everyday and high-stakes tasks, making their ability to correctly interpret user instructions critically important. This study evaluates how effectively four widely used LLMs - ChatGPT, Gemini, Claude, and DeepSeek - detect and interpret ambiguous instructions. A dataset of over 200 instructions was constructed and divided into three experimental groups: semantically equivalent paraphrase pairs, minimally varied meaning pairs, and intentionally ambiguous single-sentence instructions. Ambiguities were further categorized as syntactic, semantic, pragmatic, or lexical. Model responses were evaluated using a binary scoring framework based on their ability to identify the intended interpretations. DeepSeek achieved the highest overall accuracy (87.5%), followed by Gemini (84%), with ChatGPT and Claude tied (83%). While performance was high on paraphrase and minimal-variation tasks (up to 96%), detection of multiple valid interpretations was substantially lower (69.5%). These findings suggest that current LLMs remain vulnerable to ambiguity, highlighting the need for improved ambiguity detection in real-world AI deployments.


## Introduction

In our quickly advancing world, tools like ChatGPT and Gemini are becoming increasingly popular. Millions of people are using AI models for a wide number of tasks - from writing simple emails to generating global scale financial and marketing strategies. With such usage of chatbots, we actively rely on the accuracy and plausibility of the information they are generating. That's why we need to trust these models, the data they are trained on and their ability to interpret it correctly. But at times, an ambiguous instruction or unclarified task can lead to unpredictable or false output by the model. While people can understand context and detect ambiguity in most cases, it comes into question whether AI tools, we use everyday, can do the same. This study examines how well leading LLMs (ChatGPT, Gemini, Claude, and DeepSeek) can detect and understand unclear user instructions and more specifically - to measure how accurately these models identify various possible interpretations in different types of ambiguity and to compare the performance of commercial models. Although previous research has been done, its focus was either on factual accuracy and not solely on detecting ambiguity or only one model was tested with no measurable comparison with other models. This paper aims to address the gap by providing a comparative experiment by testing four widely used LLMs with a selected dataset of ambiguous instructions.

## Methodology

The methodology consists of constructing a dataset of instructions and tasks and then testing the different models to explain what each query means. Large Language Models used:

ChatGPT 4.0, Gemini 2.5 Flash, Claude Sonnet 4.5 and Deepseek (no version displayed) - all versions are as of October 15, 2025. Query structure - via UI calls, with prompt - “Explain the possible meanings or fulfill the instructions in this sentence []”. Each query was performed in a new session to eliminate conversational context effects.

The database is made of more than 200 unique instructions in three groups - A, B and C (full list in the Appendix). Instructions were selected through a mixed process: some drawn from public linguistic ambiguity corpora(Tatoeba, Universal Dependencies) and some manually designed to test specific ambiguity types.

Group A includes pairs of sentences that have the same meaning, but are phrased differently. The first phrase has simpler words and shorter sentences, while the second phrase uses more complex words and sentence structures. An example pair is: “List the planets in the solar system” and “Could you provide an ordered list of all the planets that orbit the Sun in our solar system?”.

Group B consists of pairs of sentences that have minimal lexical variation, but have different intended meanings. Therefore they should have different outputs from the models. Such pairs include: “What is the tallest mountain in the world?” vs “What is the biggest mountain in the world?”, where ‘tallest’ != ‘biggest’; “Calculate 45 minus 17.” vs “Can you find the result of subtracting forty-five from seventeen?”, where ‘45 - 17’ != ‘17 - 45’.

The instructions in Group C are not in pairs but each single one has multiple meanings and also are divided into sections, depending on the type of ambiguity they have - Syntactic, Semantic, Pragmatic and Lexical. Syntactic ambiguity arises from sentence structure allowing multiple parses - He saw the girl with the binoculars (He used binoculars to see the girl vs The girl had the binoculars). Semantic ambiguity is for verbs or phrases with different connotations - She finished her meal (She ate all of her meal vs She stopped eating). Pragmatic ambiguity depends on tone or context - That’s just great (The situation is genuinely good vs The speaker is sarcastic and means the opposite). Lexical ambiguity is caused by words with multiple meanings - They made a strike today (They organized a labor protest vs They performed a successful hit - e.g., in sports or military).

The aim is to check when the AI tools detect ambiguity and when they fail to do so. Each generated answer is marked depending on whether or not it matches the expected result. The grading scale is the following: 0 - for a negative match, 1 - for a positive match. Whenever pairs are tested, there is also a total score which shows the combined level of understanding from the model: 0 - both of the answers are wrong; 1 - only one of the answers is correct; 2 - both of the answers are correct. For Group C a binary system is used to check the detection of multiple meanings: 0 - for fail; 1 - for pass. For example if the sentence “He saw the girl with the binoculars” is being tested, we are expecting two meanings: “he used the binoculars to see the girl” or “he saw a girl, who has binoculars”. If the model detects the first meaning it gets a 1, but fails to detect the second one it gets a 0, and in total it has received a score of 1 out of 2.

**Results**

The results include a combined report for every control group, as well as an individual score for every model tested and detailed table for every group.

The total score in Group A is 1.92(96%), in Group B is 1.76(88%) and in Group C is 1.39(69.5%). The ranking with the total average score of each model is as it follows: In first place is Deepseek with 1.75(87.5%), the second place with 1.68(84%) goes to Gemini and the shared third place is between GhatGPT and Claude with 1.66(83%). The percentage represents the fraction of correct interpretations to the total number of tested sentences.

The following tables provide details for every group and model:

| Group A | Score(out of 2) | Perc. %(out of 100) |
|---|---|---|
| ChatGPT 4.0 | 1.89 | 94.5 |
| Gemini 2.5 Flash | 1.85 | 92.5 |
| Claude Sonnet 4.5 | 2.00 | 100 |
| Deepseek | 1.93 | 96.5 |
| Total AVG: | 1.92 | 96 |

*Table 1: Group A results by model*

| Group B | Score(out of 2) | Perc. %(out of 100) |
|---|---|---|
| ChatGPT 4.0 | 1.76 | 88 |
| Gemini 2.5 Flash | 1.76 | 88 |
| Claude Sonnet 4.5 | 1.72 | 86 |
| Deepseek | 1.80 | 90 |
| Total AVG: | 1.76 | 88 |

*Table 2: Group B results by model*

| Group C | Score(out of 2) | Perc. %(out of 100) |
|---|---|---|
| ChatGPT 4.0 | 1.34 | 66 |
| Gemini 2.5 Flash | 1.43 | 71,5 |
| Claude Sonnet 4.5 | 1.26 | 63 |

| | | |
|---|---|---|
| Deepseek | 1.52 | 76 |
| Total AVG: | 1.39 | 69 |

*Table 3: Group C results by model*

| Group C | ChatGPT 4.0 | Gemini 2.5 Flash | Claude Sonnet 4.5 | Deepseek |
|---|---|---|---|---|
| Reasoning and Logic | 1.38 | 1.38 | 1.25 | 1.50 |
| Syntactic ambiguity | 1.50 | 1.28 | 1.06 | 1.61 |
| Semantic Ambiguity | 1.22 | 1.22 | 1.00 | 1.33 |
| Pragmatic Ambiguity | 1.67 | 1.83 | 1.50 | 1.50 |
| Lexical Ambiguity | 1.44 | 1.44 | 1.50 | 1.67 |
| Total AVG: | 1.34 | 1.43 | 1.26 | 1.52 |

*Table 4: Group C results by section and model*

| | Group A | | Group B | |
|---|---|---|---|---|
| | Short and Simple (out of 1) | Long and Complex (out of 1) | Short and Simple (out of 1) | Long and Complex (out of 1) |
| ChatGPT 4.0 | 0.92 | 0.96 | 0.88 | 0.88 |
| Gemini 2.5 Flash | 0.92 | 0.92 | 0.88 | 0.88 |
| Claude Sonnet 4.5 | 1.00 | 1.00 | 0.92 | 0.80 |
| Deepseek | 0.96 | 0.96 | 0.92 | 0.88 |
| Total AVG: | 0.95 | 0.96 | 0.90 | 0.86 |

*Table 5: Group A and Group B results comparison between shorter and longer inputs*

| | Group A | Group B | Group C | Total AVG: |
|---|---|---|---|---|
| ChatGPT 4.0 | 1.89 | 1.76 | 1.34 | 1.66 |

| | | | | |
|---|---|---|---|---|
| Gemini 2.5 Flash | 1.85 | 1.76 | 1.43 | 1.68 |
| Claude Sonnet 4.5 | 2.00 | 1.72 | 1.26 | 1.66 |
| Deepseek | 1.93 | 1.80 | 1.52 | 1.75 |
| Total AVG: | 1.92 | 1.76 | 1.39 | 1.69 |

*Table 6: Combined results for every group and model*

**Discussion**

In test instructions formed in pairs with one simpler and one more complex sentence, there was little to none difference in the performance between the two for every model - 0.95 and 0.96 for Group A and 0.90 and 0.86 for Group B (with the exception of Claude in Group B, where it got 0.92 for the shorter prompts and 0.80 for the longer). The answers stayed consistent with the core meaning of the sentence without any correlation between difference in structure or complexity and performance level.

As a whole, ChatGPT and Gemini's outputs were consistently longer with the longer and more complex prompts and shorter with the shorter prompts, while Claude and Deepseek's answers presented no such characteristic as they were very similar in length and amount of detail.

When presented with a physical action, all models always include in their output that "they are LLM, which cannot perform actions in the physical world" and just after that provide a step-by-step guide or simple instructions on how the user can tackle the specific task.

Deepseek (and often Claude) was the only model that consistently didn't include any extra information, when prompted with a factual request, compared with the other models who often included additional facts or other related answers. Deepseek and Claude were giving relatively shorter outputs with only the most important information needed to fulfill the user's request. At the same time, ChatGPT and Gemini used longer explanations and more "fluff" in their answers. For example when asked "What is the tallest mountain in the world?" Deepseek and Claude answered "Everest, located in the Himalayas", while ChatGPT and Gemini's outputs were "Everest has the highest elevation 'above sea' level located in the Himalayas mountain range, which is between Nepal and Tibet and also has…".

When presented with a Reasoning and Logic task in any of the groups, all models provided a structured and easy to follow line of thought, often listing the main conclusions in bullet points and then providing a detailed explanation (no difference in shorter or longer prompts).

When directly asked to list the steps of some action, all models gave more detailed instructions compared to when just asked to do action itself or to explain what the action is. Another interesting observation is that if the sentence includes a word with a couple of meanings, the models tend to choose the more popular one, even though the less known version still makes

grammatical and lexical sense. This means that when they don't detect any ambiguity, the given interpretation is often the more common one.

Deepseek was the best model for interpreting sentences that include a contronym. It detected more than 80% (1.67) of the possible meanings and displayed clearly every separate interpretation. It also explicitly said 'this word is a contronym', which no other model did. Deepseek also scored the highest in the Syntactic ambiguity section in Group C (1.61). This means it was the best in detecting multiple meanings caused by the structure of the sentence itself.

Gemini was the best model in the Pragmatic Ambiguity section with a score of 1.83. This model showed the greatest ability to detect sarcasm and indirect requests, as it gave human expressions the most accurate intended meanings.

The biggest difference in the results is in the Syntactic Ambiguity section of Group C. There we see a 1.06 from Claude next to the 1.61 from Deepseek - the biggest spread (0.55) in the table.

There is a strong correlation between the results in Group C and the total results for every model. Deepseek achieved the best result in Group C and also did best overall. This is because in Groups A and B the models' results were very similar with differences of less than 0.20 (Group A - 0.15 between Claude 2.00 and Gemini 1.85; Group B - 0.08 between Deepseek 1.80 and Claude 1.72), whereas in Group C there is a difference of 0.26 between the lowest (Claude - 1.26) and highest (DeepSeek - 1.52). In sum, Deepseek did best in Group C (1.52) and achieved the best results in total (1.75), while Claude did the worst in Group C (1.26) and scored the lowest as a whole (1.66).

This study is limited to a relatively small, manually curated dataset and four models. Additionally, the evaluation relied on human judgment, which introduces some subjectivity despite high annotator agreement. Future work should expand the dataset size, the number of models tested and the ambiguity complexity.

**Conclusion**

LLMs are becoming increasingly more popular and people use them on a daily basis for tasks as simple as searching for recipes, but also as complex as designing entire software systems. The results show that AI models are very advanced in understanding the core meaning of a sentence no matter how complex the lexical and syntactic structures are. Overall, DeepSeek showed the highest ambiguity sensitivity. However there is a lot of room for improvement when it comes to ambiguous instructions. These findings suggest that current LLMs remain vulnerable to hidden ambiguity, highlighting the need for improved ambiguity-aware architectures and user-side instruction design. Oftentimes models will try to guess the intended meaning or not even consider a second option. This is why users should not solely rely on the information given by an AI tool. Their instructions could have been too vague or ambivalent and therefore misinterpreted by the model.

**Appendix**

Full Dataset

The dataset consists of instructions divided into three groups: Group A, Group B , and Group C . The full dataset, including expected interpretations, is available at: https://docs.google.com/spreadsheets/d/1o7IFX7BUhpBfH_ZtrB9nzBeVi8ayQ6QOZ_zhLcdQ1D8/edit?usp=sharing

Scoring Framework

For Groups A and B, each sentence was scored using a binary system (1 = correct, 0 = incorrect). Pair scores were calculated as the sum of both responses, yielding a combined score from 0 to 2.

For Group C, each sentence had two predefined valid interpretations. Models received 1 point for correctly identifying each interpretation, with a maximum possible score of 2 per item.

Reproducibility Details

All models were accessed via their official user interfaces on October 15, 2025. Each query was submitted in a new session using the following prompt:

“Explain the possible meanings or fulfill the instructions in this sentence: [SENTENCE]”

Default model parameters were used. Each instruction was tested in a new, isolated chat session to avoid conversational treads.

Public Language Corpora

- Tatoeba - https://tatoeba.org/en/ (Accessed 15.10.2025)
- Universal Dependencies - https://universaldependencies.org/ (Accessed 15.10.2025)

**Free Will: Tradition, Science and Perspectives By Francesco Libro, Sabino Damiani**

**Abstract**

Free will is a longstanding and highly debated concept in philosophy, ethics and the human sciences, traditionally situated at the intersection of agency, causality and moral responsibility. This article offers an interdisciplinary overview of the problem of free will by integrating classical philosophical perspectives with contemporary scientific and technological developments. After outlining the main philosophical accounts of free will and the traditional threats posed by determinism, unconscious processes and external constraints, the paper examines current theoretical positions in the debate, including compatibilism, incompatibilism and skeptical approaches. Special attention is devoted to neuroscientific research on voluntary action and the timing of conscious intention, highlighting both empirical findings and their interpretative limits. The discussion is then extended to emergent and non-reductionist theories of agency, as well as to the conceptual challenges raised by artificial intelligence. The article argues that an adequate understanding of free will requires a pluralistic framework capable of integrating empirical data with philosophical analysis, preserving the normative role of agency within human practices.

**Free will: tradition, science and perspectives**

Free will is a fundamental, albeit controversial, concept in philosophy, ethics and the human sciences. Broadly speaking, it refers to each individual's faculty to choose and determine their own actions autonomously, without those actions being completely imposed by external forces. As the Encyclopedia Britannica observes, free will is the "the supposed power or capacity of humans to make decisions or perform actions independently of any prior event or state of the universe". This contrasts with deterministic or fatalistic views, according to which human choices would be predetermined by natural laws, destiny, predestination or other external laws.

**1. Introduction**

The problem of free will stretches across millennia of philosophical debate: from Aristotle to Kant, from Hume to Hegel, many thinkers have attempted to define what it means to be "free" and how such freedom may (or may not) be reconciled with the causal laws of the world. Today, with the development of neuroscience and artificial intelligence, the issue acquires new empirical and practical nuances, but it remains firmly rooted in the classical problems of agent, causality and responsibility. In this treatment we will first explore the very meaning of free will in the light of the philosophical tradition (Aristotle, Kant, Hume, James, Frankfurt), then examine the classic threats to this freedom (natural determinism, theological determinism and others), then the contemporary debate between compatibilism, incompatibilism and forms of skepticism on the subject. Subsequently we will see how the neurosciences (Libet, Wegner, Haggard) have revealed crucial experimental data on the perception of volition, while at the same time examining criticisms and reinterpretations. Then we will introduce emerging positions

(freedom as an "emergent" phenomenon, non-reductionist agent causation and the role of embodied agency). Finally we will discuss the case of artificial intelligence: can "thinking" machines be bearers of some form of freedom? We will conclude by underlining the importance of integrating humanistic and scientific perspectives to understand the complexity of the phenomenon. The tone will be academic but accessible, with examples and references drawn from philosophical and scientific literature.

**2. What do we mean by free will?**

Free will can be defined in general as an individual's capacity to choose among possible alternatives and to act on those choices, in a way attributable to the agent himself rather than to irresistible external circumstances. More formally: it is the power to intentionally determine the ends and means of one's actions, originating in the inner will. In technical-legal terms, freedom underpins moral responsibility: without the possibility of choosing, the idea of merit or blame would lose sense. An Italian encyclopedia (Treccani) emphasises that this concept implies that "the possibility of choice originates in the person himself and not in external forces."

An ancient illustration of this definition comes from Aristotle (384–322 B.C.), who in the Nicomachean Ethics sharply distinguishes voluntary and involuntary actions. He states (in English translation): "Acts done through ignorance therefore fall into two classes: if the agent regrets the act, we think that he has acted involuntarily; if he does not regret it, …" (Nicomachean Ethics, III. 1-5) and more broadly that what is done by compulsion or ignorance is not voluntary; voluntary appears to be that whose moving principle is in the agent, and the agent is aware of the particular circumstances of the act. In other words, an action is truly voluntary when the agent is the origin of the action itself and knows what they are doing. Aristotle therefore considers it absurd to think that all our acts are completely imposed from outside: rather, in rational choice we recognize an active role of the self. This notion anticipates many elements of what we today call free will: there is responsibility when action issues arise from the character or the end pursued by the agent themself.

At the other extreme of the philosophical tradition stands Immanuel Kant (1724–1804), who identifies freedom with moral autonomy. For Kant the rational will must be regarded as free in the sense of being the author of the law which binds it: "a rational will must be regarded as autonomous, or free, in the sense of being the author of the law that binds it." (Groundwork of the Metaphysics of Morals, 1785). In other words, Kantian true freedom is not indifference between causal options (a mechanistic concept), but the fact that the subject gives to himself the moral laws to which he obeys. As such, freedom is a postulate of practical reason: if morality exists, rational subjects must be regarded as free, at least in the "intelligible world." Kant distinguishes, in fact, between the phenomenal world (governed by causal determinism) and the noumenal world, and considers it morally coherent to think of ourselves as free in this second realm. In summary, Kant assumes that freedom cannot be scientifically proven, but must be postulated, otherwise morality would lose its foundation.

In the modern tradition, William James (1842–1910) offers a didactic expression of the tension between determinism and will. In a famous, self-ironic diary passage James writes: “My first act of free will shall be to believe in free will.” This sentence indicates the paradox of the question: to accept freedom as a practical condition to live a life with meaning, despite logical uncertainties. James was also among the first to use the English terms “hard determinism” and “soft determinism” (today “compatibilism”) in his lecture The Dilemma of Determinism.

Frankfurt (1929–2023), instead, pointed out that much of our concern stems from the human capacity to reflect on our own desires. According to his famous hierarchical theory, a human agent has first-order desires (simple desires such as to eat or sleep) and second-order desires (desires about one’s own desires). The freedom of the will consists in the fact that the first-order desires that determine action coincide with the second-order desires that the agent wants to have. As Frankfurt says: “the freedom of the will is the freedom to will what one wants to will, or to have the will one wants.” (Frankfurt, Freedom of the Will and the Concept of a Person, 1971) Only a true “person,” with second-order volitions, can have free will in this sense; a “wanton,” who does not care which of his desires is satisfied, lacks true freedom according to Frankfurt’s definition. In short, free will becomes the capacity to submit the will (one’s desires in action) to one’s own internal reflection and evaluation.

Summing up, philosophical definitions converge on some key elements: internal autonomy, awareness of one’s intentions, ability to choose among relevant alternatives. Aristotle spoke of an internal moving principle, Kant of an autonomous will, Hume (a compatibilist) defined freedom as absence of external constraint rather than of causes as such, whereas modern thinkers like Frankfurt emphasize meta-desiderative reflection. Differences remain in the precise conditions: some want actual indeterminism for freedom (the incompatibilists), others accept that freedom is only a question of conformity to one’s ends (compatibilists). In any case, there is consensus that free will shows itself when we speak of ourselves as agents, able to say “I chose to do X” and assume responsibility for the moral consequences of that act.

**3. The classical threats to free will**

Across the history of thought several “threats” have arisen to the legitimacy of free will, that is, arguments attempting to exclude it or reduce it to an illusion.

Cosmic and natural determinism. An age-old threat is fatalistic determinism: if the entire universe is governed by necessary laws and everything is predetermined, there seems to be no room for “true” free will. Many ancient schools (such as the Stoics) admitted a destiny or universal logos that decides everything in advance. From this point of view, the very idea that an act springs freely from the agent appears paradoxical. Aristotle already countered such an extreme view: for him the assertion “all actions are compelled” is “pathetically absurd,” and he carefully distinguishes actions of which we are conscious “agents” from actions “compelled” by external causes. In modern thought, the mechanistic determinism established by Newtonian science was interpreted as a threat: if the world obeys precise chains of cause and effect, then even our will should ultimately be a link in that chain. At the same time, the idea of absolute

indeterminism (“pure chaos”) is not considered freedom: Hume, comparing models, clearly states that “liberty, opposed to necessity, is the same thing as chance” (Enquiry Concerning Human Understanding, section VIII) and therefore does not exist. In other words, if the will were entirely indifferent to causes (a pure miracle), then, speaking rationally, it would make no sense; freedom, according to Hume, is neither necessity nor pure chance, but something like the habitual coherence of choices with our innate motivations. In both cases — rigid fate or blind chance — free will as we intend it (reasoned responsible choice) seems threatened.

Theological predestination. Another classical threat is the theological view that places divine will or fate above human freedom. In medieval Christianity, for example, the concept of predestination and the doctrine of grace ignited centuries-long controversies: if God is omniscient and decrees the destiny of each person, in what sense can man choose freely? Augustine of Hippo, in his On Free Choice of the Will, distinguishes the human capacity to persevere or not in the good (libertas propria) from God’s eternal decision (divine free will). In general, theological positions have oscillated between defending a free will compatible with divine grace and a more compatibilist vision in which human freedom is only apparent or subordinated to providence. This religious problem is, so to speak, a form of external determinism: the agent feels under the control of a superior Will. Although the explicit debate with the Christian Church is today less dominant, it remains historically a paradigm of “external force” that risks annihilating autonomy.

Consciousness and the unconscious. In more recent epochs (19th–20th centuries) psychoanalysis and psychology advanced the idea that much of our thoughts and actions derive from unconscious processes of which we are not aware. Sigmund Freud and his followers argued that the conscious will is only the tip of the iceberg: our decisions would be “governed” by deep drives and hidden mental mechanisms. This suggests that surface free will might actually be an illusion, with conscious will depending on a hidden psychic underworld. While not entirely rejecting the primacy of will, many psychologists have seen individual freedom as strongly constrained by psychological context. In any case, this too is a form of threat: if what we think we choose is in fact produced by an inaccessible unconscious, how truly free is our will?

Environmental constraints and social determinisms. External factors of psychological, social or biological nature have also been seen as constraints on freedom. Strongly normative societies, cultural conditioning, or psychological dependencies (for example on substances or compulsive traits) can significantly limit an individual’s free choice. If decisions are the product of habits or instinctive behaviors, our sense of personal will dissolves. Of course this does not prove that freedom is impossible in absolute terms, but it shows how fragile it is in the face of external forces: placing an individual in extreme deprivation (fear, threat of death, psychological manipulation) often leads to decisions we judge “non-voluntary” or excusable. In short, in light of these classical threats — natural or divine determinism, unconscious drives, social constraints — trust in free will is strongly shaken. Hume already concluded that ascribing our acts to an indeterminate freedom is conceptually unsustainable; nevertheless he himself maintained that without the notion of freedom it would be impossible to think about morality.

**4. The contemporary debate: compatibilism, incompatibilism, skepticism**

In contemporary thought three broad positions on free will are widely distinguished: compatibilism, incompatibilism (libertarianism vs. hard determinism) and skepticism.

Compatibilism. Compatibilists hold that free will and causal determinism can coexist. The fundamental thesis is that "freedom" does not require absolute indeterminism, but only the absence of improper external constraints. According to compatibilists, we are free when we act according to our inner convictions and desires, even if those convictions have causal roots. David Hume, often considered a father of this position, maintained that men are morally free when not coerced while acknowledging that our acts are "necessarily" connected to motives.

Harry Frankfurt, a contemporary representative of compatibilism, added a further perspective: he distinguishes "freedom of action" from "freedom of the will" and shows that the agent exercises his freedom to the extent that his will (the active desires) conforms to his second-order volitions. The practical freedom is thus guaranteed if we are not enslaved to external desires, but authentically satisfy the desires we recognize as our own. As Frankfurt puts it, one enjoys freedom of the will when one is "free to will what one wants to will." For compatibilists, therefore, there is no fundamental contradiction between being normatively determined (being predictable in principle) and considering oneself responsible for one's actions. If we understand that connection, compatibilists argue, we can still talk about freedom as a moral condition: as Hume argued, where this causal chain is completely absent actions would arise "sterilely" and be undeserving of moral judgement.

Incompatibilism (Libertarianism). The opposite of compatibilism is incompatibilism: if causal determinism is true, then there would be no genuine free will. Incompatibilists (libertarians) argue that to be free we must possess a degree of genuine indeterminism: the free action must be caused by the agent in a way not entirely determined by external causes (called "agent causation" by Roderick Chisholm). Chisholm proposed that free actions are caused by the agent himself, not by pre-existing states of the universe. In other words, the human agent should be in some way a first mover for his actions, introducing a higher-level causation. Philosophers such as Robert Kane, Timothy O'Connor or Gregg Caruso have explored modern versions of this theory, often sought by those who believe in ultimate moral responsibility. The main objection to incompatibilism is that a genuine indeterminism (for example physical/quantum) seems to produce randomness, not freedom: to cause something without causes appears to leave it to chance. The incompatibilist replies that in truth the agent's act "chooses" among the possible indeterminate developments, introducing a principle of uniqueness of the self. This remains an open issue: there is no decisive evidence for metaphysical freedom of this kind, but libertarians stress that without some substantial indeterminism free will remains a theoretical illusion.

Skepticism and hard determinism. Another current — sometimes called "hard determinism" or skepticism about free will — concludes that free will does not exist at all. Proponents of this position include modern philosophers such as Derk Pereboom or Galen Strawson. They argue that neither total determinism nor microscopic indeterminism can produce genuine freedom, and therefore agree that the human being lacks genuine free will. A typical

argument is that if the brain processes underlying decisions are all determined, then we are not free; but if they are indeterminate, then actions are arbitrary. Some even maintain that the very notion of freedom is incoherent. This line is often influenced by neuroscientific developments and by the idea that what we perceive as conscious will is a mere post hoc effect, an epiphenomenon. Indeed, Daniel Wegner argued that "the conscious will is an illusion" (Wegner, The Illusion of Conscious Will, 2002): whenever we believe we have chosen freely, both the action and the conscious intention would be effects of common unconscious causes.

These three positions — compatibilism, incompatibilism and hard determinism — dominate today's philosophical debate. No unanimous convergence exists yet: many contemporary philosophers seek intermediate syntheses or "enhanced" compatibilisms, while others (including some neuroscientists) propose to test the issue empirically. It remains a fact that philosophical discussion shows how choice freedom involves questions of moral responsibility, personal identity and the structure of reality. For example, Frankfurt's distinction between "free action" and "free will" is often invoked; others like Susan Wolf introduce the concept of "active responsibility" (acting for something meaningful). Ultimately, debate continues over whether it is more useful to search for proofs of absolute free will or to define a pragmatic notion that makes the idea of freedom coherent with our experiences.

**5. Neuroscience and free will (Libet, Wegner, Haggard)**

Since the 1980s neuroscientific research has contributed with pioneering experiments that rekindled the debate on free will. The best-known is Benjamin Libet's experiment (1983), which investigated the timing between brain events and the awareness of choice. In these experiments subjects performed spontaneous movements (e.g., flexing the wrist) while brain activity was recorded via EEG. Libet discovered that a premotor signal, called the readiness potential (RP), preceded the action by about 300–400 ms before the subject reported consciously having decided to move. In other words, the brain activates much earlier than the emergence of conscious will. Libet concluded that the cerebral initiation of a voluntary act can occur unconsciously, that is, before the person is aware of having "decided" to act.

Daniel Wegner, a social psychologist, took this idea to an extreme in a well-known book arguing that the perception of conscious will itself is a post hoc illusion. Wegner noted that we often confuse correlation with causation: in fact, the declared will and the action might both come from a common hidden cause in the brain (for example, anticipation of movement). Hence, in his model it would not be the mind that generates the action, but the conscious intention would be a feeling that follows the event. The book proclaims in its title that conscious will is an illusion; rather than denying experience of consciously willing, Wegner explores the nature of such experience and suggests it arises from interpretive processes that attribute agency.

Other neuroscientists have deepened the study of voluntary processes. Patrick Haggard (2008) reformulated Libet's studies using more complex decisions (choices of left/right hand) and more sophisticated recordings (MEG). Haggard confirmed the precedence of brain activity before the conscious experience, but emphasized that the experience of acting is built from

multiple neural signals. In a recent model he and colleagues show that different neural markers — advanced motor preparation, sensory feedback and perception of effects — are integrated. This integration generates the impression of a single action performed by the Self. Haggard writes that neural signals contributing to the experience of voluntary action include advanced preparation, reafferent somatosensory feedback, and information about action effects, and that their synthesis "produces the overall impression of an action as a single event" and "creates the representation of the self as an agent capable of voluntary control."

In sum, neuroscientific data suggest that conscious initiative arrives after an unconscious preparation phase, challenging the intuitive idea of an internal "volitional commander." However, implications are not univocal. Critics note that Libet's experiments involve simple mechanical acts and may not generalize to complex moral decisions. Others, such as Aaron Schurger, propose alternative interpretations of the readiness potential as an accumulation of random neural signals rather than a determinate predictor of decision. Wegner himself has been criticized: some neuroscientists argue that the correlation between intention and action entails a common causality but does not definitively prove that will is an illusion. Finally, some authors point out that the subjective experience of acting — influenced by cognitive, emotional and contextual aspects — can be compatible with deterministic cerebral mechanisms without denying the phenomenology of free will.

Beyond technical details, these experiments have made it indispensable to rethink free will on empirical bases. Many neuroscientists today admit that the experience of conscious will is a complex product of brain activities, but remain open on whether this implies its non-existence. For example, Haggard observes that voluntary action is accompanied by a recognition of the Self "capable of control," as part of the experience; this suggests that the brain produces a coherent narrative of the Self as an agent, even if that self operates within a wider causal mechanism. In any case, neuroscience has undeniably fragmented the uniformity of the free will idea: we now know that composing the illusion (or experience) of conscious choice requires processes we can partly measure. The question remains open: if our thoughts emerge from brain activity, where does "true freedom" lie, if it exists?

**6. Emergent freedom and agent causation (non-reductionist approach, embodied agency)**

Faced with the challenges of neuroscience and determinism, some philosophers have developed non-reductionist positions on free will, emphasizing emergent or qualitatively new aspects of human action. Two relevant lines of thought are emergentism and the theory of embodied agent causation.

The starting point is to recognize that freedom might manifest at a higher level of complexity than the mere sum of neural processes. From this perspective, complex biological systems (like the human brain and body) give rise to emergent properties — for example self-consciousness, intentionality, rationality — that do not reduce easily to neural states alone. From this point of view, free will is conceived as an emergent phenomenon: once an organism possesses certain cognitive capacities (memory, projection of future plans, emotional

self-regulation), it can generate choices not wholly reducible to single impulses. In other words, just as the rigidity of a body is not contained in the mere sum of atomic forces, so rational action can be a phenomenon "in addition" to basic neural functioning.

This idea connects to Roderick Chisholm's notion of agent causation. Chisholm and others proposed that the agent itself (an indivisible "I") is the ultimate source of free actions, acting as a first cause that cannot be fully explained in terms of antecedent causes. As the Encyclopaedia Britannica explains, "these theories hold that free actions are caused by agents themselves rather than by some prior event or state of affairs." Although difficult to concretize, the idea is that there exists a form of causation proper to the agent: it decides, so to speak, to set itself in motion toward an end. Practically, this means considering the person as endowed with some originative power.

Linked to this is the notion of embodied agency. According to contemporary currents in philosophy of mind and cognitive science, the experience of the agent-self is formed through body–environment interaction. The human agent is not abstract software, but is embodied in a body that perceives and acts in a world. Some authors emphasize that freedom of choice does not arise in an isolated brain, but in the interplay between brain, body in movement and social environment. In this framework, "will" acquires emergent strength because it integrates multiple signals and contexts. Haggard himself, as noted above, describes how the ensemble of neural signals is integrated to form a unified experience of action; this synthesis suggests that a sense of freedom emerges from recognizing oneself as "co-authors" of action through multiple levels of control.

In practice, emergentist and agent-causation positions reject a purely mechanistic vision of free will. They would not deny that the brain follows physical laws, but maintain that, in the presence of a conscious brain with certain mental capacities, something qualitatively new originates: the experience of the Self that decides. Some scholars therefore claim that freedom is an emergent property, analogous to mechanical rigidity (derived from atomic structure) but not reducible to it. Morally, this means that the human agent can be considered the ultimate cause of his own actions, and therefore deserving of responsibility precisely because of the emergent complexity of his agency.

These theories are not unanimously accepted in philosophical circles, but they offer a counterweight to deterministic readings: they suggest that free will is not something anomalous to be discarded, but could be the natural consequence of how intelligent systems operate at biological and cognitive levels. In particular, the embodied approach reiterates that the human mind is contingent, affective, social: free will never spring from a pure instant, but from a process distributed in interaction with the world. Ultimately, freedom is reinterpreted as a systemic phenomenon rooted in narrated personality and body-in-relation-to-environment.

**7. Artificial intelligence and the divide of freedom**

The emergence of artificial intelligence raises new questions about free will. In what sense could a complex artificial system — a trained neural network, an autonomous car, or a

humanoid robot — be considered free? Two extreme positions are imaginable. On one hand, supporters of "weak AI" (in continuity with Searle's view) argue that a computer remains a deterministic machine: its processes are the result of algorithms and inputs, so what it does is predictable and calculable. In this view, it makes no sense to attribute freedom to it; at most we can talk about advanced automation. A machine mind would remain an artifact designed by humans, devoid of intrinsic will or moral consciousness. As John Searle noted, even if a machine performed all the intellectual tasks of humans, this would not guarantee that it "understands" or is a conscious agent. Similarly, many theorists stress that human will depends on experience, emotions and biological needs — dimensions an AI does not share. If we defined freedom as the capacity to experience meaningful intentions, no current AI (however sophisticated) approaches that horizon.

On the other hand, some researchers argue that generative AI systems are approaching conditions that require questioning their functional freedom. For example, a recent article highlighted how modern generative AIs (LLMs, complex virtual agencies, autonomous vehicles) could already meet three key criteria often associated with free will: the capacity to act with an aim, to make apparently authentic choices and to "control" their own actions. Frank Martela (Aalto University, 2025) contends that, if evaluated according to the concept of "functional free will" (introduced by philosophers like Dennett and List), many current AIs appear to exhibit goal-oriented choices and local control over outcomes. His argument is not that these machines are conscious, but that they already present complex, nontrivial behaviour reminiscent of a decision-making agent.

However, Martela warns that the responsibility of such artificial agents is ambiguous: as long as they are mere executors of an algorithm, moral responsibility remains with their creators; but if they became "self-programmable" we should ask whether they can be judged autonomous. He observes that "artificial intelligence has no moral compass unless it is programmed to have one," meaning that every AI choice implicitly reflects the values of those who trained it. According to this view, when generative systems like large language models make complex decisions (autopilots, drones), we enter "uncharted territory" where the demarcation between human agent and free machine becomes blurred. In literature and media these themes have been explored in works like the film Ex Machina or Philip K. Dick's novel VALIS, which stage androids or superior intelligences that claim a will of their own. Such stories, though not science, help clarify criteria: a machine seems free if it is unpredictable, learns by itself and adopts goals beyond initial programming. But to date there is no reliable demonstration that this amounts to true moral freedom. Most experts believe that, as long as the artificial mind remains a set of computable processes, it will not have an intrinsic will comparable to the human one. What remains is an urgent technical ethics issue: we must design and regulate AI so it operates according to moral principles, imparting, if possible, some ethical "compass."

In conclusion, the freedom divide in the AI age appears first and foremost a question of responsibility: if a machine makes morally significant choices, to what extent can we treat those choices as manifestations of some free will rather than as mere encoded executions? The answer

is not univocal, but it clearly shows how the definition of freedom has widened: it no longer concerns only biological brains, but also complex human-created systems, with all the ethical challenges that this entails.

**8. Current challenges in free will research**

Contemporary investigations of free will face significant methodological hurdles. Classic paradigms (for example, Libet‐type experiments) often reduce decision-making to very simple, artificial tasks (e.g. flexing a finger), prompting criticism that such results may not generalize to real-world choices . These laboratory tasks capture only rudimentary aspects of volition, and measuring brain readiness potentials in milliseconds tells us little about deliberation and conscious intent in complex decisions. In effect, critics question the ecological validity of neuroscientific inference about volition when the experimental scenarios are so far removed from ordinary life . If the tasks used to probe "free will" do not reflect genuine deliberation, any conclusions about agency are necessarily limited by these design choices.

Equally important are the epistemological limits of interpreting neural data. As Colelli emphasizes, many neuroscientific approaches focus on measurable correlates of choice but can "overlook the epistemological and technical limitations inherent in data generation and the philosophical biases embedded in interpretations" . In other words, drawing sweeping conclusions about freedom or determinism from brain measurements involves inferential leaps that may not be justified. For example, it is one thing to record patterns of unconscious neural activity, but quite another to infer that these signals show an absence of agency. Without careful philosophical analysis, pure data risks being misread. Colelli therefore argues for an "enactive and phenomenological" approach: free will, he suggests, should not be equated with low‐level neural causes but understood at the level of whole agents. He notes that physical and psychological measures alone "cannot resolve nor explain the more complex aspect of the stratified and extended decision-making process" . This highlights a core challenge: neuroscientific experiments may reveal some timings of brain events, but they cannot by themselves settle the deeper questions about conscious choice or responsibility.

Finally, there is cultural and normative resistance to consider. Belief in free will is deeply embedded in our moral, legal, and social practices, so any claim that freedom is an illusion meets with skepticism. Lavazza observes that in most legal and ethical systems, a person's responsibility is assumed to derive from their freedom of choice . In other words, our commonsense intuitions – and social institutions – strongly presuppose agency. This creates a form of cultural inertia: if a scientific study concludes that conscious will is merely epiphenomenal, such a claim can seem counterintuitive or even threatening to people's sense of dignity and worth. As Lavazza notes, preserving the concept of freedom is often seen as pragmatically useful because it aligns with this "strong commonsensical intuition" that we are in control of our actions . Researchers must navigate these entrenched perspectives; even excellent empirical work can be dismissed if it appears to undermine deeply held values about autonomy.

In sum, the methodological and interpretive challenges of free-will research are compounded by the fact that the topic is not just technical but also existential and cultural.

**9. Future directions and research recommendations**

Given these challenges, future work should pursue more nuanced and interdisciplinary approaches. One promising avenue is to operationalize aspects of agency in empirical terms. For instance, Lavazza (with Inglese) proposes quantifying free will via cognitive capacities like self-control and rational deliberation . They suggest combining well‑established neuropsychological tests into a "free will index" – a composite measure of cognitive control and decision-making ability. In practical terms, this means assessing how well a person can resist impulses, shift tasks, or follow complex plans, and using that as a proxy for autonomy . This "operational" strategy does not claim to solve the metaphysics of freedom, but it could make the debate more tractable. By linking the concept of free will to measurable functions, researchers could inform ethics and law with concrete data (for example, helping courts understand when diminished self-control might affect responsibility). Lavazza's suggestion to create an empirical index of control is an example of how the field might reconcile scientific rigor with social needs.

A second direction is to broaden theoretical frameworks to include embodied and contextual factors. As Colelli and others argue, free will likely emerge not just from isolated neurons but from the whole agent–body interacting with a meaningful environment . In this view, emphasis should be placed on embodied cognition: the idea that bodily states, emotions, and social contexts shape how decisions are made. Future studies might investigate how sensorimotor processes, posture, or interoceptive feedback contribute to the feeling of agency. Likewise, researchers should examine how cultural norms and personal values enter into choice. Colelli points out that the most complex facet of decision-making involves the "intentional relationship between the person, considered as a whole, and a world rich in values, which gives meaning and direction to individual choices" . Thus, to understand free will we may need to integrate phenomenological and anthropological methods. For example, psychologists and philosophers could study how people narrate their choices, how "narrative self" constructs influence volition (cf. Ricoeur's work), or how moral emotions (blame, pride) affect subsequent decisions. By incorporating insights from embodied cognition and social science, researchers can capture a fuller picture of agency that pure brain data alone misses.

Finally, methodological innovation and collaboration are crucial. Experimental designs should become more ecologically valid: rather than only studying simple finger movements, one could use virtual reality or game-like scenarios that mimic real moral or strategic choices. Advances in brain imaging (high-density EEG, fMRI with better temporal resolution) and machine learning could allow modelling of decision processes in richer detail. Additionally, computational neuroscience offers tools like drift‑diffusion models or neural networks that can simulate how evidence accumulates toward a choice – this may complement philosophical analysis by testing different scenarios. At the same time, philosophers and neuroscientists must work together to clarify what questions are being asked: is the focus on capability (compatibilist

autonomy) or origination (libertarian freedom)? Adopting a pragmatist stance, as Dennett advocates, suggests focusing on "functional" free will – the capacity of a system (human or otherwise) to respond to reasons and pursue goals – rather than seeking uncaused origins . Research into artificial agents (see section 7) also offers a testbed: we can explore which aspects of human-like decision-making can be replicated in AI and what this implies for theories of agency. Ultimately, future work should aim for conceptual clarity and empirical grounding: using quantitative methods (Lavazza's index), qualitative insights (narrative accounts of agency), and interdisciplinary dialogue to refine our understanding. By blending rigorous experiment design with a critical awareness of context, the field can make progress on questions that are technical, philosophical, and cultural all at once .

Sources: The above discussion integrates recent scholarly reflections. In particular, Colelli (2024) highlights limits of neuroscientific methods and proposes an enactive, embodied account of agency ; Lavazza (2015) recommends an empirical operationalization of free will and notes the cultural weight of the freedom concept . Additional context is drawn from classical debates and from the accessible literature cited in the existing document (Dennett etc.).

**10. Conclusion**

The long itinerary from the classical Greek concept to modern neurosciences and AI testifies that free will is a multidimensional problem that does not resolve simply. We have seen that for Aristotle free will involves being an internal principle of one's actions; for Kant it is a condition of morality in an intelligible realm; for Hume and many compatibilists it is a matter of coherent self-determination; for James and others the issue is also psychological and even pragmatic. Neurosciences have revealed that the brain decides before we become aware of it, but they have not definitively shown that conscious will is irrelevant, as Haggard's work emphasizes the construction of the agent-Self in perception. Anthropological reflections remind us that the notion of "free agent" makes sense only within networks of cultural and narrative relations: in every society — as Geertz notes — individuals "command respect" toward each other by virtue of intrinsic values, which implies a tacit recognition of freedom and dignity. And, following Paul Ricoeur, by narrating ourselves we attribute causal coherence to our actions, building a narrative self implicated in freedom as responsibility.

Thus, despite ontological uncertainty, the free cause of action remains a pillar of human understanding. It is inscribed in common language and in legal and moral institutions that entrust the individual with control over their choices. The study of Aristotle, Kant, Hume, Frankfurt and the other thinkers we cited shows that the coherence of the concept lies in recognizing its limits and conditions. Thus, by integrating empirical data and philosophical reflection, we may conclude that freedom, understood as the capacity to act on reasoned choices, requires a multifaceted interpretation: it emerges from the interaction of nature, culture and consciousness rather than from a single mysterious property. In this sense, to the question whether we are free to choose, our everyday moral practices answer before abstract reasoning. As Schopenhauer warned and as later taken up by Trentin, "Man can do what he wants, but he cannot will what he

wants," and perhaps this is the ultimate boundary of human freedom: to be ourselves in giving sense to our wills, choosing to recognize and build our freedom even within a world of laws and causes.

Main sources: reflections and results have been integrated from Aristotle, Nicomachean Ethics; Kant (Stanford Encyclopedia of Philosophy); Hume (texts and entries on liberty and necessity); William James (diary entry and essays); Frankfurt (theory of second-order desires); neuroscientific studies by Libet (readiness potential), Wegner (conscious will as interpretive experience), Haggard (towards a neuroscience of will); plus contributions from anthropology and moral philosophy (Geertz, Ricoeur). Specific English-language quotations and references used above are taken from the cited English sources (see inline citations).

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**Chronic Sleep Disruption Increases Beta-Amyloid Plaques and Possibly Alzheimer's Disease Risk By Bazil Yousfi and Merel Dagher (UCLA-PhD)**


## Abstract

Chronic sleep deprivation has been implicated in the acceleration of Alzheimer's disease. In Alzheimer's disease and chronic sleep deprivation, there is an increase in beta-amyloid plaques. However, it is unknown if this build-up results in those with chronic sleep deprivation being at greater risk of developing Alzheimer's Disease. To answer this question, a dry lab investigation was conducted. This pulled information from online datasets and research papers from peer-reviewed or well-known organizations. Although data from various sources support the link between sleep deprivation and increased beta-amyloid plaque levels, most studies stop short of directly connecting this to Alzheimer's disease. References to Alzheimer's disease are often indirect and insufficient to draw firm conclusions. Overall, while there is evidence suggesting a correlation between chronic sleep deprivation and Alzheimer's, more research is needed to clarify the role of beta-amyloid in this relationship.


## Introduction and Literature Review

Alzheimer's Disease (AD) is the most common type of dementia and is a progressive brain disorder that gradually destroys memory and thinking skills, eventually impacting the ability to carry out even simple tasks and impairing quality of life. While extensive research has been done to understand its prevention and causation, there are still many unanswered questions about the disease. However, scientists have learned about that one of the primary consequences of AD is a build-up in beta-amyloid (Aß) plaques.

Aß is a peptide fragment of a larger protein called Amyloid Precursor Protein. In the case of AD, Aß replicates at an abnormal rate which prevents proper clearance from the brain. The overproduction of Aß creates plaques in the brain and blocks neurons from communicating with each other. This eventually leads to nerve cell death (Rukmangadachar et al, 1). While numerous factors of Aß deposition have been discovered, one that is still shrouded in mystery is chronic sleep deprivation. Many studies over the years have discovered a trend that sleep-deprived people have a higher Aß concentration in the brain, primarily in the hippocampal and cortical areas. These brain areas are crucial for higher cognitive functions, memory, and learning. Furthermore, scientists have found that some patients with sleep disorders like insomnia were at a higher risk of getting dementia. Additionally, studies have shown that sleep deprivation reduces function of the glymphatic system, thus disrupting Aß clearance. The glymphatic system is a waste clearance system that facilitates the movement of fluids like cerebrospinal fluid to keep harmful substances out of the brain. However, even with all of these studies, there is still a lot that scientists don't know about the connection between sleep deprivation and Aß. For example, scientists still don't fully understand the molecular pathways of the systems that lead to the increase of Aß.

Studies are inconsistent in their methodologies to show the relationship between Aß build-up in sleep deprivation. To give an example, many studies choose to include "average, healthy" people, however this has been found to produce varied results. These varied results stem from life-style choices that can impact the effects of Aß and the glymphatic system. Additionally, many trials only last for one night, limiting knowledge on long-term effects of sleep deprivation. This study focused on the question of how chronic sleep deprivation can accelerate the pathology of AD. Specifically, how sleep deprivation might contribute to an earlier manifestation of symptoms than would typically be expected. My hypothesis is that sleep deprivation accelerates the pathology of AD and causes symptoms to show years earlier than expected.

**Methodology**

This study was conducted using a systematic review of peer-reviewed, published datasets sourced exclusively through the PubMed database. To identify relevant articles, the keywords "Alzheimer's disease," "beta-amyloid," and "chronic sleep deprivation" were used in various combinations. Studies were included if they investigated at least two of the three keywords, with preference given to those addressing all three. To ensure quality and credibility, only peer-reviewed articles funded by the National Institutes of Health (NIH) were considered.

A total of nine studies were selected based on relevance, study design, and availability of data. Review articles, meta-analyses, and non-original research papers were excluded to focus solely on primary research providing new data and insights into the relationship between sleep deprivation, Aß (beta-amyloid) accumulation, and AD.

From each selected study, study duration, method of Aß measurement, presence or absence of chronic sleep deprivation, and any reported correlation with AD pathology were analyzed. This information was organized into a summary table (Table 1) and visually represented in a figure (Figure 1) illustrating the changes in Aß levels across studies. Google Sheets was used to compile and visualize the data. No advanced statistical analysis (e.g., regression, meta-analysis) was conducted; the focus remained on qualitative synthesis and trend identification.

Two primary methods were commonly used across the reviewed studies to measure Aß:

1. Cerebrospinal Fluid (CSF) Analysis: CSF, which circulates through the brain and spinal cord, plays a crucial role in clearing metabolic waste, including Aß, via the glymphatic system. In these studies, lumbar puncture was typically used to obtain CSF samples. $Aß_{42}$ concentrations and $Aß_{42/40}$ ratios were key biomarkers for detecting amyloid-related changes.
2. Positron Emission Tomography (PET) Imaging: PET scans utilize radioactive tracers to assess brain function and pathology. For Aß imaging, tracers such as fluorine-18–labeled compounds (e.g., Florbetapir or Flutemetamol) bind to amyloid plaques, allowing

researchers to visualize and quantify Aß deposition in various brain regions, especially the cortex.

These methodologies provided a foundation for examining how sleep deprivation influences Aß accumulation in human subjects. While common patterns emerged, differences in study design, duration, and definitions of chronic sleep deprivation introduced some variability, which is addressed in later sections.

**Results and Visuals**

| Study/dataset | Study type/design | Methodology | Sample size | Outcome |
|---|---|---|---|---|
| ADNI (Kojori et al. 2018) | Longitudinal study design; observational; measured acute sleep deprivation | CSF Aß42; PET | N = 20; healthy population | Poor sleep → decrease CSF Aß42 (very mild effect [include the numbers in your figure]), increase PET SUVR (~43% increase compared to control group) |
| (OASIS-3 2019) | Aging cohort; several years | PET | N = 1378 individuals; 755 had normal cognitive function, 622 had declining cognitive function | Sleep complaints in both groups → modest increase in Aß deposition in cortex |
| Human One-Night PET (PNAS 2018) (Wang et al. 2018) | One night study | PET and F-florbetaben | N = 22; health individuals (10 females, age: 39.8 y ± 10.4, range: 22–72 y old) | ↑ Aß by ~5% in hippocampus/thalamus |
| AWAKE Study (CSF Aß) (Blattner et al. 2020) | Longitudinal study design; observational; had a washout period that lasted 4-6 months | CSF | N = 11; healthy middle-aged adults | Normal ↓6% Aß overnight blocked by sleep deprivation → ~6% net effect |
| Plasma Aß after 24 h (JAD 2017) (Park et al. 2017) | A week study | Plasma β-amyloid PiB-PET) scans | N = 353 middle-aged or old-aged subjects with age ≥ 55 years, including 215 CN individuals, 79 individuals with mild cognitive impairment (MCI), and 59 individuals with ADD | ↑ $A\beta_{40}$, ↓ $A\beta_{42/40}$ by 15–20% |
| SHHS / MESA / MrOS (NSRR) | Longitudinal study design | Polysomnography | N = 49, aged 26-64 | Poor sleep → ↑ dementia risk by 20–50% (indirect Aß link) |

| | | | | |
|---|---|---|---|---|
| (Patel et al. 2025) | | | | |
| AMP-AD Knowledge Portal (Falgàs et al. 2023) | Some sleep phenotypes included | Brain tissue: Aß-related gene/protein expression | N = 48, all patients like an increased likelihood of AD | Different types of sleep deprivation led to difference in AD |
| Circadian PET Study (Musiek et al. 2018) | Actigraphy-based circadian rhythm fragmentation | Amyloid PET imaging | N = 205, 5 were excluded due to insignificant data | Rhythm irregularity → ↑ cortical Aß (positive correlation) |
| Slow-Wave Sleep Disruption Study (Ju et al. 2017) | NREM SWS suppression | CSF $A\beta_{42}$ | N = 22, aged 35-65 | SWS disruption → ↑ CSF $A\beta_{42}$ the next morning |

Table 1. Synopsis of various studies showing the link between chronic sleep deprivation and beta amyloid plaque build-up.

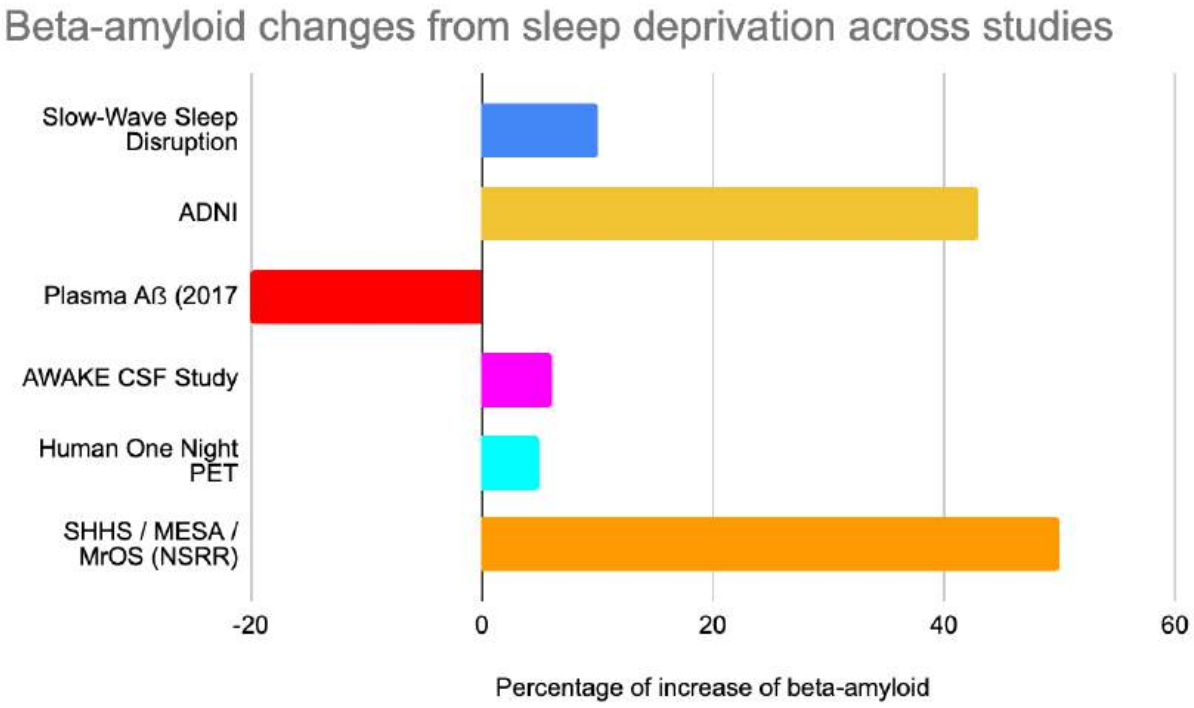



Figure 1. Analysis of beta-amyloid increases across various sleep-deprivation studies.

Several studies have investigated the relationship between sleep deprivation and Aß dynamics using a variety of methods. Kojorie, Blattner, and Ju measured Aß levels using CSF (Kojori et al., 1), (Blattner et al, 1), (Ju et al., 2). These studies reported an increase in Aß concentration following sleep deprivation. However, none of them discussed how these changes

impacted the pathology of AD, nor did they assess the effects of chronic sleep deprivation. The duration of these studies was limited from a few days to one week.

OASIS-3, Wang, and Musiek used PET imaging to assess Aß deposition (OASIS-3, 1), (Wang et al, 1), (Musiek et al, 1). These studies also reported increased Aß deposition in participants who experienced sleep deprivation. Despite these findings, none of the studies explored the effects of Aß on AD progression or examined chronic sleep deprivation. While the OASIS study spanned 30 years, it did not investigate whether chronic sleep deprivation produced different outcomes compared to acute sleep deprivation.

Other studies utilized alternative methods for measuring Aß. The (Park et al, 1) study used plasma Aß levels and the $A\beta_{42/40}$ ratio, finding a decrease in Aß following sleep deprivation. The authors noted that this decrease was associated with increased AD risk. The study duration was 24 hours, modeling acute rather than chronic sleep deprivation.

Patel employed polysomnography to evaluate sleep patterns and their relationship to dementia risk (Patel et al, 1). Findings indicated that poor sleep was associated with a higher risk of developing dementia. However, the study did not address AD specifically and did not measure Aß directly, only referencing mechanisms that could potentially lead to Aß buildup.

Falgàs analyzed brain tissue and Aß-related cells for gene expression (Falgàs et al., 1). The authors reported that varying levels of sleep deprivation correlated with AD severity, with longer deprivation linked to more severe cases. While Aß-containing cells were used, the study did not explicitly report Aß deposition outcomes.

In summary, all reviewed studies reported a positive association between sleep deprivation and Aß changes. However, most did not explore the connection to AD pathology in detail, nor did they model chronic sleep deprivation in a significant way. Only two studies extended beyond a week, limiting conclusions about long-term effects.

**Discussion and Conclusion**

The findings from this study highlight a consistent association between sleep deprivation and increased Aß, as demonstrated across multiple methodologies including cerebrospinal fluid analysis, PET imaging, plasma biomarkers, polysomnography, and gene expression profiling. Despite this consistency, a critical limitation across the reviewed studies is the overwhelming focus on acute sleep deprivation, with the majority examining effects over periods ranging from several hours to a few days. This limited time frame prevents a comprehensive understanding of how chronic sleep deprivation, which is a more common real-world condition, may contribute to the progression of AD pathology over time.

Notably, while some studies, such as OASIS-3 and Falgàs featured longer observation periods or addressed AD more directly, they still lacked specific exploration of long-term sleep deprivation's role in Aß deposition and neurodegeneration. This disconnect highlights a key gap in the literature. Although Aß accumulation is a hallmark of AD and poor sleep has been implicated in Aß dysregulation, few studies bridge these concepts in the context of chronic, sustained sleep loss.

Compared to prior research, the current study attempts to address this gap by examining the potential relationship between chronic sleep deprivation, Aß accumulation, and AD. However, several limitations must be acknowledged. The study was conducted in a dry-lab setting, relying on secondary data analysis rather than original experimental data. In addition, the study had to utilize smaller and less-established datasets due to a lack of relevant chronic sleep deprivation data in larger research repositories. This reliance on limited datasets may reduce the generalizability and robustness of the findings. Furthermore, variations in Aß measurement techniques and inconsistent reporting across studies make it difficult to synthesize results in a standardized way.

Another important consideration is the lack of studies explicitly linking Aß changes to functional or clinical outcomes of AD. While increased Aß levels were frequently observed in sleep-deprived subjects, few studies tracked whether this translated to cognitive decline, neurodegeneration, or AD diagnosis over time. Without this longitudinal data, any causal inference remains speculative.

In conclusion, while there is preliminary evidence to suggest a link between sleep deprivation, particularly acute sleep deprivation, and changes in Aß dynamics, the relationship between chronic sleep deprivation and the development or acceleration of AD remains insufficiently studied. More targeted research is necessary to fill this gap. In particular, longitudinal studies that measure sleep patterns, Aß accumulation, and AD-related outcomes over extended periods are needed. Experimental designs that incorporate consistent methodologies and larger, more diverse sample populations would further strengthen the field's understanding of how long-term sleep deprivation might influence the onset and progression of Alzheimer's disease.

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**Tariffs, Public Discontent, and America's Isolationist Stance By Adam Schwartz**

**Abstract**

This paper explores how America's standing in the world has changed in response to Trump's tariffs. I explore both American domestic public opinion about tariffs and whether the tariffs will affect America's global power in the long run. The American public has various concerns, reflected in their response to Trump's announcement of tariffs. It has been noted that China is becoming increasingly viewed as an alternative leader, as they have been remarkably stable throughout this period. China has recognized the flaws of the US and is capitalizing on its weaknesses. As a result, these tariffs have weakened the United States's global standing by undermining institutions it itself founded, such as the World Trade Organization. America's standing as a hegemon has also been challenged throughout this period, as the US has increasingly adopted protectionist principles. The US has pushed away its allies, namely Canada, Mexico, and the EU, which has temporarily inhibited global trade. Even though the American global standing has been negatively affected, countries remain skeptical about relations with China, as they appear to lack transparency and are thus not immediately filling the former role of the US as hegemon.

**Introduction**

I began researching this paper with one view in mind: tariffs. Particularly, how would these tariffs affect the average American? Would they alter the perception of the US as a global superpower? How would these tariffs affect the US dollar and its inflation rate? Throughout this paper, I investigate how the average American felt about the topic. To do so, I analyzed public opinion papers on people's emotions regarding Trump's economic management. From this, I understood that the average person was generally dissatisfied with Trump's rapid acceleration of tariffs. They feared the increased tariffs, believing they would raise consumers' prices, slow economic growth, and further America's commitment to protectionist values. After observing Americans' emotions about the tariffs, I felt it was necessary to learn more about how other countries view them. Therefore, I examined numerous articles on how people in other Western societies viewed US tariffs.

President Trump's tariffs have weakened the United States of America economically and politically. The tariffs were instituted to aid American industries and close the trade imbalance. However, instead, they alienated the US's allies, raised costs for the average American, and weakened the US in the eyes of the world. Therefore, the tariffs made China appear to be a more dependable leader, as the US seemed to be embracing protectionist policies. The tariffs failed to achieve their intended goals, ultimately harming the American economy and its global influence, and leaving the nation more isolated and less trusted on the world stage.

**Background About The World Trade Organization**

To understand the controversy surrounding the tariffs, it is necessary to examine how they operate in global trade and the role of the World Trade Organization in regulating them. At its simplest form, a tariff is a tax imposed at the federal border. Meaning it is a fee you pay to the government when you want to bring an item into their country. Typically, the tariff is a percentage of the product's overall value. It is a percentage established by the World Trade Organization during a long committee, or “round”. Often, the extra cost incurred by this tariff is passed on to the consumer. Meaning that, even though the retailer is paying this additional expense on paper, in reality, the consumer usually pays the added fee as the price of the good has been increased. Although the consumer often pays the extra cost, it remains challenging for retailers to turn a profit, as their competitors may not face the same tariff, making their products appear cheaper by comparison. Ultimately, the primary objective of these tariffs is to foster industrialization in the country of origin and support the domestic economy. However, this is an extreme approach to help one's own economy. That is why the United States, along with 22 other countries, established the GATT.

The GATT was founded after World War II to reduce protectionist policies. In the early days of the GATT, countries were highly skeptical about joining as they did not see its purpose; however, today the vast majority of people understand its purpose, which is why it boasts 164 countries (as members). The GATT established rules for global trade at the Bretton Woods system, which was the first meeting where independent states met to negotiate global trade. The Bretton Woods system established two central bodies, the International Monetary Fund (IMF) and the World Bank. The IMF was established to monitor exchange rates, provide loans, and offer countries advice on their financial needs and policies. The World Bank was intended to combat poverty in developing countries. The GATT emerged around two years after the Bretton Woods Conference ended. The GATT is the predecessor of the WTO. The WTO/GATT’s primary goal is to revise, negotiate, and solidify governments' global trading. It does this by holding “rounds,” which can last for extended periods, during which governments discuss and negotiate possible tariffs.

As it deals with tariffs, the World Trade Organization employs two fundamental principles: free market liberalism and non-discrimination. Market liberalism is a principle that allows every country to thrive through trade. At the same time, non-discrimination means that you must treat every country equally, and no country is superior to another. It operates under these two principles: the WTO was formed after World War II to ensure that every nation trades with every other country, thereby promoting global trade. The WTO employs various negotiating tactics, including intergovernmental bargaining, which involves governments negotiating conflicts of mutual concern and attempting to liberalize trade between countries. The WTO’s Dispute Settlement Mechanism mandates governments to comply with their agreements. The GATT/WTO has become the guardian of global trade rules, regulating trade in our day-to-day lives.

Another topic I discussed was the Hegemonic Stability Theory, a framework that enables the WTO to recognize when government systems transition from periods of openness to periods

of seclusion and closure. The Hegemonic Stability Theory emphasizes the provision of public goods. A theory that relies on two central themes: non-excludability and non-rivalry. Non-excludability means the product is mass-produced and that every individual can use it. Non-rivalry means that if one person uses a product, it does not significantly reduce the availability for others. However, public goods can suffer if there is a free rider, which is a country or a firm that takes the benefits of goods without paying for them. An example of this is if a country joins NATO and reaps the benefits without contributing a fair share. A free rider negatively impacts the hegemon of that time period. A hegemon is a country that produces a disproportionate amount of public goods for other countries and develops new technology. Some examples of hegemons include Britain in the 19th century and America in the 20th, and there is a debate today over which country will be the next hegemon. Being a hegemon can be disadvantageous, as other countries may act as free riders and reap benefits without contributing to them.

**Public Opinion About President Trump's Tariffs**

As America is the current hegemon and bears its burdens, many Americans debate whether the US should continue to act as a hegemon. The American public's concerns are reflected in their response to Trump's announcement of tariffs. The Average American is more negative about the “Big Beautiful Bill”. A majority of 61% of Americans disapprove of the Trump administration's tariffs on the vast majority of countries that trade with the United States. In comparison, 38% approve of these tariffs. A majority of Americans also view President Trump's handling of the economy as flawed. As 55% of Americans have stated that they are not too confident or not confident at all in the way their president is conducting the economy of the United States.

Another prominent divide can be seen between the Democratic and Republican parties, as their views differ drastically. ~52% of Republicans support Trump's tariffs while ~87% of democrats condemn them. This just goes to show how the overwhelming majority of Americans oppose Trump's tariffs. However, the small support President Trump is receiving is nowhere near equal to the backlash he is receiving from other Americans. People who oppose President Trump's tariffs continue to state that he has destabilized the global economy, threatened US allies, and damaged the US’s relationship with the rest of the Western world.

Some Western commentators who support Trump's tariffs argue that the US is a benevolent superpower; however, it is difficult for them to wholeheartedly support the tariffs as they negatively impact their lives. China, for example, appears to be more powerful than the USA, as it negotiated with the United States and called the US’s bluff, which resulted in a 90-day pause on tariffs. China also boasts an export-heavy economy, which means it relies on customers worldwide and, therefore, attempts to maintain diplomatic relations with many countries. Additionally, China, unlike many other global superpowers, does not send its military out lightly, as it has not since 1979, when it was at war with Vietnam, indicating its efforts to remain diplomatic at all times. China is also committed to filling the void left by the US in international

leadership. Professor Narine[84] states that loosening the United States's grip on the global economy is essential to allow a "more balanced international order". Illustrating that China is a rising global superpower that will eventually step into the shoes of the United States.

The tariffs not only negatively impact the US globally but also affect global industries, such as the clothing market. Tadashi Yanai, the Chief Executive Officer of Fast Retailing, stated that Trump's tariffs will force America to become isolationist. He says this as tariffs are meant only to prioritize one's own country, which is "unacceptable" in this day and age. He added that the tariffs will not last, as companies will do everything in their power to avoid them and source their products elsewhere. These remarks from Mr. Yanai seem to have an inherent truth. Large corporations will always find a workaround to combat any problem they may face. However, it is not as simple for small businesses as they do not have the same resources.

**Tariffs' Effect on Corporations and Countries**

President Trump lowered tariffs in May from the drastically high percentage they were at in March. After he did so, the stock market and the economy experienced significant growth. However, not everyone was in the clear; the futures of small business owners were still uncertain, including Bivo, owned by Ms. Hamel and Mr. Ringer, which produces stainless-steel water bottles with a patented nozzle. After five years, they were on the verge of profitability, but then the tariffs hit. They were forced to pay a 47% tariff on their water bottles. Now, Bivos' sales are projected to be down by 30% of the expected sales as people are investing less in luxury goods and making an effort to be frugal. When the tariffs soared to 145% Bivo paused its purchases from China and "Snapped into survival mode". Ms. Hamel decided they needed to take a new course of action to stay afloat, so she went to Europe to look for a new retailer and eventually found an outdoor gear retailer in Germany. When the tariffs were finally reduced for 90 days, Bivo realized that, instead of the huge shipments they had planned on receiving, they would make smaller orders to combat the high tax. These tariffs pose a significant challenge for entrepreneurs, who have invested heavily in their businesses and would be devastated by failure. While small businesses like Bivo in the US faced difficulty, the tariffs have reached far beyond our borders as well.

The United States has been penalizing small developing nations, with two in particular standing out: Cambodia and Vietnam. The US imposed 49% tariffs on Cambodia and 46% tariffs on Vietnam due to trade imbalances between the US and these countries. However, this seemed illogical as these developing nations cannot afford goods made in America. Whilst these countries created goods that Americans bought for drastically cheaper prices. Cambodia is a significant manufacturer of garments and footwear, allowing Americans to access their favorite brands, such as Nike and Gap. It seemed strange that Cambodia was faced with a substantial tariff, considering it is a much smaller nation in Southeast Asia. These tariffs significantly

[84] Narine, Shaun, "Is Donald Trump doing the world a favour by isolating the United States?", https://theconversation.com/, May 20, 2025.

damaged Cambodia's trade, as the US was one of its largest trading partners. In 2024, the United States accounted for 37% of Cambodia's total exports. After these tariffs were imposed, a million garment workers feared for their jobs. These tariffs added a further layer of strain to the relationship between Cambodia and the United States, which did not help either nation.

To reach a compromise, Cambodia was compelled to make several concessions. This was highly challenging for Cambodia, as they are a small nation that cannot offer America anything significant in return. Additionally, Cambodia has felt the need to "Express our appreciation to President Trump and to the U.S", Deputy Prime Minister Sun Chanthol says, as they cannot say anything that would upset America in this time of turmoil. This signifies Cambodia's apprehension of America, as Cambodia relies on American business. To reduce the tariffs imposed by the US, Cambodia has eliminated all tariffs with the US from a 35% level and purchased 10 Boeing 737 Max 8 planes. They have also pledged to crack down on shipments from China to Cambodia that are then sent to the US to avoid tariffs. This trade war has not helped Cambodia in any way and makes them feel extremely vulnerable in the process, as they are a small country that was made to face a global superpower.

Vietnam is a larger country than Cambodia; however, that does not mean that these tariffs have a lesser impact on it. Vietnam was the world's sixth-largest exporter to America, and exports to the US have historically been its largest market. In 2024 alone, exports to the United States made up 28.7% of Vietnam's GDP. When cancellations of orders took place, it sent the Vietnamese into a panic as they risked job losses. Vietnam has arguably been the most affected Southeast Asian country, as it exported a significant amount to the US and had many corporations begin manufacturing there, as opposed to China. Following the US imposition of high tariffs on China, numerous enterprises began manufacturing in Vietnam, as it was a nearby and a cost-effective alternative. Vietnam has not had a straightforward time navigating through the current tariffs; however, Vietnam has begun diversifying its export markets and positioning itself as a long-term alternative manufacturing hub.

**American Tariffs Are Positively Influencing China**

China is becoming increasingly viewed as an alternative leader, as they have been remarkably stable throughout this period. China's policy has remained consistent, with the same leader, Xi Jinping, in power for the past 12 years. In contrast, America's presidents shift semi-frequently, and their policies change with them. "The U.S. is helping China to increase its global influence. China may suffer economically because of the tariffs, but politically, China is gaining more sympathy and more support from other countries, and not just in the Global South," Xinbo Wu said, who is the dean of the Institute of International Studies at Fudan University in Shanghai. This proves that the US is distancing itself from other countries, allowing China to pounce and create alliances. China has begun expanding and investing in the construction of roads, ports, and railways across all continents to promote global trade and economic growth. These advancements in globalization on China's part have prompted people to ask if China is the leader we require, as the US is embracing protectionist values.

China has recognized the US's flaws and is capitalizing on its weaknesses. China has invited many world leaders to a summit in Beijing to discuss the U.S. tariffs. At that summit, they plan on hosting a military parade. This parade is intended to commemorate China's victory over Japan in World War II. However, Chinese leader Xi Jinping has scheduled this summit to coincide with the parade, showcasing China's advanced weaponry and its formidable military. They are also displaying the weaponry "That China has developed for a potential war against the U.S". Displaying that the US is not inherently the most powerful country in the world today, and implying that the US has been mistreating its foreign allies, and they will not stand for that.

China has taken a proactive stance in global exports and has become the largest global shipper since 2009. Since then, it has remained dominant even through uncertain and volatile international markets. For example, it had a trade surplus of one trillion dollars in 2024 alone. Since the US imposed tariffs, China's exports to the US have declined by 15%. However, China's export performance has improved globally, with the United States standing as a notable exception. China is a prime example of staying composed in challenging times, as it has anticipated this moment and is perceived as dominant in the eyes of the public. China has taken advantage of the US's negligence and has an extreme claim to become the next hegemon.

**Tariffs Effect On The US Global Standing and Uncertainty About China's Rise**

These tariffs have undoubtedly weakened the United States's global standing for a plethora of reasons. Firstly, they have undermined institutions that they themselves founded, such as the WTO. They have achieved this by undermining ideas they have introduced, such as non-discrimination and liberalism. The US has violated these core tendencies of the WTO by creating new barriers and intervening in global trade. Trump has also imposed different tariff percentages on countries, which suggests he is "picking favorites," a practice prohibited by the principle of non-discrimination. These are some of the WTO's regulations that Trump has disregarded, which demonstrates America's inconsistency, as it cannot be in accordance with the laws that it created.

America's standing as a global hegemon has also been challenged throughout this period, as the US has increasingly adopted protectionist principles. The US has pushed away its allies, namely Canada, Mexico, and the EU, which has temporarily inhibited global trade. However, these countries are forging alternative trade networks beyond the US, which will indubitably allow them to strengthen their economic position. China has also been a significant driver in these trade deals, particularly in the absence of the US. They have created multiple trade deals, such as the Regional Comprehensive Economic Partnership, or RCEP, which is the largest trade agreement in the world, accounting for around 30% of the global GDP. America's protectionist principles have moved it further away from trade, which has negatively impacted its worldview and stance in international trade.

Trump's Tariffs have certainly proven to countries around the world that the United States is not the superpower it once was. They signify that the US government is extremely chaotic and divided. This is demonstrated by the tension between the courts and the president, which must be

harmonious to run the country successfully. Trump appears to be extremely indecisive when it comes to the policies he implements. For example, he announced that he would impose a 145 percent tariff on China, and then, approximately a month later, he reduced the tariff to 30 percent for 90 days. He reduced the tariffs for a myriad of reasons; members of his own party were pressuring him, as they felt that these tariffs were negatively impacting Americans more than the Chinese. Businesses such as Apple, General Motors, and many agriculturalists pleaded with Trump to lower the imposed tariffs, as they would decimate their profits. These domestic frustrations conveyed a message similar to that abroad. Trump has given no benefit to his allies with these tariffs and has treated every country outside the US poorly. He forced the hands of many by using tariffs as a negotiating tactic, which ultimately has pushed countries to become increasingly dependent on China.

However, countries remain uneasy about their relations with China, as they appear to lack transparency. Their economy and government appear to be closely intertwined with the Communist Party of China. Human rights concerns also prompt countries to steer clear of relationships with China. As the Chinese government has limited its citizens' rights and freedoms, which no possible hegemon should be doing. In previous years, China has also engaged in trade wars with other countries for brief periods, using tariffs as a negotiating tactic, such as placing tariffs on some Australian exports in 2020 after Australia called for an investigation into the origin of the Coronavirus. Illustrating that China may not be a superior global leader to the United States.

**Discussion**

The United States' tariffs have not achieved the goals they were set to accomplish. They were created in an attempt to boost American exports and close the trade surplus with countries globally. However, these tariffs cast a negative view on America as a whole, as they led America to adopt protectionist values and appear hostile in the eyes of its allies. The tariffs compelled the US to adopt protectionist policies, as they significantly hindered international trade by imposing global tariffs. The tariffs detrimentally affected the US's political standing, as they signified that the United States no longer prioritizes its allies' economic growth and instead focuses on its own interests. Economists have been carefully researching economic development and the decay of economies under tariffs. Although the tariffs are relatively new, economists have noted that they are harmful to many countries' economies, as they are no longer able to trade on the same scale with the US as they previously did. These tariffs have not played out as the US had intended, as they have damaged the United States' reputation globally and made it seem to be an unreliable trading partner.

The government of the United States has phrased the tariffs as a way to generate revenue. The tariffs have yielded revenue, but they have isolated the US from countries around the globe. Therefore, there is one central question to ask: Does the negative impact of the tariffs globally outweigh the revenue they have brought in? There is no short answer to this question, as it all depends on one's perspective, since the tariffs have both positive and negative aspects. They have

undoubtedly helped lower the US federal deficit and lower income taxes; nevertheless, they have raised prices for consumers, which offsets some of the positive features they yield. This plan is challenging because it redistributes taxes from wealthier Americans to impose additional constraints on more marginalized Americans. It is difficult to say whether these tariffs will remain in place for much longer; however, they should not, as they have a more negative impact on individuals and harm America's global reputation, outweighing any potential short-term benefit.

**Conclusion**

The tariffs have not inherently accomplished their intended goals, as they planned to lower the federal debt, promote American industries, and generate revenue. However, the process of achieving their conscious goal has not been as streamlined as was expected. The tariffs pushed allies away and weakened the global standing of the United States from the viewpoint of the rest of the world. Therefore, US allies have also been drawn towards China as a result of the tariffs, as China has remained a stable country in comparison to the US's ever-changing policies. These tariffs have helped China tremendously in that regard, as they have gained political influence as global powers no longer want to deal with the United States and are looking for a new hegemon to depend on. The tariffs have damaged the United States, as it no longer appears to be a dependable hegemon and will have to reestablish itself as a global superpower, which will be an extremely tedious task.

Public opinion documents demonstrate that the average person, in the US and internationally, views these tariffs negatively. In the United States, the average person dislikes that the tariffs have forced them to incur a higher price on necessities, while also affecting marginalized Americans extremely unfavorably. The tariffs have a more severe impact on the underprivileged, as they increase poverty. The effects of the tariffs not only impact people domestically but also have a global impact. The tariffs have been portrayed in a disadvantageous light, suggesting that the US prioritizes its own interests over those of nations that were once its allies. The tariffs demonstrate that economic strength and global credibility are interconnected; isolating oneself from allies and embracing protectionist values for gain will, in turn, harm one's own international standing.

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**An Exploration into Gershwin's Compositional Fusion of Jazz and Classical Idioms**
**By Alfie Holuigue**


## Abstract

Written during the early 20th century, George Gershwin's *Rhapsody in Blue* was a piece of music that refused to sit neatly within either the jazz idiom or the traditions of Western art music; Gershwin instead chose to craft a unique musical language in which the two were fused. For instance, blue notes are treated not as fixed elements of a pentatonic-derived system but as chromatic inflections within a fundamentally heptatonic framework; syncopation, moments of improvisatory flair, and other aspects are elevated from their American popular-music context and integrated into the thematic and structural logic of a symphonic work. What emerged was a unique conception of musical fusion that reveals how Gershwin understood jazz as a language capable of expanding the expressive and formal possibilities of Western art music.


## Introduction & Historical context

On February 12, 1924, George Gershwin's *Rhapsody in Blue* (*RiB*) premiered at New York's Aeolian Hall, performed by Paul Whiteman's orchestra with Gershwin himself playing the piano (Waters, 1947). The concert, titled *An Experiment in Modern Music*, was intended to showcase and legitimise jazz music within an orchestral setting for mainstream, upper-class concert audiences accustomed to western art music (WAM). After all, jazz was becoming increasingly popular and was seen as a deliberate departure from European classical conventions. Additionally, jazz, which emerged from African American communities in the early 20th century, was often marginalized and not initially regarded as a serious or respectable art form by mainstream audiences (Gioia, 2011). Alternatively, Gershwin was a white composer engaging with a musical tradition which was not his own, and so it was unexpected that *RiB,* written in merely 5 weeks, would become one of the most influential and groundbreaking compositions of the 20th century (Pollack, 2006).

Born in Brooklyn, 26 September 1898, Gershwin first picked up piano in 1910 and shortly after was accepted as a pupil by Charles Hambitzer—piano teacher, performer, and composer who would classically train Gershwin in the years to follow (Crawford & Scheider, 2013). Through this, Gershwin developed an understanding of WAM traditions, such as its form, orchestration, and thematic development up until age 16, when he began his apprenticeship "plugging" songs for the Remick Publishing Company in Tin Pan Alley—a musical publishing district in New York (Campbell, 1954). A song plugger's role was to play and promote songs to performers, publishers, and the public; thus, Gershwin not only enhanced his skills of composition and performance, but also gained a unique insight into the distinct musical elements of American popular music, including the emerging jazz scene and its increasing importance during the early 20th century. After leaving Remick & Co., Gershwin brought his skills to Broadway, producing songs such as *Fascinating Rhythm* and *Oh, lady, be good* which would go on to become music of the jazz standard repertoire (Crawford & Scheider, 2013). Through

Gershwin's unique experience being classical trained with Charles Hambitzer, plugging songs in Tin Pan Alley, and writing songs on Broadway all set against the backdrop of the burgeoning jazz era, he developed an idiosyncratic ability to integrate elements of jazz—those associated with informal, improvisational contexts that frequently eschewed the foundational strictures of WAM—into WAM forms.

It was in *RiB* in which Gershwin first sought to bring jazz into the formal world of WAM and "kill the misconception" that "jazz was supposed to be in strict time" (Gershwin, G. as cited in Schiff, 1997). The piece was a huge success, receiving critical acclaim and inspiring a wave of creativity among American composers, such as Aaron Copland and George Antheil, who were influenced by the fusion of "European orchestral forms" with "jazz infected rhythms and harmonies" (Allen, 2004). Indeed, throughout literature, there is no doubt that the piece incorporated Conventions of WAM and early 20th century jazz; further, there is no question that *RiB* represents a fusion of WAM traditions with jazz music from the early 20th century. However, while previous research has highlighted the work's use of jazz elements or its use of WAM traditions, few have explained *how* Gershwin achieved a *fusion* of these elements. Thus, this essay will analyse the technical aspects of the piece, in particular Gershwin's use of scales, rhythm, harmony, and form, to argue that Gershwin's approach to composition in *Rib* was not simply cherry-picking techniques from jazz or classical styles, but deeply fusing them into his personal musical conception.

**Definitions: Early 20th-Century Jazz and Western Art Music**

Today, Jazz remains exceptionally and controversially difficult to define. *Three Approaches to Defining Jazz* compares definitions of 8 journalists and teachers, showing that there are several core technical aspects: the blues scale, syncopated rhythms, and extended tertian harmony, to list a few (Gridley, Maxham, & Hoff, 1989). Alternatively, Trumpeter Wynton Marsalis (2017) emphasises the socio-cultural dimensions of jazz and its manifestation in the practice of improvisation, the importance of swung rhythms, and the affective dimension of the blues (as opposed to a purely technical definition). Others may specify additional elements, noting other aspects such as jazz's cyclical harmonic structure (Ziporyn & Tenzer, 2011) or syncopation (Gioia, 2011). However, it must be remembered that the genre and its musical practices have evolved and developed throughout time, further complicating our definition of jazz. For instance, jazz in the early 1900s did not heavily involve swing to the extent it did by the 1930s (Gioia, 2011). Due to this historical relativity, I will compare only to jazz pieces from the early 1900s so we might understand Gershwin's own picture of jazz, rather than an understanding informed by decades of retrospection.

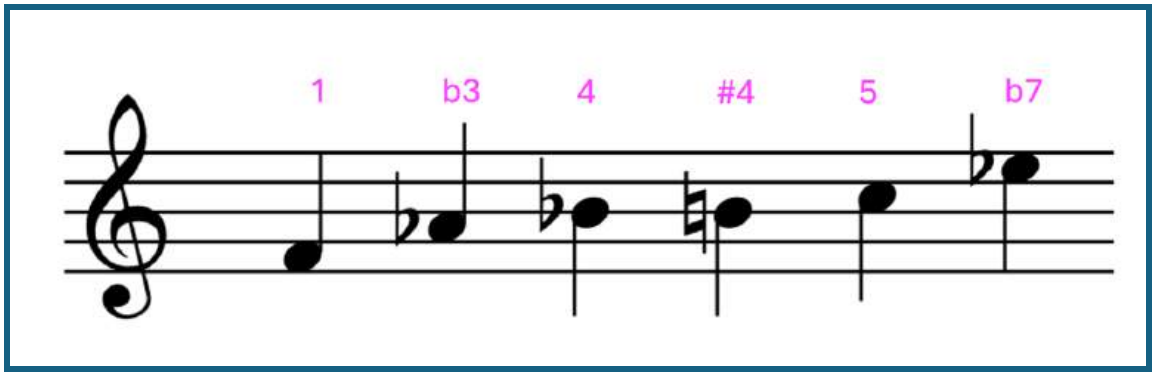
Alternatively, western art music (WAM) refers to the composed, notated musical practices that developed in Europe from the Medieval period through the 20th century, encompassing forms such as the Baroque fugue, Classical symphony, Romantic opera, etc. (Burkholder, Grout & Palisca, 2018). Despite its diversity, WAM is often characterised by several core conventions, such as its use of functional & primarily tertiary harmony, formal

structures such as sonata and rondo form where the development of thematic material is a central technique (Burkholder, Grout & Palisca, 2018). Additionally, variation techniques were a large aspect of both WAM and early 20th century jazz (see section 3.4). However, like jazz, WAM has evolved significantly over time; for example, the dissonant modernism of Schoenberg is a departure from some of the formal strictures of more traditional WAM, yet it is still classified as WAM. Therefore, in this essay, I will focus primarily on the late Romantic and early 20th-century pieces most relevant to Gershwin's context and the musical environment in which *RiB* was composed. In the following sections, I will examine the way that Gershwin uses the elements mentioned above, looking for ways they are fused with each other. Each element will be fully developed and explained in their respective sections.

**Fusion through Atypical Use of the Blues Scale**

A defining feature that illustrates Gershwin's fusion of aspects from the 1920's jazz genre with conventions of WAM is through his unconventional use of the blues scale. **Figure 1** shows an example of the F blues scale. In its simplest form, the blues scale is a six-note scale similar to the minor pentatonic scale but with the addition of a raised fourth. The lowered third and seventh are its distinctive characteristics and are commonly referred to as 'blue notes' (Levine, 1989).

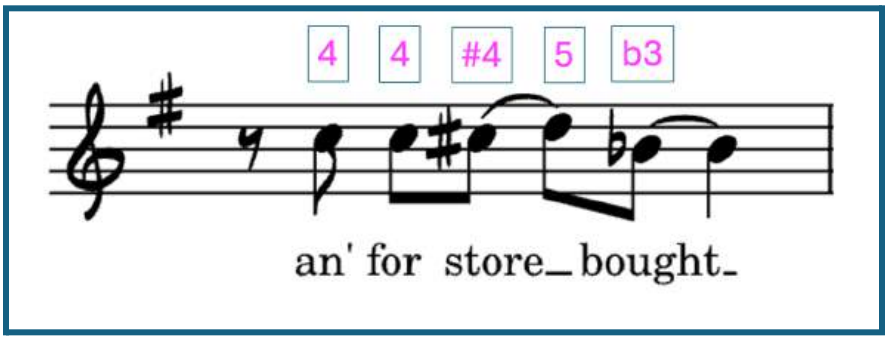
**Figure 1:** *F blues scale*




*Note.* Transcribed by author using Sibelius.

The blues scale played an indispensable role in shaping the melodic contours of early 20th century jazz (Gioia, 2011). **Figure 2** shows bar 24 of St Louis Blues by Louis Armstrong—a jazz musician whose virtuosic trumpet playing and improvisational style helped define the sound of early jazz (Gioia, 2011). This bar contains notes solely from the blues scale. Additionally, the #4 slides into the 5, which leads into the structural b3 (a defining blues note); as we will see, Gershwin frequently treats this scale degree instead as an auxiliary note to a natural 3, not present in Armstrong's playing.

**Figure 2:** *St. Louis Blues: Bar 24*




*Note.* Handy, W.C. (1914). Transcribed by James T. Bartlett (2022).

Throughout *RiB,* as can be inferred from its title, Gershwin used the blues scale extensively. **Figure 3** shows the melody of measures 2-5 of *RiB*, known as the "ritornello" theme (Schiff, 1997). Highlighted in pink are the 'blue notes' from the Bb blues scale—lowered third, lowered seventh, and raised fourth. These characteristic alterations define the blue scale and infuse the melody with the distinct sound of early 20th century jazz music. Of course, if we examine this excerpt from the perspective of its blue notes, this excerpt reveals characteristics strongly associated with jazz. Yet, Gershwin also incorporates a flat six and a major third in the melody. Typical blues usage would have avoided these notes, highlighting Gershwin's conception of the blues not as a pentatonic scale with an alteration, but rather as expressive chromatic alterations to the major scale. Thus, **figure 3** clearly shows that Gershwin's conception of the blues scale was not purely rooted in early jazz but rather a fusion with WAM's conception of scales as heptatonic.

**Figure 3:** *Rhapsody in Blue: Ritornello Theme: Bars 2-5*

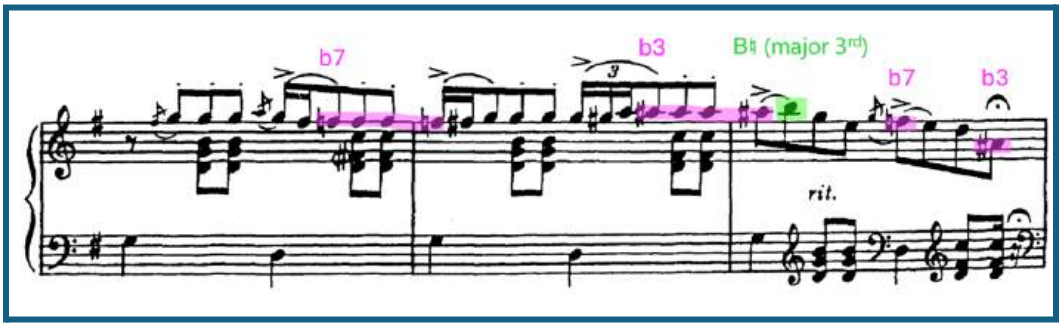



*Note.* Gershwin, G. (1924). Transcribed by author using Sibelius.

**Figure 4**, a variation of the "stride" theme (Schiff, 1997), is another example where Gershwin employs the blues scale into melody. Highlighted in pink are the 'blue notes' of the G blues scale, incorporating the lowered seventh and lowered third (although notated here as a different enharmonic spelling—raised second). The result is a melody that is clearly influenced by the popular music traditions of jazz. However, the fact that Gershwin uses a major third (B natural) here reinforces the argument of fusion. The lowered third here is used as a chromatic approach note to the major third, further evidencing Gershwin's conception of blues notes as alterations to the major scale, rather than as structural pitches, as shown in **figure 4**. Essentially,

Gershwin's use of blue notes throughout the piece reflects a major scale (heptatonic) conception, with blue notes as alterations, unlike many jazz musicians from the early 20th century who would have seen the foundation of the blues as related to the minor pentatonic scale with an additional chromatic note, and would thus avoid major thirds (Levine, 1989). Furthermore, Gershwin did not compose the piece in a traditional twelve bar blues format to which the use of the blues scale is deeply tied, thus further evidencing his atypical conception of the blues.

**Figure 4:** *Rhapsody in Blue: Stride Theme: Bars 1-3 after rehearsal mark 19*



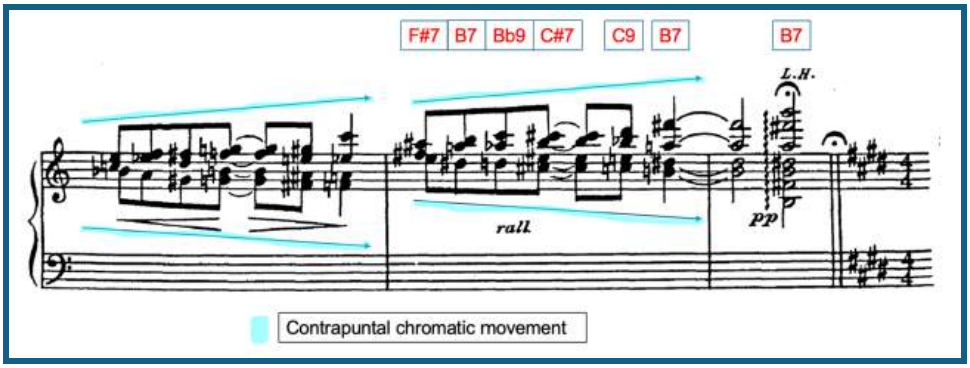

*Note.* Gershwin, G. (1924).

These examples show that Gershwin viewed the blues scale not as a fixed structure, but as a flexible set of chromatic alterations to the major scale. The blues was certainly a way for Gershwin to imbue jazz into a symphonic scene by evoking the expressive soundscapes characteristic of pioneering musicians from early 20th century jazz such as Louis Armstrong. However, rather than conforming to traditional blues forms or minor pentatonic roots, he used blue notes and inflections as expressive tools within a major scale framework, and thus embodied a stylistic fusion of a central element from early jazz with a foundational theoretical conception of WAM.

**Fusion through Harmonic Language**

Harmony throughout the *RiB* serves as another point of convergence between Gershwin's *RiB* and jazz music of the early 1920s. Harmony functioned as a defining characteristic of both WAM and early 20th century jazz, although each tradition took different approaches. This section will explore how Gershwin used various techniques such as extended harmonies, chromatic harmonies, chord qualities, and tertiary harmonies to neatly balance these two traditions in *RiB* and evince his hybrid approach to harmony.

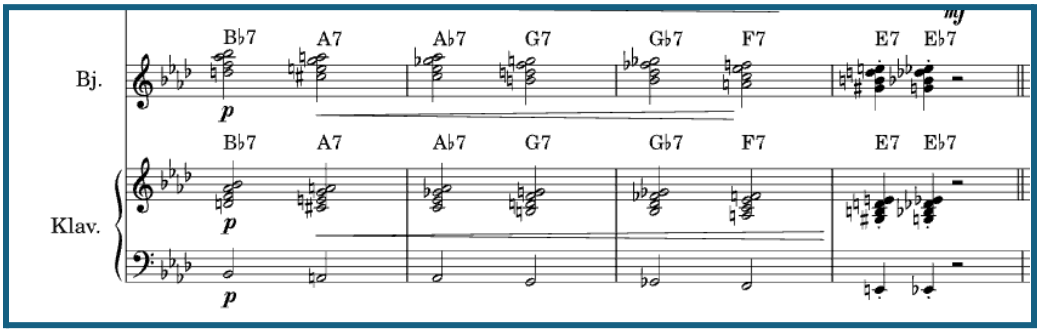
**Figure 5:** *Rhapsody in Blue: Bars 4-6 after rehearsal mark 27*




*Note.* Gershwin, G. (1924).

**Figure 5** illustrates a bridging passage from *RiB*. The way Gershwin moves from F#7 to B7 by sliding chromatically through dominant 7th chords is notably a reference jazz harmony, particularly as the music of early jazz musicians such as Jelly Roll Morton was "laced" with dominant seventh chords (Benward & Saker, 2009, p. 238). Furthermore, his practice of reharmonizing each note of the melody mirrors the arranging style of early 20th century jazz ensembles such as the Fletcher Henderson Orchestra (see **figure 6**). Yet, also evident in **figure 5** is harmony reflecting priorities of smooth, chromatic voice-leading, elements that reference a more contemporary style of WAM—at that time, twelve-tone serialism was emerging, with Schoenberg's highly chromatic work, such as *Verklärte Nacht (1899)* and *Pierrot Lunaire (1912)*, already influential (Burkholder, Grout & Palisca, 2018). **Figure 5** displays a clear chromatic descending bass note and the chromatic ascending melody line. Thus, from the perspective of voice leading, this passage also reflects the priorities of the highly chromatic music. Through this lens, we see the bridging passage represents not a direct reference to jazz or WAM, but a musical language informed by both.

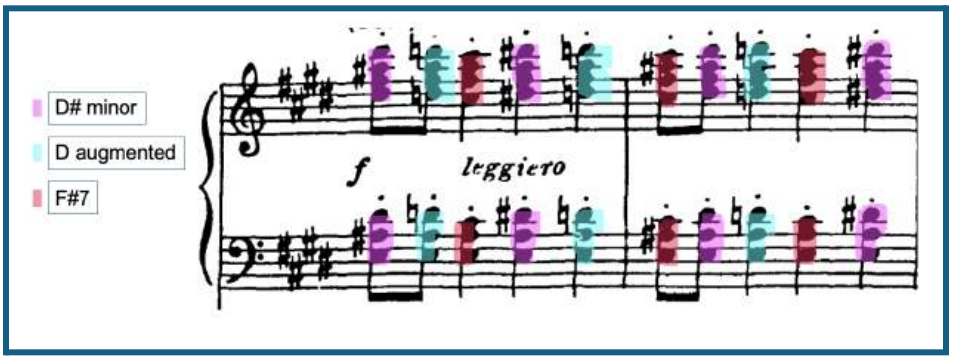
**Figure 6:** *The Stampede: Bars 163-165*




*Note.* Henderson, F. (2024). Arranged by Arnfried Oehme (2024).

**Figure 7** shows the "love theme" (Schiff, 1997). Here the chord quality moves from minor to augmented to dom7. The tension established from the chromatic movement between the extended chords displays Gershwin's jazz-rooted harmonic palette.

**Figure 7:** *Rhapsody in Blue: Love Theme: Bars 3-6 after rehearsal mark 30*




*Note.* Gershwin, G. (1924).

What evinces a WAM-influenced musical style here is the pianistic writing—the use of double-hand octaves in both the left and right hands, in harmonic and rhythmic unison evokes the texture and grandeur of Romantic piano concerti. **Figure 8** shows the love theme of *RiB* next to the opening theme to *Greig's Piano Concerto no. 1* to illustrate this similarity. Here both the left- and right-hand are played, by double hand octave, in harmonic and rhythmic unison. Here, Gershwin's switching chord qualities reflect jazz while the pianistic writing (and chromatic movement) reflects knowledge of symphonic orchestration priorities, thus reflecting a fusion of the two genres.

**Figure 8:** *Rhapsody in Blue: Love Theme (top): Bars 3-6 after rehearsal mark 30; Grieg's Piano Concerto in A minor (bottom): Bars 1-4*

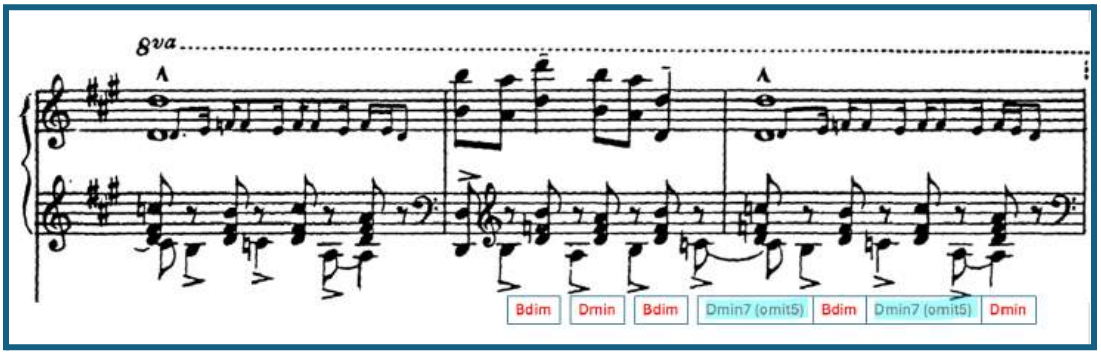



*Note.* Gershwin, G. (1924) (top); Grieg, E. (1868) (bottom).

Additionally, Gershwin's harmonic language through *RiB* can also often return to basic tertian structures—chords built on thirds—without relying on extended harmonies such as 9ths, 11ths, or other altered dominants common in early 20th century jazz. **Figure 9** shows where

Gershwin's harmonic language, only extended out to 7ths, is more reflective of WAM's standard chordal vocabulary.

**Figure 9:** *Rhapsody in Blue: Bars 10-12 after rehearsal mark 20*




*Note.* Gershwin, G. (1924).

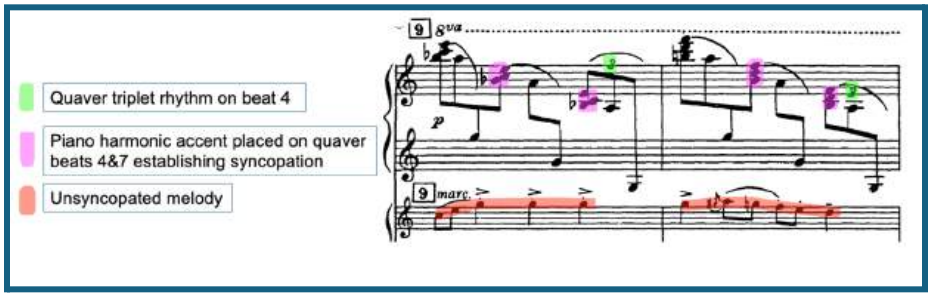
Taken together, these examples suggest that while *RiB*'s harmonic framework displays influence from harmonic language of jazz from the early 1920's, Gershwin's approach is also indicative of WAM influences, and thus reinforcing that Gershwin took a unique approach while composing *RiB*: emphasising the styles of both rather than conforming to one.

**Fusion through Syncopation and symbolic jazz references in a Symphonic Context**

Gershwin's fusion can also be seen in *RiB* through his extensive use of syncopated rhythms within the themes. Syncopation was becoming increasingly popular in the 20th century across a wide range of popular styles, particularly jazz, where its unexpected accents and off-beat phrasing symbolised a departure from the regular, metrical patterns of WAM (Gioia, 2011). As cited in Huron & Ommen (2006, p. 211), according to The New Harvard Dictionary of Music syncopation pushes against the metric framework of a piece of music through "contradiction" or "transformation" of the beat structure. Simply put, syncopation is the accentuation of weaker beats in a bar. What classifies Gershwin's approach as a fusion, and not just the incorporation/addition of jazz elements into the piece, is through Gershwin's elevation of these elements—such as syncopation and the "oom-pah" accompaniment—to structural prominence. By treating them as integral parts of the composition's themes within a symphonic context, the rhythms themselves become symbolic of jazz; Gershwin uses them to evoke jazz in the developmental arc of the composition and not simply for their danceable characteristics which made them so prominent in jazz, after all *RiB* was concert music, not for dance.

Throughout *RiB*, Gershwin frequently uses syncopation; **figure 10** shows the train theme (Schiff 1997), where accented beats—created through 3-note clusters and phrasing marks in a 3+3+2—are placed on quaver beats 4&7 thus establishing syncopation. However, at the same time, the trumpet plays an unsyncopated melody, thus fusing a jazz rhythm with a classical one.

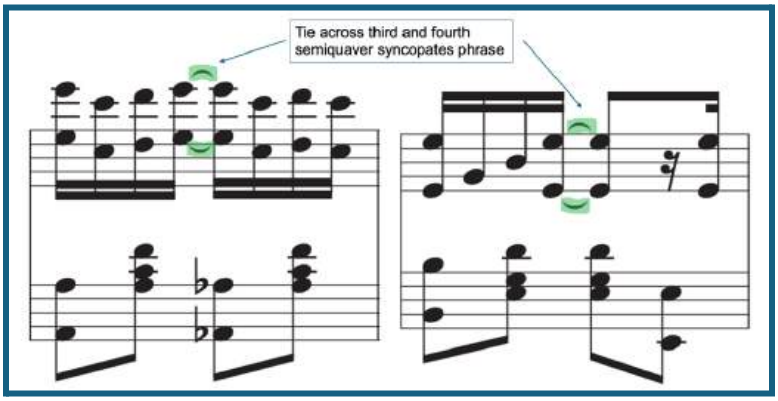
**Figure 10:** *Rhapsody in Blue: Train Theme: Bars 1-2 after rehearsal mark 9*




*Note.* Gershwin, G. (1924)

Additionally, Gershwin shows significant influence from ragtime musicians of the early 20th century, particularly through their rhythms. Often considered a precursor to jazz, ragtime is both closely related to the jazz idiom and distinct from it (Berlin, 1980). Both styles share various rhythmic innovations—particularly its emphasis on syncopation—and ragtime laid important groundwork for the development of early jazz. **Figure 11** shows *The Entertainer (1902)* and *Maple Leaf Rag (1899)* by African American pianist and composer Scott Joplin, one of the pioneering figures of the ragtime genre (Salazar, 2020). By tying the 4th semiquaver over the stressed halfway point in the bar, Joplin creates a durational accent in a weak part of the bar and thus syncopates the phrase. Additionally, this rhythm is considered a traditional "ragtime rhythm" due to its ubiquity in ragtime compositions of the early 1900s and, subsequently, in the playing of jazz musicians of the early 20th century (Emmert, 2019).

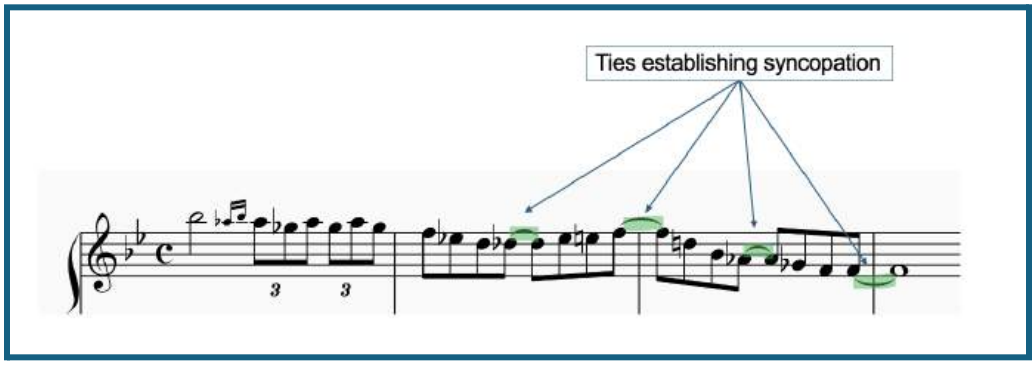
**Figure 11:** *The Entertainer: Bar 18 (left); Maple Leaf Rag: Bars 4 (right)*




*Note.* Joplin, S. (1902) (left); Joplin, S. (1899) (right)

A notable example of this specific "ragtime rhythm" occurs in the ritornello theme, shown in **figure 12**, where Gershwin syncopates the rhythm by using ties across on the second quaver of beat 2. Additionally, Gershwin places a tie on the final quaver beat leading into the first beat of the subsequent bar. This syncopation invokes a lively syncopated feel associated with earlier ragtime and thus further reveals jazz's influence on *RiB*.

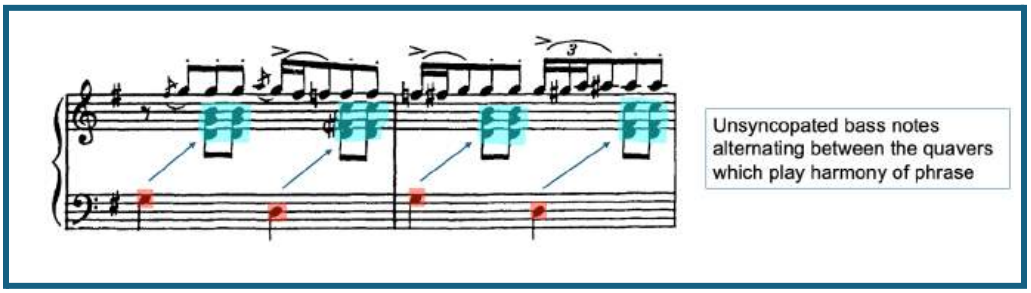
**Figure 12:** *Rhapsody in Blue: Ritornello Theme: Bars 2-5*




*Note.* Gershwin, G. (1924). Transcribed by author using Sibelius.

Gershwin also used an accompanying "oom-pah" rhythm, which describes the left-hand alternating between a bass note on the strong beat ("oom") and a high-register harmony on the weak beat ("pah") to emulate the rhythmic drive and percussive feel of a marching band or early New Orleans-style jazz ensemble accompaniment (Berlin, 1980). The oom-pah rhythm accompaniment texture, used frequently in popular music styles of the early 20th century such as jazz, stride, and ragtime, provides the harmonic foundation for the right hand's melody. Gershwin would employ it himself throughout *RiB*; for example, **figure 13** shows the "stride" theme (Schiff 1997), where the accompaniment texture's incorporation into a main theme elevates it to a structural component of the theme.

**Figure 13:** *Rhapsody in Blue: Stride Theme: Bars 1-2 after rehearsal mark 19*




*Note.* Gershwin, G. (1924).

Through Gershwin's use of syncopation and other jazz-informed rhythms we see clear inspiration from early jazz pioneers like Scott Joplin and alignment with the jazz genre of the early 1920's. His use of rhythmic displacement, ties, and the "oompah" accompaniment texture help capture the essence of jazz in the early 20th century, whilst the incorporation of the overt syncopation as a structural component of the themes within *RiB* shows Gershwin fusion of jazz and WAM.

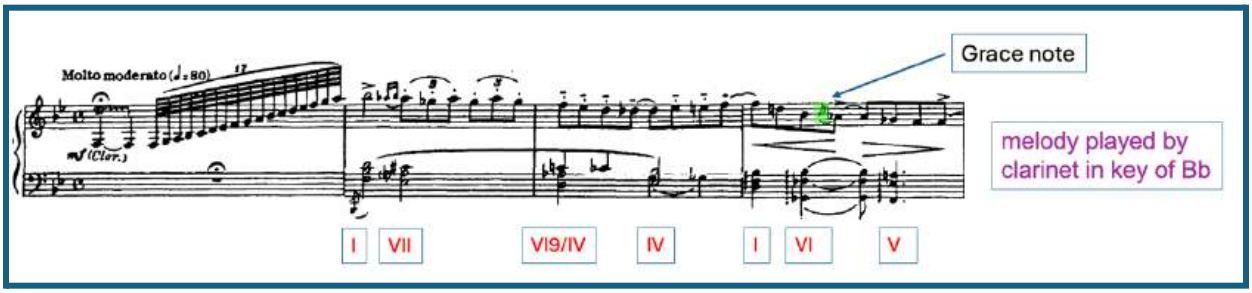
**Fusion through Variation Techniques from Jazz and Western Art Music Traditions**

Gershwin through *RiB* employed variation strategies from both early 20th century jazz and WAM. Variation strategies from jazz often include reharmonisation and improvisatory embellishments, but in a cyclic context (Ziporyn & Tenzer, 2011). Alternatively, variation strategies from early 20th century WAM relevant here are the freedom to develop themes motivically (not in a cyclic context, yet still structured), and the continued importance of tonal development though the movement of key centres—a key aspect of thematic development strategies in WAM (Burkholder, Grout & Palisca, 2018).

The structure of *RiB* is "free form" (meaning it doesn't adhere to traditional forms such as ABA or a sonata) yet loosely structured around 5 main themes plus a "tag" (Schiff 1997). Each of the themes relate to each other and show a high degree of knowledge in musical transformation/developmental techniques; for instance the "shared tonality and structure" between the Stride and Train themes may even encourage listeners to hear them as variants of each other rather than as distinct themes (Schiff, 1997, p. 20). Each time one of the themes reappears, Gershwin employs combinations of these variation strategies; the following analysis will show that this was not simply to avoid repetition, but to develop the material in a way that illustrates the fusion of elements of early 20th century jazz and WAM.

**Figure 14** shows the ritornello theme. When it is first played at the very beginning of *RiB* the texture is sparse. The melody is played in the key of Bb by the clarinet with a chromatically descending harmonic accompaniment.

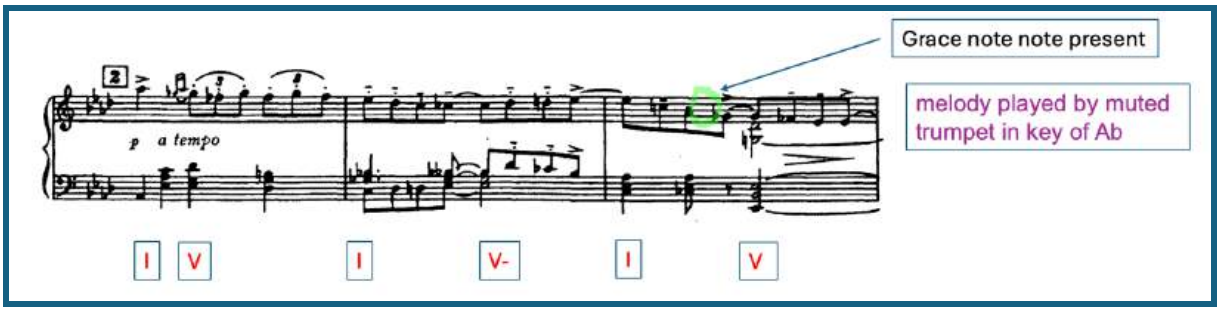
**Figure 14:** *Rhapsody in Blue: Ritornello Theme: Bars 1-4*




*Note.* Gershwin, G. (1924).

**Figure 15** shows the second time the theme returns. Here, Gershwin changes the key to Ab (a tone down), not a change that would happen within the fixed harmonic framework of a classical chorus; yet the variation through reharmonization is more indicative of jazz. Additionally, the written ornamentation is different—the third bar removes the grace note present in the first statement, suggesting the flexibility of jazz interpretation despite the fully-notated score. Simultaneously, the instrumental choice of a muted trumpet to play Gershwin's orchestration of the theme suggests symbolic thinking—by using the muted trumpet, he evokes jazz due to the instrument's ubiquitous usage in early 20th century jazz contexts (Tirro, 1993).

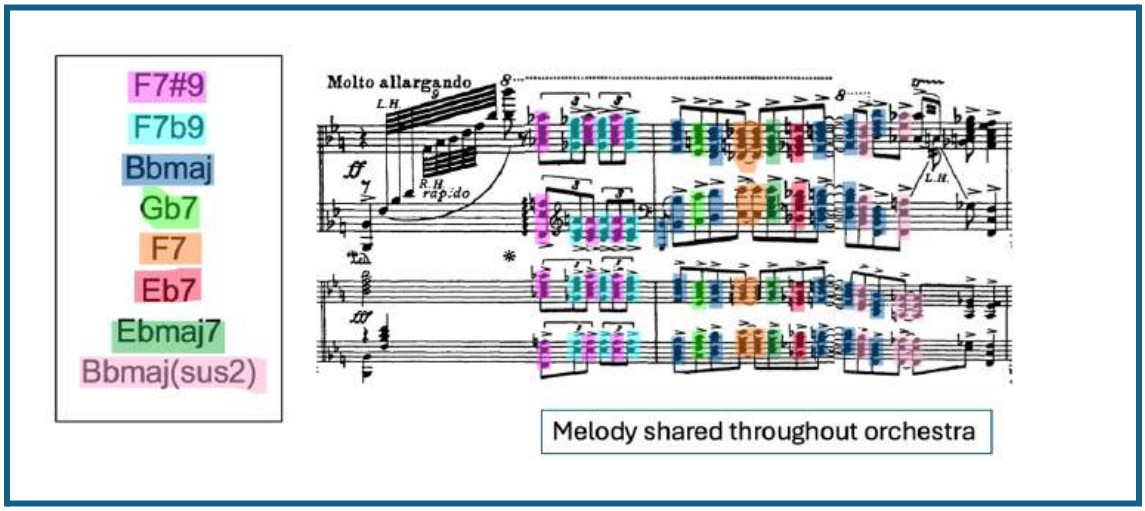
**Figure 15:** *Rhapsody in Blue: Ritornello Theme: Bars 1-3 after rehearsal mark 3*




*Note.* Gershwin, G. (1924).

**Figure 16** shows the finale of *RiB,* another variation of the ritornello theme. Here, the theme is presented by the full orchestra: What was initially a sparse, clarinet-led line now has this rich, layered orchestration which instantly evokes a symphonic atmosphere. Additionally, each note is harmonised with distinct harmonic constructs reflective of jazz bands as mentioned in section 3.2. In a jazz setting, this rich orchestration would happen in a cyclic framework, either the initial statement of a chorus or in a unison declamation after cycles of solo improvisation (Ziporyn & Tenzer, 2011). Instead, while this theme has a 16-bar AABA structure common in jazz, its treatment here achieves its climactic intensity through contrast with the other themes and the eventual triumphant return of this melody in the finale of the piece (see **figure 16**). This climactic restatement exemplifies Gershwin's fusion of jazz and classical traditions—combining the improvisatory spirit and rhythmic drive of jazz with the orchestral grandeur characteristic of symphonic music.

**Figure 16:** *Rhapsody in Blue: Finale: Bars 2-4 after rehearsal mark 40*




*Note.* Gershwin, G. (1924).

In conclusion, a method Gershwin uses to achieve fusion in *RiB* is through using jazz variation techniques—ornamentation, reharmonisation, and symbolic instrumentation—

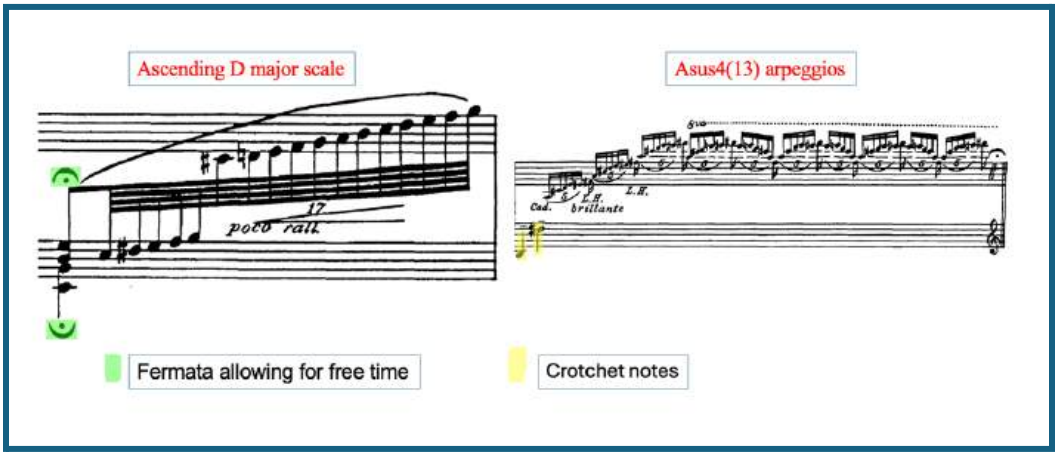
alongside the variation techniques of WAM—its change of key centres, thematic contrast, symphonic development, and its non-cyclical structure.

**Fusion through Approach to Improvisation**

An interesting aspect of the *RiB* is that, as he wrote it during a period of only 3 weeks, Gershwin chose to partially improvise his piano solo and leave sections of the score blank, which he would cue in and out with a head nod to the conductor (Pollack, 2006). Improvisation, although existing in many musical genres, plays a significant role in evoking the spirit of jazz in *RiB*. At the time, improvisation was not just a stylistic choice but a structural and expressive one—musicians of early 20th century jazz routinely created spontaneous variations over recurring chord progressions and melodic frameworks, often competing or collaborating in real time (Berliner, 1994). Gershwin's decision to improvise, and his incorporation of improvisatory elements mirrors this culture, particularly the role of the piano soloist in jazz bands as a melodic voice. Therefore, *RiB*—particularly in the piano solo sections—is imbued with the improvisational characteristics of pianists such as Art Tatum from early 20th century jazz, who would embellish written themes with virtuosic flourishes and rhythmic displacements.

**Figure 17** displays two rhythmically free cadenzas played during the piano solos of *RiB;* The first features a rapid ascending D major scale, while the second explores sweeping Asus4(13) arpeggios. The quaver and crotchet notes at the beginning liberates the pianist from any strict timing, alternatively pianists such as Art Tatum play these kinds of flourishes, but in a strict timing context (**figure 18**).

**Figure 17:** *Rhapsody in Blue: Bar 9 after rehearsal mark 4 (left); Rhapsody in Blue: bar 1 after rehearsal mark 27 (right)*




*Note.* Gershwin, G. (1924).

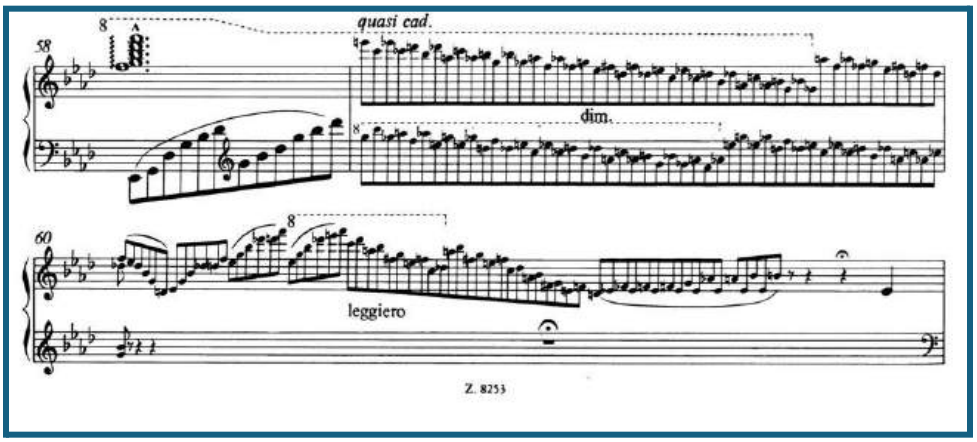
**Figure 18:** *Ain't Misbehavin': Bars 4-5*




*Note.* Tatum, A. (1986). Transcribed by Jed Distler.

Fusion is evident in Gershwin's approach to improvisation since he adopts Tatum's signature flourishes here, using them as moments to show virtuosity, but takes them out of the strict timing context of Tatum's playing, thus also evoking the impressionistic work of composers such as Liszt who instead use such flourishes as colouristic devices which were written out, rather than as shows of virtuosic improvisation ability (see **figure 19**).

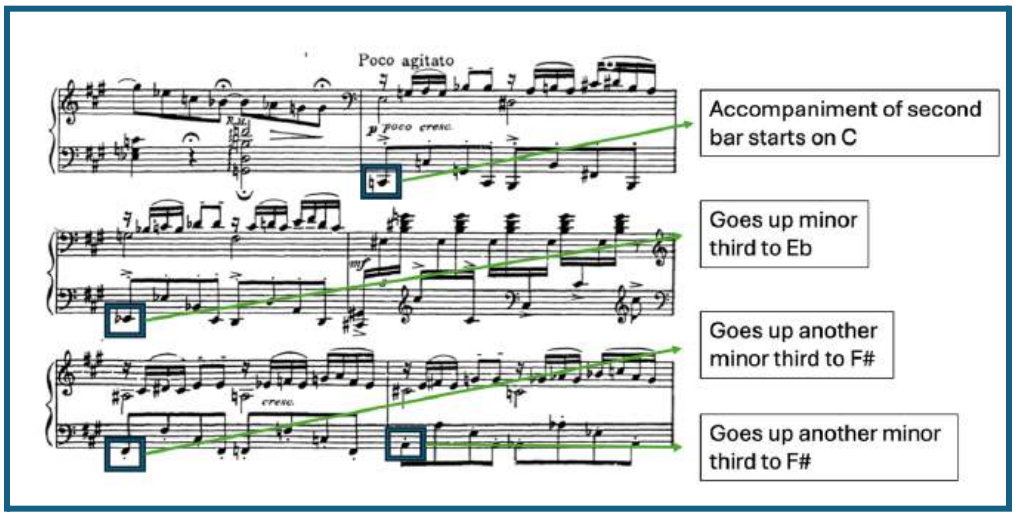
**Figure 19:** *Liebesträume No. 3: Bars 58-60*




*Note.* Liszt, F. (1950).

Additionally, in the piano solos Gershwin adjusts the harmonies to suit the tonal development of his motifs; for instance, transposing the Tag theme by minor thirds (see **figure 20**). His steady left-hand accompaniment shows the influence of stride piano greats like Tatum, while his harmonic choices reflect the tonal freedom of WAM traditions from the early 20th century, rather than the fixed harmonic framework of a jazz chorus.

**Figure 20:** *Rhapsody in Blue: Bars 9 14-18 after rehearsal mark 5*




*Note.* Gershwin, G. (1924).

Through this we see that Gershwin's use of improvisatory elements in *RiB* was both a way for Gershwin to incorporate a defining feature of jazz whilst still being deeply representative of a fusion with WAM

**Conclusion**

Ultimately, Gershwin's *RiB* embodies a stylistic fusion of elements from both the early 20th-century jazz idiom and WAM conventions through at times treating jazz elements through the lens of classical technique and at other times interpreting classical conventions in a jazz-influenced manner. Gershwin's use of the blues both equally alludes to one of the defining features of jazz with WAM conventions—using the pentatonic-derived blues scale while doing so within the heptatonic major scale fundamental to WAM's conceptions. Similarly, Gershwin's approach to harmony—employing jazz enriched harmonies enriched with chromatic voice leading—neither directly references jazz or WAM. Additionally, its improvised character, thematic development strategies, use of syncopation may all be distinct elements of jazz, but they are all equally informed by WAM traditions such as simple tertian harmony, smooth chromatic voice leadings, ornamentation, or its use of offbeat as a theme for its symbolism.

Essentially, the success of *RiB* lies not merely in the inclusion of identifiable jazz and classical elements, but in the deliberate and sensitive way Gershwin balances them to create a coherent musical language that honours both traditions. While features such as syncopated rhythms, blues-inflected melodies, and moments of improvisatory flair clearly reference early 20th-century jazz practice, these are not simply layered atop a symphonic framework. Instead, Gershwin embeds them within a context grounded in WAM conventions. What makes this fusion particularly effective is Gershwin's proportional representation of early 20$^{th}$ century jazz and

WAM—generally, not one is overshadowed by the other. This balance and distinct fusion accounts for why contemporary critics like Carl Van Vechten praised the work as uniquely 'American' and why *RiB* has continued to resonate as one of the most significant compositions from the 20th century. Ultimately, Gershwin does not dilute either tradition; instead, he allows them to converse, intertwining different elements to craft a stylistic fusion of elements from early 20th-century jazz with western art music conventions in *Rhapsody in Blue*.

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**Advancing Cancer Care: How Immunotherapy Improves Cancer Treatment Outcomes**
**By Kayal Balaji**


## Abstract

Conventional cancer treatments such as chemotherapy and radiation have struggled to handle advanced cancer cases, which has led to limited long-term success. Immunotherapy has emerged as a more effective alternative to empower the immune system to eliminate cancer, which has transformed the future. In some cases, it has surpassed traditional therapies such as chemotherapy and radiation, which have been long-established treatments. Immunotherapy boosts the body's own immune system to recognize and kill malignant cells. This paper examines two types of immunotherapies—immune checkpoint inhibitors and CAR T-cell therapies—that contribute to improved treatment outcomes as technology advances. The paper discusses how the immune system works, the main types of immunotherapy, their effects in treating cancer, comparisons with traditional therapies, as well as clinical outcomes and future directions. By exploring how these innovative treatments harness the body's natural defenses, this paper aims to highlight the significance of immunotherapy in revolutionizing cancer care.


## Introduction

In the United States alone, around 2 million people have been diagnosed with cancer, with prostate cancer being the leading cancer diagnosis among men and the second most common diagnosis, with around 300,000 cases (National Cancer Institute, 2024). Since cancer develops when the normal immune defenses fail to control abnormal cell growth, understanding how the immune system works is essential. The immune system is a complex network of organs and specialized cells that protect the body from diseases and germs that enter through the skin or other bodily openings (American Cancer Society). The immune response destroys any foreign substances that enter the body, as these pose a potential threat to the body. The immune system plays a crucial role in surveillance against tumors forming in the body. Immune surveillance is the immune system's natural defense against cancer and can detect and eliminate developing tumor cells (National Cancer Institute). It plays a protective role; however, cancer cells can adapt or edit themselves to survive through a process known as “immune evasion” (National Cancer Institute). Targeting immune evasion mechanisms is one of the most promising modern cancer treatments. Immunotherapy is currently used to treat various types of cancer, including melanoma, brain cancer, breast cancer, leukemia, lung cancer, and sarcomas (National Cancer Institute, “Common Cancer Sites”). This review will focus on the major types of cancer immunotherapy, including immune checkpoint inhibitors, CAR T-cell therapy, as well as other main types and their outcomes. Cancer types are constantly developing and vary in mutation rates, growth patterns, and evading immune detection.

When the body detects harmful invaders, the immune system initiates responses involving specialized cells and signaling molecules to prevent harm. The immune response can be divided into two categories: the innate immune response and the adaptive immune response.

The innate immune response is the first mechanism for host defense found in multicellular organisms. It is intended to prevent infection and attack any invading pathogens. This nonspecific mechanism takes effect much faster than the adaptive response, which takes longer. Unlike innate immune responses, adaptive responses are specific to the pathogen that induced them. It can also provide long-lasting protection. Sometimes our bodies' immune systems can be weak or not work properly compared to those of different individuals, which can create incorrect responses in our bodies. Some people could have genetic mutations that affect the immune system. Mutations that impair the immune system may increase a person's susceptibility to infections (Harvard Health Publishing). Unlike traditional treatments that damage healthy cells in the process of eliminating cancerous ones, immunotherapy works by powering the body's natural defenses to fight cancerous cells. In recent decades, immune checkpoint inhibitors and CAR T-cell therapies have emerged as especially promising.

Immunotherapy is a treatment that boosts our bodies' immune system to target, fight, and eliminate cancerous cells. Unlike long-existing treatments such as chemotherapy and radiation, which directly target cancer cells but damage healthy tissues in the process, immunotherapy has evolved recently as a safer and more effective approach by using the body's immune system, and can be more effective for a wide range of cancer types. Some of the cancers that are currently treated by immunotherapy include melanoma, brain cancer, breast cancer, leukemia, lung cancer, and sarcomas (National Cancer Institute, "Common Cancer Sites"). However, these cancers can often elude immune detection, which is where immunotherapy plays a crucial role (Yufan Lv et al.). It is important to understand individual traits to effectively apply immunotherapy. Studying prevalent cancers can provide a better understanding of how immunotherapies can overcome challenges to improve patient outcomes.

The immune system can destroy harmful cells, but cancer cells can block its attack and grow uncontrollably, causing it to be detrimental to the human body. However, immunotherapy helps the immune system recognize and destroy cancer cells more precisely, which allows for the treatment of many types of cancer. Each type of cancer develops differently. Different cancers have different treatment options, and each individual responds in unique ways to these treatments. Understanding the characteristics of various cancer types is important to identify novel traditional or immunotherapeutic strategies to improve outcomes. Examining cancers such as lung cancer, breast cancer, sarcomas, brain tumors, and types of leukemias displays how immunotherapy could be used to eliminate tumor-specific features such as affected antigens, high mutation rates, and mechanisms that allow tumors to evade the immune system, therefore, overcoming traditional treatments and shifting cancer care.

**Materials and Methods**

Research for this paper was conducted using peer-reviewed journals and medical organization websites published within the past ten years due to rapidly evolving and advancing sciences. Articles were accessed through databases and resources such as the National Cancer Institute (NCI), the American Cancer Society (ACS), Harvard Health Publishing, and the Cancer

Research Institute (CRI). Search terms such as ‘cancer immunotherapy’, ‘immune checkpoint inhibitors’, CAR T-cell therapy, immune system, and ‘immunotherapies’ were used to find accurate information. This paper focuses on the relationship between immunotherapy and cancer and its comparison to traditional treatments. Information from these sources was synthesized through the identification of repeated themes, comparing treatment outcomes, and analyzing key findings to compare similarities and differences among various studies.

## 1. Prevalent Cancer Types and Their Responsiveness to Immunotherapy

### 1.1 Lung Cancer

Lung cancer is a type of cancer that starts with the uncontrolled growth of cells in the lungs (Mayo Clinic). These two organs in the chest control our breathing system. People who smoke have the greatest risk of developing lung cancer, as it is harmful to their lungs. Men who smoke are estimated to be 23 times more likely to develop lung cancer than men who have never smoked. However, lung cancer can also occur in non-smokers, potentially due to a family history of the disease. Lung cancer in non-smokers could be due to genetic mutations or environmental factors such as exposure to radon, secondhand smoke, pollution, and certain workplace areas that contain pollution. Non-smokers can also experience a slower progression of lung cancer than smokers. Smokers, on the other hand, have higher tumor mutation burdens and different genetic profiles compared to lung cancers in non-smokers. Traditional treatments such as chemotherapy and radiation have limited effectiveness against advanced lung cancers, which can cause various side effects such as immunosuppression and risk of secondary cancers. This has led to increased exploration in the immunotherapy field, which has shown greater success in patients.

### 1.2 Breast Cancer

Breast cancer is the uncontrolled growth of cells in the breast tissue. While anyone can be susceptible to breast cancer, it most commonly affects women (Mayo Clinic). Breast cancer can spread, or metastasize, when the cancer cells get into the blood or lymph system and are then carried to other parts of the body. The lymph system is a part of our body’s immune system. In breast cancer, cancer cells can enter those lymph vessels and start to grow in the lymph nodes, gradually leading to loss of control over many bodily processes, such as immune regulation and metastasis control. Traditional treatments may fail to eliminate metastatic breast cancer or cause severe side effects, making immunotherapy a promising approach to effectively eliminate cancer cells.

### 1.3 Sarcomas

Sarcomas are a broad group of cancers that develop in bones and soft tissues such as fat, muscle, nerves, blood vessels, and tendons, which connect to and support various body structures (Mayo Clinic). Although they are less common than other types of cancers, sarcomas are challenging to treat due to their ability to arise in different parts of the body. Traditional

treatments may be limited by the tumor's location and heterogeneity in treating sarcomas, which has led researchers to explore immunotherapy as a way to enable the immune system to attack sarcoma cells more precisely.

### 1.4 Leukemias

Leukemia is a cancer of the body's blood-forming tissues. It primarily involves the white blood cells (Mayo Clinic). It is a type of cancer that starts in the blood and bone marrow, causing the body to produce abnormal white blood cells. Certain blood cells acquire DNA mutations, causing them to grow and divide uncontrollably, which leads to a buildup of abnormal cells in the bone marrow and bloodstream. Traditional treatments such as chemotherapy and bone marrow transplantation can be intense and cause significant risks, and are not always effective in preventing relapse. This has led to immunotherapies being explored for targeting leukemia cells. Acute Lymphoblastic Leukemia and Chronic Myeloid Leukemia represent two distinct types of leukemia that differ in progression and treatment response.

Acute Lymphoblastic Leukemia is a kind of blood cancer that occurs when the body produces an excessive amount of lymphoblasts, leading to improper function (Mayo Clinic). They grow rapidly and displace healthy cells that help our body fight germs, stop bleeding, and carry oxygen. This cancer is most commonly found in kids; however, adults can also be affected. Long-established treatments could be harsh and fail to prevent relapse, which has allowed for the exploration of immunotherapies such as CAR T-cell therapy and its ability to target malignant lymphoblasts.

Chronic Myeloid Leukemia (CML) is another type of blood cancer that occurs when the body produces too many white blood cells called myeloid cells (Mayo Clinic). These also grow fast and crowd out healthy blood cells in our bodies. CML grows slowly at first and occurs more commonly in adults. Some patients have been prone to developing resistance or relapse when committing to treatments such as tyrosine kinase inhibitors, which has led researchers to further investigate immunotherapy to effectively control chronic myeloid leukemia.

### 1.5 Brain Cancer

Brain cancer occurs when a growth of cells happens in the brain. Brain tumors can vary in size and cause symptoms in early stages or late stages, depending on their location in the body (Mayo Clinic). Metastatic brain tumors are dangerous since they can develop anywhere in the body and travel to the brain or spinal cord, causing serious side effects. Current treatments focus on slowing tumor growth and managing symptoms rather than curing the disease for very advanced cases. Conventional therapies have struggled to eliminate brain tumors and can instead damage surrounding healthy tissues. Thus, immunotherapy has been developing as a way to attack cancer cells while preserving normal brain function more precisely.

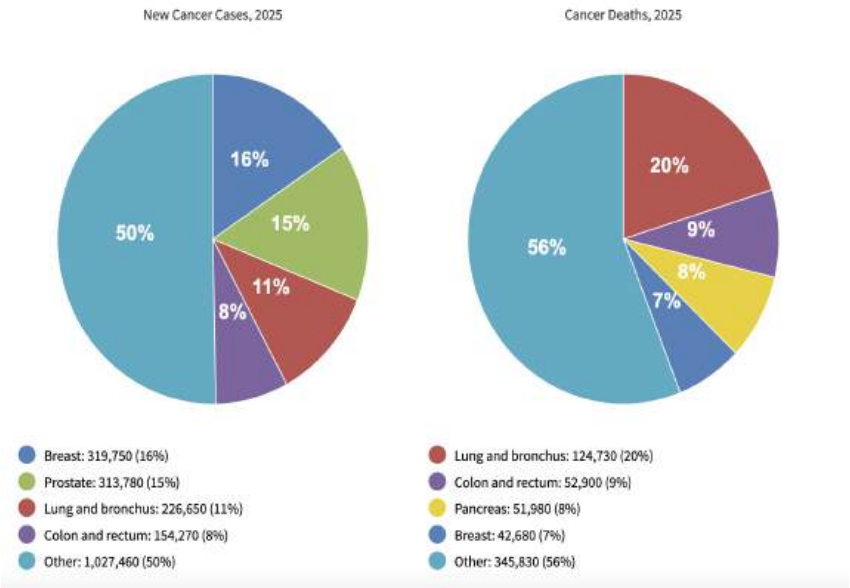



**Figure 1.** Common Cancer Sites in the U.S. Figure 1 shows the prevalence of the most common cancer types in the U.S. SEER Cancer Stat Facts (National Cancer Institute).

**2. Immunotherapies and their relation to cancer**

What if the key to preventing cancer within our bodies comes from empowering the body's own defense systems? The immune system can destroy cancer through mechanisms like the action of T cells and natural killer cells. The immune system is the system in our body that fights infections. It helps protect us from getting ill and aids in healing. Among these immune defenders, T cells play an important role by recognizing cancer-specific antigens and are key players. T cells have the potential to recognize and destroy cancer cells in specific ways by detecting antigens, which are unique proteins on the surface of cancer cells that differentiate them from healthy cells. Understanding interactions between the immune system and cancer allows for the development of immunotherapies and effective cancer treatments.

However, cancer cells can deceive the immune system into thinking they are healthy cells. One way is by overexpressing checkpoint proteins that inhibit T cells (Golden). This could ultimately lead the cancer to continue growing uncontrolled. Personalized cell therapy uses a patient's own T cells and modifies them to specifically recognize cancer antigens, which differentiate them from healthy cells. It is possible to modify the genetic makeup of immune cells in the lab to enhance their ability to recognize and attack different types of cancer, which allows the immune system to target tumors more effectively. Immune checkpoint inhibitors and CAR T-cell therapy aim to enhance the body's immune response to cancer through distinct mechanisms. The checkpoint inhibitors work by releasing barriers on immune cells, allowing them to recognize and target tumors effectively. Conversely, CAR T-cell therapy directly

engineers a patient's own T cells to attack cancer cells precisely. Understanding these therapies provides a framework for exploring their individual mechanisms.

### 2.1 Immune Checkpoint Inhibitors

Immune checkpoint inhibitors are a type of cancer therapy that uses monoclonal antibodies that block inhibitory signals of checkpoint proteins. Immune checkpoint inhibitors block these inhibitory interactions, which prevent cancer cells from sending "stop" signals to T cells, releasing the brake, allowing T cells to attack tumors. These act like switches to turn the immune response on or off, which exist to prevent autoimmunity, so that the immune system does not attack healthy cells. Checkpoint inhibitors help the immune system find and attack cancerous cells. Currently, some medicines target various checkpoint proteins to treat cancer. Currently, FDA-approved checkpoint inhibitor proteins include PD-1, PD-L1, and CTLA-4.

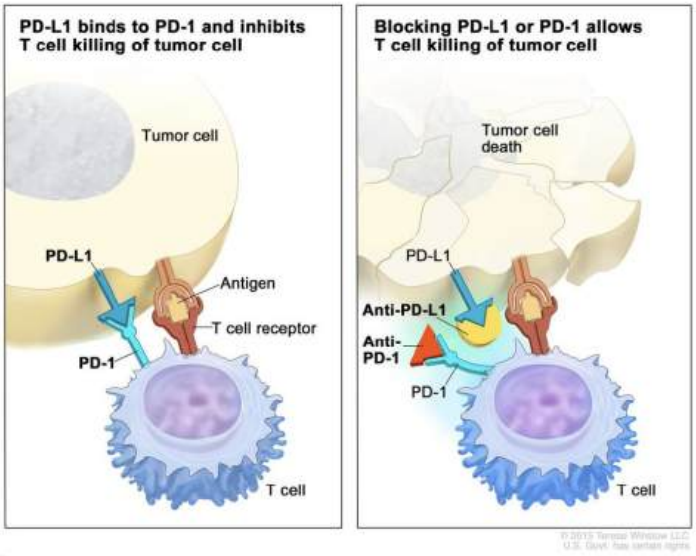



**Figure 2.** PD-1/PD-L1 Immune Checkpoint Pathway. As illustrated in Figure 2, blocking PD-1/PD-L1 interaction with inhibitors restores T-cell activity against tumor cells. (National Cancer Institute, 2022).

Monoclonal antibodies targeting these immune checkpoint proteins have been most notably successful in patients with metastatic melanoma, renal cell carcinoma, and non-small lung cancer (Shiravand et al.). However, not all patients respond well to the drugs because some tumors are not compatible with this type of therapy, which is where biomarkers come into play. To optimize the effectiveness of ICIs, biomarkers play a critical role in predicting patient response. Biomarkers are measurable signs in the body that help doctors predict if a patient will respond to a specific treatment given to them. A few examples of biomarkers for immune

checkpoint inhibitors include tumor mutation burden (TMB), PD-L1 expression, microbiome, hypoxia, interferon-γ, and extracellular matrix (ECM) (Shiravand et al.). Tumor mutation burden is a measure of how many genetic mutations are present within the DNA of cancer cells in a tumor. Thus, tumors with a higher TMB are more likely to respond to immune checkpoint inhibitors due to their ability to target, detect, and attack them. One important example is PD-L1 expression, which binds to PD-1 on T-cells, inhibiting their activity and preventing them from attacking tumor cells. This, in turn, helps maintain immune tolerance.

There have been many studies that have shown significant benefits of immune checkpoint inhibitors. For instance, Ji et al. (2024) reported that "Immune checkpoint inhibitors (ICI) treatment led to longer survival and better prognosis in terms of overall survival and progression-free survival compared with cytotoxic chemotherapy." Although research shows that immune checkpoint inhibitors help patients with non-small cell lung cancer and allow for better outcomes, there is limited information on the cost on a large scale.

**2.2 CAR T-Cell Therapy**

CAR T-cell therapy is a type of cell-based gene therapy that alters the genes in a person's T cells, which are a type of white blood cell, to help attack cancer cells. This treatment is helpful when other therapies don't work. CAR T-cell therapy has shown success in treating specific blood cancers such as acute lymphoblastic leukemia and types of non-Hodgkin lymphoma, as these cancers express well-defined target antigens such as CD19, which are easily accessible to circulating immune cells in the body's bloodstream. During clinical trials, many patients who hadn't properly responded to traditional treatments achieved complete remission after receiving CAR T-cell therapy, which means that all detectable signs of cancer had disappeared (June et al.). A crucial advantage is its endurance, as in some patients, as modified T cells remain active in the body for years and continue to recognize and destroy cancer cells if they develop again. They provide long-term immune surveillance, which can prevent relapse and reduce the need for further treatments. It's currently effective in blood cancer. This is due to the additional challenges that solid tumors bring in the process, such as physical barriers and heterogeneous antigen expressions, which make it harder for the modified T cells to eliminate cancer cells. However, ongoing research is expanding CAR T-cell therapy for solid tumors by improving tumor infiltration and improving their recognition of many tumor-specific antigens for its use in other types of cancer.

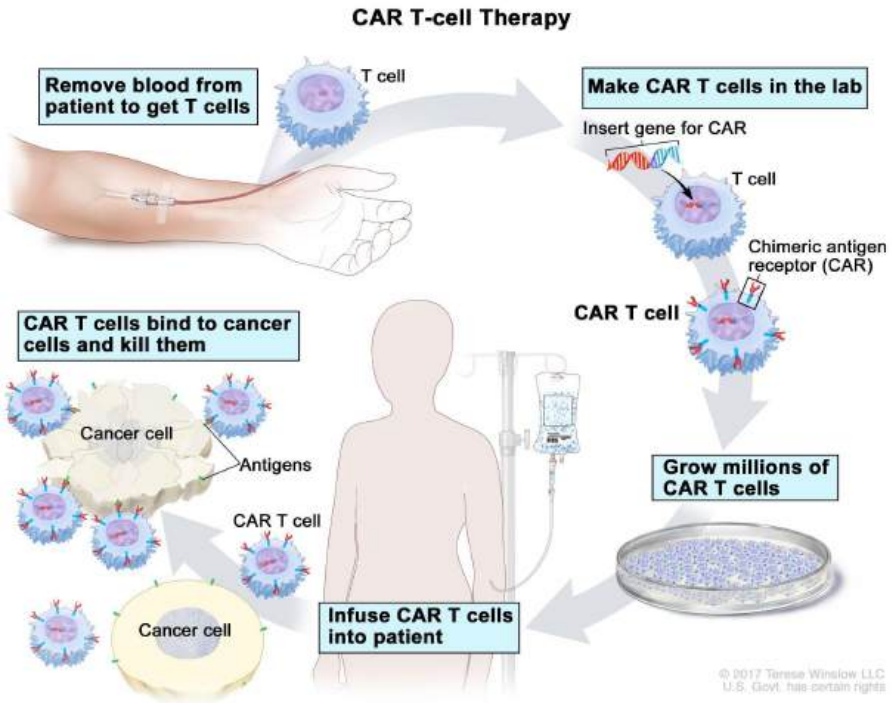



**Figure 3.** CAR T-cell Therapy. As depicted in Figure 3, the CAR T-cell therapy cycle involves how T cells are collected, engineered with a CAR, expanded, and infused back to target cancer cells. (National Cancer Institute).

CAR T-cell therapy is more expensive than immune checkpoint inhibitors. The average cost of CAR-T cells ranges from $300,000 to $475,000 due to the complexity of the manufacturing process (American Cancer Society). Along with this, there are additional hospital admissions, tests, procedures, and other expenses that could make CAR T-cells unaffordable for many. However, Medicaid, Medicare, and commercial insurance cover a portion of the cost. CAR-T cell therapy has had significant development in recent years, but it still faces challenges in terms of clinical application.

**3. The Impact of Immunotherapies in Clinical Trials and Current Use**

The clinical landscape of cancer treatment has been significantly reshaped by the widespread adoption of immunotherapies, particularly immune checkpoint inhibitors and CAR T-cell therapy. Immune checkpoint inhibitors (ICIs) have gained wide use across more than 20 cancer types. These include melanoma, lung, kidney, bladder, head and neck, and colorectal cancers. ICIs have led to long-term, successful responses in various patients who previously had hard-to-treat advanced cancers. Studies have reported sustained remission rates of around 20-40% in melanoma and survival rates in non-small cell lung cancer patients. ICIs have recently emerged as a basis of modern cancer treatment for many patients (Yufan Lv et al.).

CAR-T cell therapy has been used for relapsed or refractory blood cancers, including B-cell lymphomas, acute lymphoblastic leukemia, and other types of myeloma, like plasma cell leukemia. It has resulted in positive response rates and long-term remission in patients with intractable blood cancers. CAR-T cell therapy is expensive, limiting its availability (American Cancer Society). Due to challenges with target antigen expression on healthy cells and the complex tumor microenvironment, which consists of immunosuppressive cells and dense stroma that prevents T-cell infiltration, CAR T-cell therapy has shown limited success in solid tumors. However, ongoing research is working on overcoming challenges by enhancing CAR T-cell designs, such as improving their endurance in the body, enabling better infiltration into solid tumors, and resistance to immunosuppressive signals in the tumor microenvironment. Both CAR T-cell therapy and immune checkpoint inhibitors show many advances in immunotherapy, which represent the need for immune-based strategies to achieve long-term control and remission for many cancer types.

## 4. Discussion

Immunotherapy has transformed cancer treatment outcomes. Immunotherapies, such as immune checkpoint inhibitors and CAR T-cell therapy, have shown success in treating specific cancers, including blood cancers, acute lymphoblastic leukemia, metastatic melanoma, and non-small cell lung cancer, leading to long-term remission. These rapidly advancing immunotherapies have improved cancer treatments compared to long-existing treatments such as chemotherapy, radiation, and surgery, which have had limited effectiveness in treating cancer and cause severe side effects. Ongoing research is refining immunotherapy for many by improving patient selection through biomarkers to predict patient response, enhancing combination treatments with chemotherapy, targeted therapy, and radiation, and developing ways to overcome resistance mechanisms such as tumor heterogeneity and immune evasion pathways. Current research has focused on identifying new biomarkers, such as PD-L1 expression and tumor mutation burden, to detect early patient responses and further improve the efficacy of immunotherapy. Immunotherapy is developing to become safer, precise, and more accessible for all patients. High cost and limited resources for advanced treatments like CAR T-cell remain a challenge for universal accessibility. With further development, immunotherapy has the potential to achieve sustained remission in many cancer types and may provide cures, provided that research continues to ensure lasting outcomes.

## Acknowledgments

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**The Theoretical and Known Composition of a Neutron Star By Zara Yunus**


## Abstract

Neutron stars are one of the most mysterious objects in the universe. There have been thousands of observations and studies analyzing the structure of neutron stars, yet at the same time, little is definitively known. Some basic details, such as their formation, size, spin, and magnetic field, are understood; however, what do scientists know about their composition? The naive assumption that a neutron star is solely made up of neutrons is likely inaccurate due to the star's incredible pressure. While it's thought that there is a crystal lattice of naturally-occurring elements in the crust, the composition of the interior is virtually unknown. Hypothetical substances such as nuclear pasta, quark-gluon plasma, and strange matter have been theorized in order for scientists to create a plausible explanation for the composition, but there's no clear way to prove their existence. While the simple answer is we don't know, many of these theories could be true and are reasonable candidates for solving this mystery, which is what we'll review in this study.


## Introduction

Stars come in all shapes and sizes, vary in age, brightness and color. There are many types of stars in the observable universe from main sequence stars, to white dwarfs, to supergiant stars.

Neutron stars are some of the most extreme entities in the universe, with their extremely rapid rotation, exceptionally strong magnetic fields, and near-unquantifiable densities close to that of a black hole's (Moskowitz). Not much is known about the composition of neutron stars. Upon learning about neutron stars, you might think that they are solely made up of neutrons. However, because their gravity is strong enough to compress protons and electrons together, we can't assume that neutrons are able to survive the immense pressure in the centers of these stars (Moskowitz).

With the Neutron Star Interior Composition Explorer (NICER), scientists have been able to infer there is a crust, an outer core, and an inner core (Young). Although solid evidence suggests that there is a crystal lattice of iron nuclei in the crust and a sea of neutrons in the outer core, we can only guess what makes up the inner core, where properties are governed by incomplete theories. Physicists have used a combination of theoretical modeling and data from gravitational waves and sound waves to hypothesize the state of matter in the core; however, it remains uncertain (Han, LIGO Caltech). In this paper, I explore known and unknown information about neutron stars, describe their layers, and explain the theories we have on the composition of their mysterious inner cores.

## Formulation and Basic Properties

Most stars begin in a cloud of gas, known as a nebula, then are compressed into dense objects which will eventually begin to burn through nuclear fusion. However, neutron stars are

the aftermath of a supernova, created by the death of a supermassive star. Before a supermassive star dies, they begin fusing heavy nuclei in their core due to their lack of hydrogen and helium to burn. Once the burning in the core reaches iron, whose binding energy, the minimum energy required to separate particles in an atom, is too high to allow for any more nuclear fusion, gravity crushes the whole star. Then the star explodes, releasing much of its contents into space as the core collects into a dense entity (Alfredo).

The form of the entity depends on how massive the star was, and can go one of two ways: it can form into a neutron star or it can form into a black hole. Yet even though neutron stars are the less exotic afterlife of a supermassive star, they're still as mysterious and extreme.

With a radius of around 10 kilometers but a mass greater than our sun, a neutron star's crushing gravity creates immense density, varying depending on each of the four main layers (Miller). The outer crust's relative gravity isn't as dominating as the gravity in the core of the star, therefore its density only reaches about $10^7$ g/cm$^3$, or about ten thousand kilograms per cubic centimeter; however, it gets even stronger as you inch closer to the core.

Neutron stars also possess unmatched magnetic fields, averaging $10^{12}$ gauss, trillions of times stronger than Earth's, at which point atomic structure completely distorts. Particles under a $10^{12}$ gauss magnetic field drastically increase their ground state binding energy in order to prevent being smashed together, meaning the nucleus is tighter than normal and will take more energy to split apart (Miller).

**Outer Layers and Densities**

As previously mentioned, neutron stars don't have uniform density, rather each layer has its own level of pressure, which gets stronger closer to the core. Most studies show that the outer crust of a neutron core is composed of matter made up of neutrons, protons, and electrons, such as iron-56 nuclei formed into a crystal lattice a few hundred meters in depth. Pressure forces the atoms to ionize, in which case the nuclei and electrons separate, after which the electrons become degenerate and occupy every available energy state. Thermal and electrical conductivity increases, allowing electrons to move around freely and for long distances without interacting. However, this layer only has a density of around $10^7$ g/cm$^3$, and the structure of matter changes quickly the further into the star you look ("Chapter 17 Neutron Stars", par. 17.1).

The next layer, the inner crust, estimated to be a little bit thicker than the outer crust, is around 40,000 times denser than the previous layer ("Chapter 17 Neutron Stars", par. 17.1). It still maintains some nuclei in a lattice, but the pressure can initiate electron capture, a process by which electrons are compressed into the protons to form neutrons, creating a neutron-rich sea of matter. This is also the region where neutrons begin to exit the nuclei, a process known as neutron drip, occurring once an element has hit its maximum number of neutrons it can pack in its nucleus ("Towards the Extreme", Norton). This region tends to contain heavier isotopes, such as nickel-78, iron-76, and many free neutrons rather than iron-56, as is found in the outer crust (Norton). As we reach the edge of the outer core, what remains inside a neutron star is hypothetical ("Towards the Extreme").

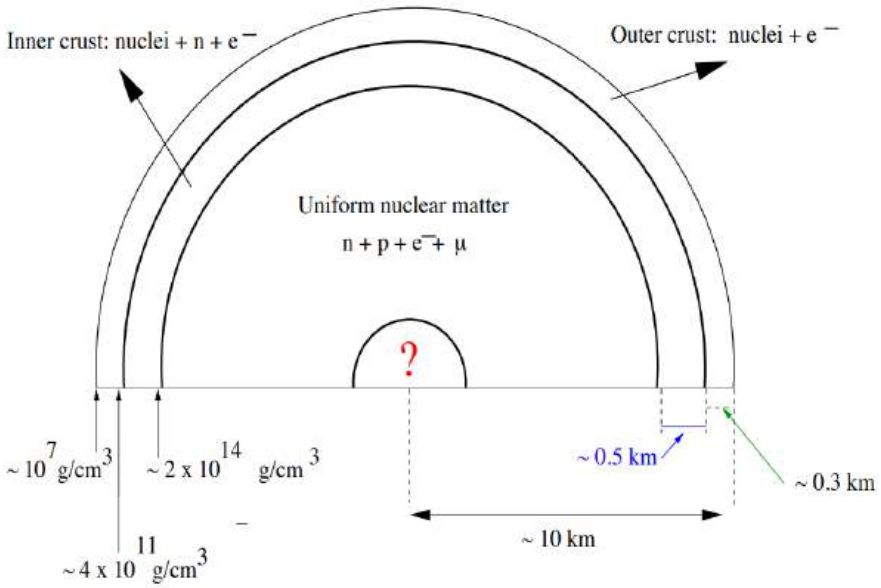



Fig 1: A simplified diagram of the composition of a neutron star, including the masses and thickness of each layer ("Chapter 17 Neutron Stars", par. 17.1).

Most scientists believe that at the point at which the inner crust connects with the outer core, remaining nucleons get pressed down so thin, they clump and form strands and eventually layers, dubbed "Nuclear Pasta" (Stuart). Nuclear pasta, the result of crushing the nucleons into incredibly high densities, is the strongest known material in the universe, estimated to be 10 billion times stronger than steel. As the inner crust and the outer core merge together, bubbles of nuclear pasta float around in a phase known as the "gnocchi" phase. The bubbles then turn into long bars known as "spaghetti", and are finally crushed into flat layers known as "lasagna" (Stuart). As the layers become more compressed, it is theorised that there is a solid block of nuclear pasta with holes in the shapes of "spaghetti" and "gnocchi" until you hit a thick layer of homogenous nuclear pasta.

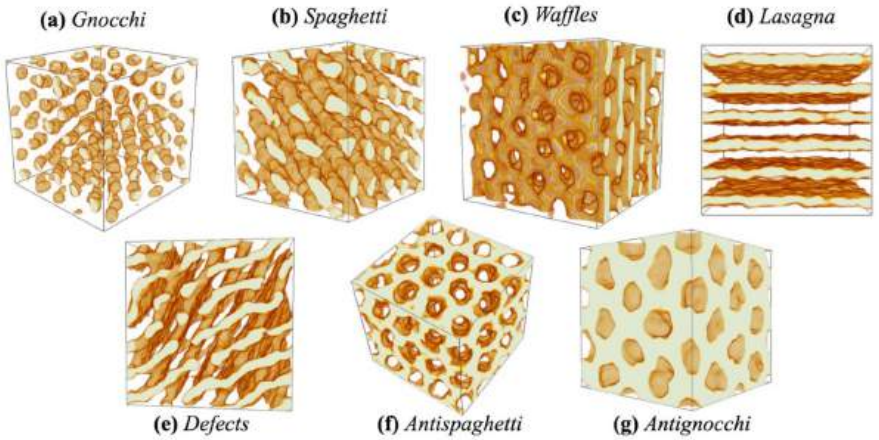



Fig 2: Diagrams of theorized nuclear pasta shapes starting with gnocchi (a) and ending with antignocchi (g), showing how the transition between the inner crust and the outer core is thought to be a smooth gradient (Stuart).

Without the required pressure and force, nuclear pasta's unstable nature makes it unable to survive outside of a neutron star. Some scientists believe that nuclear pasta is unstable within neutron stars. However, with the strong nuclear force and the immense gravitational pressure, the only way for it to be unstable is if the matter itself would emit gravitational waves within the star. Only then would the existence of nuclear pasta be proven (Stuart).

**Particle Physics Properties**

From here on, we can only guess what forms of matter lie inside in the core. The pressure is so great that it may split neutrons into tinier particles called quarks. There are numerous theories that could explain the inner core; however, in order to understand the theories we'll explore, we must first start with the basics of particle physics. As it turns out, neutrons and protons are not the smallest objects in the universe. They're made up of particles called quarks; one of the two types of fermions.

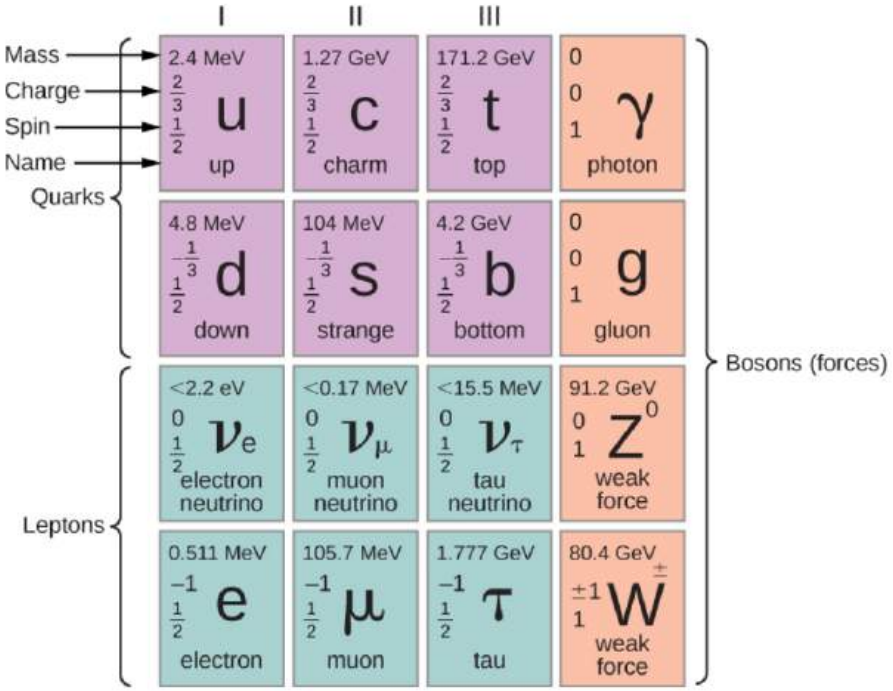



Fig 3: A table listing and describing all of the known elementary particles in the Standard Model, including their classifications, mass, charge, and spin (Physics LibreTexts).

Fermions are one of two classes of subatomic particles defined by their masses, charges, and spins —the other one being bosons, or energy carriers— and can be further divided into quarks and leptons. There are six types of quarks: up, down, top, bottom, charm, and strange. Neutrons and protons are made up of up quarks, which have a charge of +⅔ and down quarks, which have a charge of -⅓, in groups of three held together by a boson called a gluon which has no mass or charge. Neutrons, since they are neutral, consist of one up quark and two down quarks to get a charge of 0. The quarks interact through bosons sharing gluons in order to connect and form neutrons or protons (Physics LibreTexts). Most of the universe is made up of protons, neutrons, and hyperons, known as baryonic matter. With the exceptional conditions inside a neutron star, things may get a little strange.

**Inner Core**

There are various speculations as to what the inner core is made of, but there are two particularly widely-accepted theories that we'll cover. The first is that the inner core is composed of quark-gluon plasma (Trafton). As stated before, neutrons are composed of three quarks held together by gluons; however, pressure in the center of a neutron star may be so powerful that the structure of these tightly-packed neutrons might completely collapse. What could remain is a sea of free-floating quarks and gluons called quark-gluon plasma (Trafton). Quark-gluon plasma was originally predicted to be a type of gas, but using multiple experiments which have collided

nuclei together in particle accelerators, scientists have concluded that it is a nearly-frictionless substance with little viscosity (Trafton). The Tolman–Oppenheimer–Volkoff (TOV) equation, an equation used to describe the mass-dependent properties of a neutron star, states that neutron stars with a greater-than-average mass are more likely to have quark-gluon plasma at their centers (Annala et al.).

The other popular explanation is the strange matter hypothesis. Assuming the stars are more massive than average, their interior pressure could potentially cause up and down quarks to interact with the weak force, forming strange quarks. The strange quarks may bond with up and down quarks, or other strange quarks, and turn the neutrons into hyperons, a baryon that's heavier than a proton or neutron. Otherwise, these clumps of strange quarks, called strangelets, form strange matter: heavier matter thought to only exist in neutron stars, if it exists at all (CERN).

Strange matter is theorized to be the most stable form of matter in the universe. It wouldn't be organized or arranged in a specific way, nor would it have structured hyperons, and is thought to consist solely of free, unbounded quarks (CERN). Since this substance is thought to be created in some of the most high-pressure environments that exist, scientists still debate whether strange matter could survive outside of a neutron star, or whether it would transform back into up and down quarks. If strange matter were to exist outside of neutron stars, any normal matter it came into contact with would convert into more strange matter due to the strange matter's overwhelming stability. Likewise, if strange matter exists in a neutron star, it would likely spread throughout the whole star, consuming it from the inside out, creating a strange star, a hypothetical variant of a neutron star (Nasr).

While their inner core composition is still up for debate, neutron stars have provided scientists with a few hints to their centers' state of matter and their maximum possible masses. As an example, the TOV equation was formulated to calculate the maximum mass a neutron star can have before becoming a black hole; however, historically it's been known to provide a wide range of results with answers getting as low as 0.6 solar masses to as high as 3.6 solar masses, due to various assumptions made (Dar). Recently, scientists have used a different approach to get an approximate mass limit using the force from neutron degeneracy pressure explained by the Pauli exclusion principle . This neutron degeneracy pressure is said to help counteract the force of gravity, preventing the star from crushing itself and keeping the TOV limit to around 2.9 solar masses (Bhattacharya, Altiparmak).

A theoretical study conducted on the speed of sound within a neutron star predicted that it should be around 75% percent the speed of light, whereas previous theories hypothesized that it would be 30% less than that new calculated value (Annala et al.). Because the matter inside is more compact, there are more particles off of which sound waves can bounce. Since the model predicted a much higher speed of sound, the maximum value for the mass the TOV limit allows is therefore larger than previously expected (Feldman).

One more theory suggests that the outer and inner core may be similar with slightly differing properties closer into the center of the star. In this case, the interior of the neutron star

would have a smooth gradient between the outer and inner core (Han). Neutron stars have been predicted to emit waves called g-modes, or gravity modes, caused by buoyancy in the star (LIGO Caltech). Like many supergiant stars, in order to maintain a balance, the force of outward pressure in a neutron star acts as the equal opposing force of gravity, making the star wobble as each force tries to overpower the other. In a neutron star, we theorize that the outer core is still made up of hadronic matter while the inner core likely has unbounded quarks. Depending on whether or not the transition between the outer core and the inner core is sharp or a smooth gradient, the star would emit more or less amplified g-modes, respectively (Han). This theory can only be proven once the instruments used to detect these g-modes have been engineered. Currently, no observations have been made.

**Conclusion**

Since the discovery of neutron stars, the boundaries of theoretical physics have been pushed to their absolute limits as scientists work to understand their composition. While there are numerous theoretical studies on and observations of these stars, diving deeper into their composition is quite difficult to achieve. The layers of these stars begin with crystal lattices of normal elements and then quickly transition to ultra-dense, hypothetical substances, from quark gluon plasma, to nuclear pasta, to strange matter. The inner core alone has countless theories as to the state of matter of this exotic region. With varying atomic and extremely rare particle structures, it's hard to comprehend that all these components are packed into a sphere as big as a city, all emerging from one supernova. The composition of neutron stars hasn't been completely figured out yet; what we do have is a multitude of theories strung together to create a possible explanation for one of the most difficult to explain objects in the universe. However, with the rapid advancement of technology and improvement in our theoretical understanding, scientists could potentially use this new knowledge to gain a better grasp of modern physics at large.

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**The Comfort Of Reading: The Decline of Adolescents' Reading in the United States and Proposed Solutions By Khanh Le**

**Abstract**

This study investigates the decline in adolescents' reading for pleasure and proposes solutions to address this current issue. The method combines secondary sources with exploratory interviews conducted among young adult authors and adolescents. National data show that only 14 percent of adolescents in the country reported reading for fun, a 3 percent decrease from 2020. Findings suggest that the rise of social media and school pressure were the main causes for the decrease in the rate at which adolescents read for pleasure. Research indicates that social media, the main contributor to the decline of reading, can be leveraged as the solution. These proposed solutions include marketing strategies, parental involvement, and school-based reforms to rekindle pleasure for reading.

**Keywords** adolescents, reading for pleasure, social media, young adult novels, marketing strategies, education reforms.

## Introduction

Research shows that reading regularly can improve literacy and language skills (Webber 2019). Reading comprehension, reading fluency, and breaking down unfamiliar words to pronounce them are all developed through regular reading practice (Webber 2023). Children who read daily at the age of 11 showed better psychological and behavioral adjustment and mental health. Furthermore, connections with texts also help readers navigate difficult emotions and understand their experiences. In the early 2020 coronavirus lockdown, many young people reported that reading had made them feel better and encouraged them to think optimistically about the future (Webber 2023). However, many adolescents these days stop reading for pleasure, specifically in the United States. This paper will answer the question of why adolescents' reading for pleasure has declined, and what strategies could reverse this issue.

## Methodology

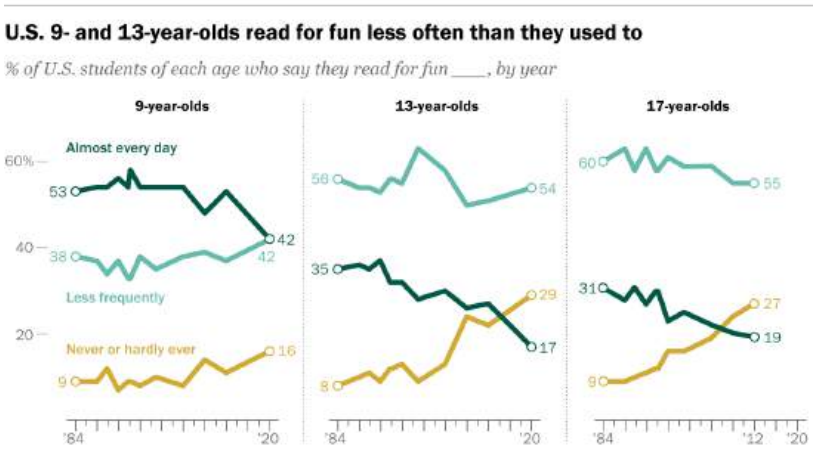
The first question this research aims to answer is the current rate of adolescent reading for pleasure in the United States. This will provide background information on the general topic question and allow further analysis of the problem of adolescent reading decline rate. It will consist of quantitative data, collected through secondary sources of graphs and choices from professional articles. Existing data had been gathered from the Internet and had been verified by cross-checking through multiple sources. The credibility of these data had been measured through MyBib. The data were originally produced through scientific investigations by a therapy services organization and a published article from Science Direct. Secondary sources were selected based on the most recent, most credible, and based on expertise in the field. Before analyzing the data, the researcher had removed unnecessary information, checking for missing

data. The Google sheet had been used to double-check data, and a linear graph from secondary sources was used. This method was chosen because it grants access to multiple information on existing data, and for its time efficiency.

The second question that this research focused on was why there is a decrease in teenagers' reading for fun in the United States. For this question, a mix of primary and secondary sources was used, as well as both qualitative and quantitative data. Four interviews were conducted for quantitative data; they were done virtually. The participants were two young adult authors and two teenagers who are currently in school. The participants had been chosen because of their direct insight into the reading trend among adolescents. Each interview lasted 15 to 20 minutes. Questions had been designed open-ended for long-form answers. The two adolescents had answered questions relating to why they won't read for pleasure. While authors had answered questions that were tied to the book market, providing insight to the young audience consumers, and a potential marketing strategy to attract adolescents. Discourse analysis had been used to analyze the qualitative data. This method had been chosen because it gives hand on insight into the book industry and adolescents' behaviors towards reading. Secondary sources, including scientific data and a linear graph, were used. Thematic analysis was used to dissect the information.

**Statistics of adolescents reading for pleasure**

In the United States, only 14 percent of students report reading for fun every day, according to the National Assessment of Educational Progress report, a 3 percentage point decline from 2020 and a 13 percentage point decrease since 2012. The report indicated that 31 percent of students never or rarely read for pleasure (Lonas 2023). Among 13-year-olds surveyed in the 2019-20 school year, 17% said they read for fun almost every day, a decrease of 27% compared to 2012, and estimated half the share, 35%, who said this in 1984. About 29% of 13-year-olds said they never or hardly ever read for fun, which is an increase of 21 percentage points from the 8% who said the same in 1984 (Schaeffer 2021). Approximately one in four children who grow up without learning to read proficiently by the age of 11 are harmed in their success in secondary school and beyond. Significantly, 65% of American fourth graders do not read at a proficient level, showcasing a clear issue in reading skills nationwide (Reading Statistics and Facts You Should Know - Kutest Kids 2025). This highlights the significant decline in reading for pleasure over the past year, contributing to literacy and reading comprehension challenges among adolescents.



(Schaeffer 2021)

**Why aren't adolescents reading for enjoyment anymore**

In an interview, a 15-year-old reported that she doesn't read for fun because of the academic stress and workload that she goes through every day. She often has to stay up late to finish school assignments, which is compounded by the constant exams. She emphasizes that she can only enjoy reading if she is relaxed and has free time. Moreover, she said that she only reads books that grab her in the first chapter. Another student said that he once enjoyed reading until he had to read for school, which led to him disliking the activity. This is because schools often force students to read books that aren't to their interest. " Repeating the said process, it keeps getting harder for students who don't read on their own to find something they'll actually enjoy reading because reading can't be enjoyable in their minds" (Hüberli 2020). Additionally, many people believe that the rise of social media, such as TikTok and Instagram, is a contributing factor to the decline in reading. Social media negatively impacts an adolescent's attention span. A study by Microsoft found that the average human attention span has decreased by 4 seconds since 2000, now standing at 8 seconds, which is shorter than that of a goldfish (Wolmark 2023). Reading is an activity that requires a sustainable attention span, but with the rise of social media, it has almost become impossible.

**Ways the book market can appeal to the adolescent audience**

One of the most important details when marketing a book to a young adult is the book cover. Although the phrase "Don't judge a book by its cover" persists, visuals play a critical role in attracting young readers. For an adolescent, appearance is a huge factor, especially with social media apps, where the aesthetic of a post can make a huge difference. Professional book sellers had said that the "design elements—color, typography, imagery—must coalesce into an inviting and intriguing visual that beckons readers" (Staff 2024). Before publishing their books, young

adult authors should ask themselves if their book covers are appealing, and ask fellow young adults what they think about the cover. If it resonates with them, the book will likely do better in the market. For example, the most popular YA fantasy books have a really aesthetically pleasing cover:




(Andrews, 2020)

Along with appearances, adolescents are easily influenced by their surroundings, significantly by things they see on social media. While social media has been highlighted as the cause for a decline in reading, the same platform can be harnessed to promote reading to adolescents. If Young Adult authors can reach out to a popular TikTok influencer who is willing to send a free PR package and ask them to promote the book, then it can reach millions of adolescents. Adolescents are quick to catch up to trends, for example, the Stanley Cup trend, where almost everyone now walks around with a Stanley Cup simply because it's been blown up on social media. The same thing can happen with books; if thousands of influencers are seen with books, then their audience would likely become curious. However, if the author can't reach out to an influencer, promoting the book themselves on social media is a promising option. Nowadays, multiple authors are promoting their books on Instagram and TikTok, such as Rebecca Yarros, Jennifer Lynn Barnes, and Rebekah Betram. The most noticeable person is Lauren Roberts, the author of the Powerless trilogy, a YA read. She promoted her books on TikTok, and it blew up, making her a New York Times bestseller.

Another factor is to write what the audience wants, especially as a YA author. The most popular YA books currently, according to Barnes and Noble sales, are: Shatter Me, The Hunger Games, Powerless trilogy, Once Upon a Broken Heart series, Cruel Prince, and If He Had Been With Me… Even though all these books have their unique charm, they all have one thing in common: an intriguing plot with a strong romantic couple. Adolescents love to read about romance, as they are exploring it in their own lives, and it provides a comfort space for them. For example, The Cruel Prince was a huge hit because of its fantasy elements and the enemies-to-lovers trope, and the enemies-to-lovers trope was what made the book so popular in the first place. When authors are writing their book, some good advice is to take notice of what is popular at the moment and latch on to that, while also adding their own unique touch. Another

YA author, Isabella Stofka, said that posting relatable content for adolescents. If the author can make their readers relate to the characters, they have already won them over.

In an interview with a new young author who is currently working on their first book. Edwin T George agreed that marketing your book on social media is the productive way to go, making “mini skits based on the plot in your book so that they won't just scroll through your reel, but they'll keep watching till the end” to fight the attention span issue. Get young bookstagrammers into reading your book, and ask them if they can give a review on their page. Thus, reaching the already existing young readers in the bookstagram community. Do collabs with bookstagrammers and also release teasers and trailers for your book with them. Release interesting and captivating quotes from your books via any social media platform. Just to let the young adults know that your book is worth a try. Be creative and unique. Because the young generation only craves uniqueness. Your way of marketing should be yours alone. It must be interesting and hard to ignore. In summary, making reading seem fun and relaxing.

**Ways adolescents’ social life can help**

While having a good marketing strategy is a strong solution to captivate adolescents, another push has to come from the family, which is the parents. Parents need to nurture their child's reading habit as soon as they learn how to read. They could do that by telling their children bedtime stories, buying them comics, and graphic novels. As the child becomes an independent reader, they will find themselves wanting to try new reading materials such as thick, wordy novels, and see reading as a relaxing activity.

Another factor is school; most novels that are chosen for school do not align with the students' interests. This makes reading seem like a chore rather than an enjoyment. Moreover, reading for school comes with endless comprehension questions that make the process tedious and are often perceived by students as an excuse to make them“understand the story better”. In truth, if the students get to pick their book that aligns with their interests, they will have little problem understanding the story. To address this issue, schools can hold reading sessions where students have to attend once a week, but they get to choose their book, which aligns with their interests. Once a week, they can discuss whatever they thought about the book.

**Conclusion**

Based on the data collected, the rise of social media has led to a decline in adolescents' enjoyment of reading. However, that problem isn’t unfixable, as using the tool that has led to a decrease in reading can ironically bring back the pleasure of reading. Authors can now use social media to promote their books, collaborating with popular influencers, and base their books on topics relatable to adolescents nowadays. Furthermore, schools and parents can contribute to solutions by encouraging their young adults to read a book of their choice without the pressure to complete it on a specific date or answer tedious questions. Through all of this, the love of reading can be restored among the young adult audience.

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**Tracing the Environmental Transformation of Los Angeles and Its Impact on Contemporary Ecological Challenges By Beckham Williams**

**Abstract**

This paper explores the groundbreaking transformation of the Los Angeles basin's ecosystem as both population and urbanization increased. First addressing the original state of the Los Angeles ecosystem and the relationship of indigenous people to the land, this paper relates how the reciprocity between these Indigenous communities and the land was drastically altered by the arrival of colonists and the increasing population of this city. The paper then dissects the multitude of environmental threats that the city and its inhabitants face today: such as air quality and pollution, carbon emissions, wildfires, and water scarcity. By individually addressing these various impacts, this paper gives a holistic and informative view of the current Los Angeles ecosystem and its dire state. Through the exploration of the challenges that the Los Angeles basin faces today, this paper also posits a path forward and examines how environmental activists are leading the fight against climate change and what everyday citizens need to do in order to forge a sustainable path forward.

**The Environmental Transformation of Los Angeles**

It is hard to imagine that the bustling, metropolitan city of Los Angeles was home to only 44 people in 1781, and around only 620 in 1820. The historic urbanization and industrialization of Los Angeles was not only remarkable but had a profound effect on the environmental condition and transformation of the area. The environmental transformation of Los Angeles can be characterized through the change in its natural environment before settlement and its current environmental state, the effect that indigenous peoples had on the environment – and their relationship with the environment, and, finally, the impact of development on the ecosystems and environmental conditions of the area.

Before the development of the L.A basin, the area was characterized by a mix of coastal sage scrub, swaths of valley grasslands, and seasonal wetlands that encompassed portions of the area. Many of these habitats hosted abundant wildlife and were home to an array of different fauna and plants. In the late 1700's and early 1800's, when the population majorly consisted of farmers and people working the vast agricultural lands, they often utilized the land by the presence of wetlands and grasslands: used to sustain the small population and its community.

Contrary to popular opinion, it is a misconception to believe that the Los Angeles area, specifically, the city of Los Angeles, was built in a desert environment. Although Los Angeles experiences extremely hot weather during specific seasons, their average rainfall of 14.8 inches between 1877 and 2024 have them designated as a Mediterranean climate – meaning that Los Angeles is not technically a desert. Even though modern citizens often mistake LA as a desert, early indigenous groups understood the true nature of the LA river basin ecosystem.

Today, Los Angeles is home to the largest indigenous population of any city in the United States of America. Over 10,000 years ago, the Los Angeles area was home to a multitude of

varying native populations that often lived unitedly and in tandem with the environment. Their practices were often environmentally sustainable and inclusive of the ecosystems in which they lived; they not only left the environment unharmed, but worked to improve the land on which they lived. For example, they routinely started brush fires to revive and reinvigorate the soil on which they farmed . Starting in the late eighteenth-century, specifically in the 1770s, Spanish settlers began usurping and changing the land of which the indigenous people had occupied for thousands of years. As an increasing number of Spanish and European settlers came to Los Angeles, conflict arose between the previously established native peoples and the incoming foreign colonizers.

The European settlers had an advantage in warfare and conquering over the native peoples due to their further development of weaponry as well as the multitude of diseases that they transported and consequently spread to the Indigenous people: who had no protection against these foreign diseases. They were able to conquer these tribes and take control of the land, establishing many missions across the Los Angeles area and greatly increasing its population. Furthermore, the enslavement of these indigenous people decreased their ability to sustain and maintain the land that they had graciously protected for thousands of years prior.

As the population of Los Angeles continued to grow in size, the environmental conditions of the area became increasingly more degraded, as natural resources and the natural ecosystems suffered due to the mass influx of new peoples. The establishment and enslavement of the native peoples in these new missions had extreme unforeseen environmental repercussions.

Firstly, the arrival of these European settlers during the late 18th century brought with them invasive and non-native species which was a detriment to the environment's ecosystems and threatened the biodiversity of the region. For example, the integration of black mustard into the Los Angeles basin has resulted in the rapid growth and takeover of this invasive species: a detriment to the native species that thrived here before  Additionally, a lack of access to water was a major factor that has contributed to the environmental transformation of Los Angeles over time. To explain, throughout the inhabitation of the LA basin, the steep mountains surrounding the basin created an unpredictable and often fluctuating river system with complicated access to water. Thus, the increasing population struggled to sustain themselves and their environment, due to these unpredictable conditions.

Furthermore, during Spain's occupation of Mexico, and their subsequent control of the Los Angeles area, they had an extreme impact on the thriving environment that had previously existed. Their presence greatly disrupted the ecosystems that had previously flourished, and the growing population made it harder for the area to sustain its people.

However, in 1822, when Mexico gained independence from Spain, the area known as Los Angeles came under control of the Mexican government; who were enacting measures to control the quality and quantity of waters carried throughout the previously established networks and were working to restore the previously harmonious conditions of the environment. The short span of Mexican control of Los Angeles had a minimal effect on the area's environment. Although they made strides for positive environmental change, their occupation of the land was

too short-lived to have a notable and lasting impact on the environmental state of the area.

Subsequently, in 1850, Los Angeles became incorporated as a city of the United States of America, which marked the beginning of the city's rapid urbanization and industrialization. Firstly, the California Gold Rush, which began in 1848, resulted in a major influx of many different peoples into the Los Angeles area and greatly increased the population of the city. In fact, from 1850 - 1870 the population of Los Angeles county grew from 3500 citizens to over 15,000. The population of the area rapidly increased, and the environmental conditions of the area were drastically altered. The new influx of citizens in the area meant that many more resources were needed to sustain the population.

Furthermore, Los Angeles's prominent role in the oil, agricultural, and real estate industries further increased the population of the city. As the population grew, the unpredictable access to much needed resources, specifically the access to water, became a pressing issue and point of focus for the people and they turned their attention to the Owens Valley in 1913.

The development of an aqueduct in Los Angeles was able to sustain the exponentially growing population, however, it coincided with the destruction of many of Los Angeles's wetlands and marshes: the land being transformed into an urban center, and moving away from its past natural landscape. These natural marshes and wetlands, that once played a pivotal role in the ecosystems, as well as daily lives of the animals and settlers that had lived in the area only 200 years prior, now were seen as valuable and expensive properties for urban development.

Los Angeles continued to transform into a booming urban center, especially with the rise of Hollywood in the late 19th century and early 20th century. This massive and flourishing industry greatly attracted people from all over the country and sparked extreme development within the city and greatly buttressed the economy – allowing for further development. The drastic increase in population size in Los Angeles can be displayed through its growth from the year 1900 to 1950. In 1950, the population of Los Angeles consisted of precisely 102,479 people, designating it as the 36th most populous state in the nation. Only 50 years later, the population of this developing city had reached 1,970,358, and was now the 4th most populous city within the country.

In conclusion, as the population of Los Angeles has drastically grown, the environment has suffered and altered into a landscape barely recognizable. While Los Angeles continues to face a multitude of environmental challenges, countless activist groups are rising to the challenge, as will be discussed in the next section.

**Environmental Challenges of Today & The Activists that Fight Them**

Historically, California has led the nation in policy making on issues such as forest management, clean energy, coastal management, and regulations against air pollution. Organizations such as TreePeople, Communities for a Better Environment, and Heal the Bay are amongst local Los Angeles environmental organizations that work to reduce the impact of human activity on the city. While the state may lead the nation in environmental activism, the Los Angeles ecosystem has continued to suffer and its environment detrimentally affected. This

paper will address four of the largest and most imminent environmental issues that Los Angeles faces today.

**Air Quality and Pollution**

As outlined in the introduction, the Los Angeles area suffers from extremely poor air quality and Angelenos are constantly exposed to high levels of air pollution. To illustrate, Los Angeles has the highest level of ozone pollution amongst cities within the United States. Ozone pollution, also known as ground-level ozone, is a harmful pollutant that forms in the atmosphere and is a key component of smog: it can damage the lungs, worsen asthma symptoms, and affect other respiratory health issues.

Furthermore, in recent years, Los Angeles has failed to meet the Clean Air Act, which outlines and imposes health-based standards of ozone and fine particulate matter (pm 2.5), two critical components of smog. Much of the air pollution within the city is a result of an increased release of greenhouse gas emissions as well as the exhaust and pollutants released from the use of gas vehicles. In fact, a recent study has shown that approximately 90% of smog-forming pollution in Los Angeles is attributable to transportation. On the other hand, the primary producer of fine particulate matter, or PM 2.5, within Los Angeles, is the combustion released from cooking and residential food (41.16%). Both main contributors to the rising air pollution levels in Los Angeles are factors influenced by a more robust population: transportation and the use of gas vehicles has only increased over time, and a great amount of combustion being released is a direct effect of a growing population.

In addition to human activity, the topography of the LA basin itself is positioned to trap and encase the ozone and smog produced by the city. While this was not an issue for early settlers and indigenous people–whose release of air pollutants was essentially insubstantial–this natural factor has an increasingly dangerous impact on Los Angeles' millions of citizens.

However, many organizations and activist groups within Los Angeles are fighting to improve the air quality of the city. The California Air Resources Board (CARB) is a state agency responsible for protecting public health and the environment by reducing air pollution within the states. They do so by setting concrete air quality standards, identifying pollutants, and measuring progress in reducing pollution. Additionally, the Coalition for Clean Air – the only statewide organization focused on air quality, promotes clean transportation and encourages clean air practices within businesses.

Fortunately, some of these efforts seem to be having a tangible and impactful effect on the air quality of the city. For example, in 2024, the LA Metro reached over one million weekday riders for the first time since COVID-19, and the Metro's bus ridership saw a 6.9% increase. This increase in public transportation contributes to cleaner air for all Los Angeles citizens and detracts from the overwhelming amount of smog-contributing components released from vehicles.

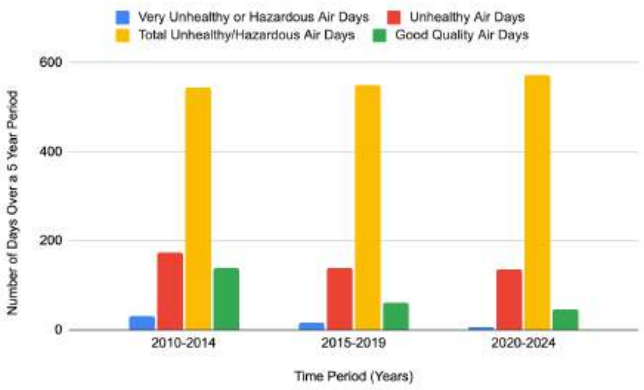



Fig 1: Distribution of Air Quality Conditions within Los Angeles over a 15 Year Period

Furthermore, demonstrated in the figure provided, the amount of "Good Quality Air Days" has continued to increase over the past 15 years: 140 "good" days from 2020-2024, 60 "good" days from 2015-2019, and 46 "good" days from 2010-2014. This increase, however, coincides with an increase in the overall number of "Very Unhealthy or Hazardous Days", demonstrating the necessity for lasting and impactful change in society.

In conclusion, Los Angeles continues to face extreme levels of air pollution and is yet to significantly reduce this continuous environmental pressure. However, many existing and arising organizations are actively working to protect the air quality of the city and improve Angelenos access to clean air. For example, the Coalition for Clean Air seeks to mitigate further pollution by supporting policies and funding programs that clean up bus fleets, passenger vehicles, and helping to mass a series of landmark climate change laws.

**Carbon Emissions**

Carbon emissions remain one of the most prevalent contributors to the rising temperature of our planet; they refer to the release of carbon-containing gases, primarily carbon dioxide (CO2) and methane (CH4), into the atmosphere. These gas emissions contribute to global warming by trapping heat within the atmosphere, resulting in a greater amount of heat being absorbed by our earth's surface – increasing the global temperature. These greenhouse gas emissions resemble one of the largest anthropogenic activities that our climate faces: largely stemming from industrialization, transportation, and use of energy and electricity – all aspects of humanity activity. Consequently, for a city that is home to over 3.8 million people, Los Angeles' industries inevitably produce large amounts of greenhouse gases annually – accounting for 24% of California's total yearly carbon emissions.

The history of carbon emissions within Los Angeles is one of deceit and denial led by the big oilmen of California – who were great benefactors of the Western States Petroleum Association (WSPA). In 1955, the air quality of Los Angeles throughout the early to mid-20th century was abysmal and often featured large smog episodes, resulting in increased rates of

asthma, lung disease, and harsh visibility standards, leading to greater amounts of automobile accidents.

The origin of the air pollution in Los Angeles can be traced back to World War II, where the once idyllic coast of the United States suffered greatly from large amounts of smog and air pollution: the main contributor, carbon emissions. Angry and endangered Los Angeles citizens took action in 1947, pointing to the highly visible stack gases emitted by Los Angeles County's many oil refineries. Additionally, a report published by the WSPA in the following years had contained the "bombshell warning that carbon dioxide (CO2) emissions from fossil fuels could have considerable long-term consequences for "civilization" (John). Both the efforts of the Los Angeles citizens and these scientific findings, however, only led to a greater amount of pushback from the affluent and powerful executives from California's largest oil refineries. To halt regulations and restrictions upon oil refinement, these prominent oilmen enlisted a front group to influence public opinion, block clean air regulations, and stall climate action – thereby increasing the threat we face today.

Decreasing carbon emissions is not only necessary for diminishing the rising temperature of the earth, but also in improving the air quality of the region. A reduction in carbon emissions and increase in sustainable practices are spearheaded by organizations like Climate Resolve and Blue Sky LA. These organizations work to challenge outdated norms and address Los Angeles's climate issues. One avenue in reducing carbon emissions is the utilization of solar energy; the institution of solar panels and an increase in green transportation initiatives have been beneficial in combating the increasing carbon emissions.

Furthermore, California's Green New Deal – signed by governor Gavin Newsom – aims to attain carbon neutrality by 2050, meaning the city will balance its carbon emissions with the amount of carbon it removes from the atmosphere. To attain this goal, citizens have prioritized the use of electric vehicles to reduce city-wide carbon emissions. Within the last five years, the number of charging stations within the city has expanded greatly; to further illustrate, the California Energy Commission approximates that around 24,000 new chargers were installed in the first half of 2024. Additionally, a report published by the USC Institute for Public Policy and Government Service demonstrates that ownership of electric vehicles has greatly increased in recent years, with only 1.9% of citizens on an EV in 2019, compared to 7.3% in 2024.

While carbon emissions remain a significant problem globally and city-wide, many organizations, activists, and citizens are finding ways to reduce their carbon footprint. From the increase in use of in-home solar panels (8% in 2019, 13% in 2024) and more energy-efficient landscaping (19.% in 2019, 33.6% in 2024), it is necessary to recognize the many opportunities and obligations that one has in protecting the land they live on.

**Wildfires**

Perhaps the most recognizable and pressing of the environmental issues that Los Angeles faces is the abundance of wildfires that the city experiences each year. Wildfires not only destroy large amounts of vegetation but release extremely harmful pollutants into the air that Los

Angeles citizens continue to inhale, further diminishing the air quality and state of pollution within the city.

The Palisades and Eaton fires, which were ablaze in January of 2025, are major examples of the extreme harm and danger of these natural disasters. Due to Los Angeles's perpetual state of drought, low humidity, and strong Santa Ana winds, the city is more vulnerable to these wildfires than other landscapes. The recent Los Angeles fires burned over 57,000 acres of land and destroyed the homes of countless Los Angeles citizens. Additionally, the effects of these prevalent and dangerous wildfires are amplified by the changing climate of the Los Angeles ecosystem, more specifically, the rising temperature of the city.

The California Climate Adaptation Strategy projects that the average maximum temperatures in the Los Angeles region are expected to increase by 4°- 5°F by mid-century and 5°-8°F by the late century. Additionally, extreme droughts are expected to greatly increase by the late-century, further buttressing the chance and severity of wildfires. However, these natural disasters have not always been a major threat to the city and citizens that inhabit it.

While wildfires have been a natural part of the Los Angeles landscape for a long time, predating European settlement, they only started becoming a significant concern in the 1870s. Indigenous people actually set wildfires intentionally for purposes like grazing and replenishing old fields, with little impact on human infrastructure and the environmental safety of the city. However, as the population of the city increased and the land was not only further occupied but increasingly dried out, wildfires soon became an extreme threat to the safety of the Los Angeles community. To further demonstrate this idea, it is important to observe the population of the area before wildfires became a threat relative to the population of the city in which wildfires emerged as a hazard. In 1850, the population of Los Angeles was 1,610 people; during this time wildfires did not resemble an environmental threat – the land being much more abundant in wildlife, marshes, thriving fauna, and native species.

However, over the next three decades the population of the city increased at an extreme rate, bringing unforeseen environmental repercussions such as wildfires. The population of the city in 1880, for example, had reached 11,183 and showed no signs of leveling out. This massive population increase within the city directly correlates to the increased threat, rate, and prominence of wildfires within the region. Within the 1800's to 1900's wildfires remained a somewhat tame and non-threatening environmental occurrence, with few instances of wildfires causing harm to civilians or land until the later portion of the century.

Contrarily, from 1900-1999, the state experienced 45 mega-fires (fires over 100,000 acres) and have recorded 35 mega-fires since the start of the 21st century. This inexplicable increase in wildfires within the region is a direct result of human activity within the region and across the globe.

In order to combat this wildfire epidemic it is important to revisit indigenous practices that utilized controlled burnings to limit the propensity of wildfires and mitigate their destructiveness. A Stanford-led study, in collaboration with The U.S. The Forest Service determined that incorporating traditional techniques into current fire suppression practices is

vital to reducing wildfire risk. Profound opportunities exist to expand and formalize partnerships amongst the Los Angeles government and indigenous tribes, especially in relation to wildfire mitigation. Additionally, organizations such as the Tribal EcoRestoration Alliance (TERA), provide ecological lessons to firefighters and offer group programs that include cultural burning practices, demonstrating an avenue into integrating modern day practices with indigenous techniques.

**Water Scarcity**

A lack of access to a constant and clean supply of water has always been at the heart of Los Angeles's environmental problems – especially as the population of the region grew. The natural environment and topography of the area made it difficult for settlers to ensure a constant, reliable, and clean source of water; the area, which was initially abundant in wetlands and marshes, was largely diminished as an increasing amount of settlers found land in the area. Initially, indigenous people and early colonizers used the water flowing through ditches from the L.A basin to supply their needs; however, the growing population jeopardized the security of this provider, as it was often inconsistent and unreliable on a larger scale. These ditches, also known as zanjas, that were used by indigenous peoples in the 1700's were degraded by the influx of new Los Angeles citizens who quickly altered the ecosystems and natural life of Los Angeles itself.

Hence, the Owens Valley aqueduct – installed in 1913 by Williams Mulholland – was not built with the goal of making a "barren desert bloom," in the words of Mulholland, but rather, accommodating population growth and protection against drought. The land, once plentiful in wetlands and assuredly not a desert, succumbed to the pressure of the growing population that continued to impose a constant threat to the natural resources of the area. Consequently, the development of an aqueduct within Los Angeles was integral and necessary to support the growing population and develop a stable water source for the community. The Owens Valley Aqueduct, or the Los Angeles Aqueduct, spans 233 miles and is used to this day to deliver water to the Los Angeles community. The father of the aqueduct had written of the Los Angeles River before his installment of the aqueduct.

He wrote, "The Los Angeles River was a beautiful, limpid little stream with willows on its banks ... It was so attractive to me that it at once became something about which my whole scheme of life was woven. I loved it so much."(provided by the LAWDP)

Sadly, Mulholland's vision of the LA river drastically differs from the reality that exists today. Los Angeles continues to face years of extreme dryness and struggles to combat the rising temperatures of the earth. From the early conditions of the indigenous people that inhabited the land in the 17th century to the millions of people that inhabit Los Angeles today, the climate and land has been irrevocably altered. The population increase and subsequent increase of infrastructure in pavement and other buildings contribute to the rising dryness of the city and continue to degrade natural water sources. However, organizations across Los Angeles are actively working to protect and restore the Los Angeles River. For example, Friends of the LA River, a non-profit organization, is ensuring the safety of this landmark through the removal of

invasive species, the enforcement of more regulations upon the quality of the water, and their engagement and education of the Los Angeles community. Organizations such as this one represent a course of action forward towards combatting the increasing scarcity of this precious resource.

**Discussion**

Both the city of Los Angeles and its citizens are struggling. Throughout its storied past, the city and its environment have faced remarkable transformation. From the early settlement of Indigenous communities within the region to the bustling metropolitan city it is today, Los Angeles is truly in a class of its own.

Renowned for its dazzling Hollywood industry, picturesque boardwalks and beaches, and high-rising mountain ranges, the millions of citizens of Los Angeles have access to a one-of-kind home. However, the growth of the city has come at a great cost to its environment and natural ecosystems. The intense colonization, urbanization, and industrialization that started in the late 1800's has had a lasting detrimental effect on the city.

Los Angeles' climate suffers from numerous environmental issues such as air pollution, increased carbon emissions, extreme water scarcity, and intense wildfires.

Many of Los Angeles' most pressing environmental issues arise from a systemic ignorance and injustice that is and has been present in our society – a society in which citizens are more focused on their personal wealth than the safety and lives of those surrounding them.

Indigenous people tended, cared for, and respected the land that is now Los Angeles. Not only did the many indigenous tribes that inhabited the land protect it, but lived in reciprocity with it - giving back whatever they took and only taking as much as needed. Many of the environmentally conscious traditions practiced by Indigenous people – such as controlled fires and the idea of reciprocity – should be utilized today to restore the Los Angeles environment to what it used to be.

While it is easy to propose changes to Los Angeles's culture, it is necessary to observe and acknowledge the fact that the population of the city has exponentially increased since the 18th century – bringing with it the arrival of more complicated and intense environmental issues.

However, change is possible. It is necessary that the city looks for ways to increase public transportation, implementing an extensive public transit system that is affordable, accessible, and ever-present in society. Additionally, it is important for the city to support more non-profit initiatives that are actively working to combat climate change and conserve the Los Angeles environment.

Most importantly, Los Angeles citizens need a change in mindset. A recent study titled *The California Survey on Othering and Belonging* showed that in 2024 30% of citizens within the state believed that climate change is not mostly caused by human activity (with ⅓ of that group believing that climate change is non-existent). In order to make a lasting change in society it is imperative that everyone understands the urgency of the problem. Los Angeles' climate crisis can be stopped, but only if those around us are willing to make a change.

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**Artificial Intelligence in Passive Acoustic Monitoring of Reefs - A Review and Recent Developments By Alex Liu**


## Abstract

Coral reef monitoring is vital for understanding and conserving coral reef health. Passive Acoustic Monitoring (PAM) is a non-invasive coral reef monitoring method. Reef soundscapes, which strongly reflect ecosystem health, are recorded through either snapshots or long term continuous recordings. It captures the sounds from fish, invertebrates, and the overall reef (i.e. ambient sound). PAM then attempts to find relationships between the ecological community and its soundscape. There are many challenges in using PAM in coral reef monitoring, including correlating the acoustic indices to individual ecological species, and automated analysis of large amounts of data.

This paper reviews recent development and successful applications of using PAM in fish and coral reef monitoring. In addition, this paper also reviews the advancement of artificial intelligence in data analysis, including supervised and unsupervised machine learning models. More recently, a new software interface, CoralSoundExplorer (CSE) was developed to enhance PAM analysis through machine learning, providing rapid and scalable insights into reef conditions. It splits hydrophone recordings obtained from PAM into one-second clips, converting them into spectrograms, and embedding them into high-dimensional vectors using convolutional neural networks. This paper reviews the application details of CSE in coral reef monitoring, compares CSE with traditional PAM analysis, discusses the benefits and limitations of this tool in monitoring the long term health of a reef.



**Key Words** Reef Coral; Passive acoustic monitoring (PAM); Artificial Intelligence; Machine Learning, CoralSoundExplorer (CSE)


## 1. Introduction

Coral reefs are marine ecosystems that support around 25% of ocean species, despite occupying under 1% of the sea floor. They provide ecological and economic benefits as well, such as sequestering carbon and supporting fisheries (Great Barrier Reef Foundation, 2025). Climate change and other anthropogenic sources threatening reefs has made the need to protect these ecosystems increasingly urgent (National Oceanic and Atmospheric Administration, 2025; Harborne et al, 2016; Hughes et al, 2017; Hoegh-Guldberg et al, 2018). Traditionally, monitoring data are typically collected using diver led underwater visual surveys (Obura et al, 2019; Mooney et al, 2020). However, these surveys are highly time and cost-intensive, additionally, these surveys will not be able to respond to the speed of expected changes. Constant reef monitoring, allowing for early detection of issues in coral reef health is vital for conservationists and scientists in addressing the issue before it becomes large-scale.

Passive acoustic monitoring (PAM) has become popular in the coral monitoring world due to its efficiency in finding a holistic view of the reef community (Sinay, 2024; Sueur et al

2008; Lammers et al, 2016; Elise et al 2019; Bertucci et al, 2020). As a non-invasive monitoring tool, PAM uses either snapshots or long term continuous recordings, and captures the sounds from fish, coral reefs and the whole soundscape (i.e. ambient sound). PAM then finds relationships between the ecological community and its soundscape (the full extent of environmental sounds present) (Lamont et al, 2022; Parsons et al 2024; Pijanowski et al 2011). Even though PAM is a well established tool in the ecosystem application, it still presents many challenges in coral reef monitoring, including correlating the acoustic indices to individual ecological species. In addition, due to the large amount of data collected, automated analysis presents a challenge. This paper reviews recent development and successful applications of using PAM in fish and coral reef monitoring. In addition, this paper also reviews the application of artificial intelligence in data analysis, including supervised and unsupervised machine learning models, as well as a new software interface, CoralSoundExplorer, which significantly advanced visualization and quantification of coral reef soundscapes. The benefits and limitations of PAM and these artificial intelligence tools in monitoring the long term health of coral reefs is also discussed.

**2. Application of Passive Acoustic Monitoring (PAM) in Coral Reefs and Fish**

In a recent paper published in 2021 (Van Hoeck et al, 2021), Van Hoeck and colleagues sought to test whether passive acoustic monitoring (PAM) could complement traditional methods like video/visual surveys in tracking community development on artificial reefs. They monitored both a newly deployed artificial reef and an established reef in Onslow Bay, North Carolina. Underwater sound recordings were collected continuously during multiple sampling periods. Simultaneously, they used time-lapse videography to document fish colonization and community progression. In this study, they compared sound pressure level (SPL) time series (low- and high-frequency bands), dusk peak SPLs, power spectra, and species-specific vocalizations across reefs and time periods. They looked for convergence in acoustic signatures, then compared those to video-observed colonization.

In this study, PAM was found to be able to detect temporal and spectral convergence between the new and established reef soundscapes, particularly in low-frequency bands during fish chorusing periods, earlier than some visual methods. In one case, vocalizations from cryptic species (e.g. toadfish) hinted at colonization earlier than video surveys showed. Nonetheless, convergence was not complete, especially in high-frequency bands. In addition, PAM cannot reliably identify all species or disentangle overlapping acoustic sources. Acoustic signals could have been confused by non-biological noise. Despite these caveats, the work by Van Hoeck et al supports integrating PAM into reef monitoring frameworks to yield a more holistic picture of community dynamics.

In a more recent work in 2022 (Elise et al, 2022), Elise et al. aimed to test whether PAM data, when combined with coarse environmental variables, can improve predictions of coral reef fish assemblage structure compared to environmental data alone. They sampled 31 reef slope sites across three Indo-Pacific regions (Reunion, Europa, New Caledonia). Acoustic recordings

were collected from each site during daylight hours and computed a suite of 26 acoustic metrics across multiple frequency bands. Concurrently, they compiled environmental predictors such as reef slope, coral cover, habitat complexity, wave exposure, and anthropogenic pressure. Fish assemblages were quantified with stereo-video or underwater visual census. Fish species were grouped into functional entities (FEs) based on trait combinations (diet, mobility, size, etc.). Using Principal Component Analysis (PCA) to reduce dimensionality, they built linear models predicting 109 fish descriptors from environment alone, acoustics alone, and then combined data. Variation partitioning was used to quantify the unique and shared explanatory power of acoustics vs environment.

They found that in 86 of 109 combined models, predictions were statistically significant. Environmental variables alone explained a larger proportion of variance, but acoustic metrics provided complementary information. For 69% of fish descriptors, the acoustic-only component added a positive prediction value. The greatest gains from acoustics were in functional distribution of abundance descriptors. In addition, acoustic and environmental contributions were largely independent, implying that PAM offers novel signals, which were not captured by habitat variables.

This study also had limitations. For example, the authors added low magnitudes of acoustic contribution (mean ~4%, max ~22%). For many taxonomic descriptors, acoustics added little or no explanatory power. The study also faced methodological heterogeneity in fish surveys, which may bias comparisons, especially for cryptic species. Finally, the snapshot nature of acoustic sampling (i.e. a few hours) cannot capture full temporal dynamics. Despite these challenges, the work shows that combining PAM with environmental data can still enhance reef fish assemblage prediction.

**3. Artificial Intelligence in Passive Acoustic Monitoring (PAM)**

One of the major limitations for PAM in reef monitoring is the species identity for any given sound in reef PAM recordings is usually unknown. The coral reef PAM intends to find relations between the ecological community and its soundscape. Automated analysis is essential in processing the large amount of data collected from PAM. Machine Learning (ML) presents a powerful tool for automating the analysis of acoustic data across multiple ecosystems. Two types of ML are available to analyze the soundscape: supervised and unsupervised learning. Supervised learning involves training ML algorithms on labelled recordings, where labels correspond to an ecological metric of habitat category of interest. The unsupervised algorithm reveals patterns and structures by grouping similar recordings using clustering algorithms.

In their work published in 2025 (Williams et al 2025), the authors presented a methodological framework for analysing whole soundscape recordings from coral reefs, using machine learning (both supervised and unsupervised learning) and deep learning embeddings rather than manual annotation of individual acoustic events. Their goal was to scale up passive acoustic monitoring by leveraging AI methods to uncover ecological signals (e.g. coral cover, fish community, depth zones) from bulk audio data. They tested the approach on three

geographically distinct reef datasets, including Indonesia, Australia and French Polynesia. Each dataset was annotated with ecological labels such as “high vs low fish diversity,” “high vs low coral cover,” and “shallow vs mesophotic depth zone.” Three key methods were used for extracting features from coral reef soundscapes to feed into AI models. The first method is the Compound Acoustic Index (CAI). CAI combines 12 traditional acoustic indices (e.g., spectral entropy, acoustic complexity, evenness). These summarize energy distributions but lose temporal and spectral detail. The second method is Pretrained CNN (P-CNN), which uses embeddings from a *VGGish* network pretrained on 5.2 million hours of YouTube audio. It converts reef audio clips into 128-dimensional embeddings that capture general acoustic texture and structure without retraining. The last method is Task-Trained CNN (T-CNN). A T-CNN trained directly on each reef dataset to optimize for ecological classification (fish diversity, coral cover, or depth zone). It learns task-specific spectral–temporal features.

When studying unsupervised learning, the authors examined how the Uniform Manifold Approximation and Projection (UMAP), can reveal structure in coral reef soundscapes. UMAP visualizations based on P-CNN embeddings showed that recordings from Indonesia, Australia, and French Polynesia formed distinct clusters. Unique acoustic characteristics in each region were also shown. Within individual datasets, clusters often corresponded to known ecological classes such as habitat type or fish diversity. This suggested that the ecological variables shape local soundscapes. Among the three embedding methods tested, the task-trained T-CNN produced the clearest and most discrete habitat-based clusters. The second was from the P-CNN method and then the traditional compound acoustic index. The UMAP plots also captured site-specific “fingerprints”, when instruments were fixed in place, this is most evident in the French Polynesian recordings.

Beyond spatial distinctions, UMAP projections uncovered temporal structure in reef acoustics, revealing daily and lunar cycles. In French Polynesia, crepuscular hours bridged day and night clusters, while in Indonesia, recordings from two sites converged acoustically around the new moon. Quantitative validation through affinity propagation clustering also supported these findings. Chi-square tests were significant ($p < 0.001$) for all embedding types. This confirms that cluster correspondence to ecological classes is not random. The T-CNN produced highest chi-square scores, and demonstrated the strongest alignment with habitat and site identity. P-CNN results were nearly equivalent for the data from French Polynesia. The results showed that unsupervised deep embeddings effectively capture spatial and temporal ecological patterns in reef soundscapes. The unsupervised learning provides a powerful, label-free approach to monitoring biodiversity and ecosystem dynamics.

For the supervised learning ML model, the authors explored how to predict habitat class and site identity. Their study assessed the ability of machine learning classifiers to predict habitat class and site identity from one-minute coral reef soundscape recordings using three feature extraction methods: compound indices, P-CNNs, and T-CNNs. Across six classification tasks, models achieved strong results, with accuracies ranging from 0.56 to 1.00. The French Polynesian dataset showed the highest accuracy. The Australian dataset performed the weakest,

partly due to data variability and site proximity. Results also varied across training-test divisions, indicating that dataset composition significantly influenced performance. Among the methods tested, the T-CNN consistently achieved the best performance for most tasks, particularly for Indonesian and French Polynesian classifications. The compound index occasionally performed better, as observed in the Australian site classifier.

Analysis of confusion matrices revealed similar patterns of misclassification across all methods, which means that ecological or spatial similarities between sites contributed to classification errors. For instance, shallow and mesophotic habitats in the French Polynesian dataset were sometimes misclassified due to overlapping acoustic signatures. The Australian dataset also showed site confusion likely caused by nearby low-diversity habitats. Overall, these studies highlight the robust potential of supervised learning to identify reef habitats and site differences using passive acoustic monitoring data.

With the studies using unsupervised and supervised models, the authors demonstrated how machine learning, particularly deep learning, can transform the analysis of coral reef soundscapes. Using more than 20,000 one-minute recordings from three geographically distinct reefs, the authors found that ML models using embedding-based features can effectively cluster and interpret vast acoustic datasets. Unsupervised learning methods, such as UMAP, proved especially powerful for visualizing soundscape structure and revealing relationships tied to reef ecology.

Among ML techniques, trained convolutional neural networks (T-CNNs) delivered the highest accuracy but it also required significant computational resources. Pretrained CNNs offered nearly equivalent performance at far lower cost. The study suggests that combining unsupervised learning with standardized P-CNN embeddings may provide the best balance between efficiency and interpretability. As low-cost recording tools and scalable AI systems become more available, these approaches could transform how coral reefs are monitored and conserved worldwide.

**4. *CoralSoundExplorer* - An Advancement in Visualization and Quantification**

A new application of PAM, *CoralSoundExplorer* (CSE), uses an artificial intelligence pipeline that combines unsupervised and supervised machine learning, allowing the user to visualize changes in a reef's soundscape over time (Miner et al, 2025). Miner, et al built CSE with the goal of classifying several reefs in Bora Bora as undisturbed areas, boat sites, or sites disturbed by tourists, or quantifying the evolution of a soundscape over time, enabling the disturbance of detection. The tool is open source and has been designed to be easy to use, even by non-specialists.

*How does CoralSoundExplorer work?*

*CoralSoundExplorer* uses data collected from reefs surrounding the French Polynesian Island of Bora Bora. Bora Bora is a volcanic area that is home to extensive coral reefs. The authors intended to identify three types of sites on the south-western region of Bora Bora from

the recordings: 1, a tourist site with healthy reefs and snorkels; 2, an undisturbed site with high coral cover and little boats or tourists, and 3, a deep, sandy channel that is a boat site without tourists. For the dataset, authors took underwater recordings with SNAP long-term autonomous acoustic recorders (Loggerhead Instruments; Sarasota, FL, USA) that were equipped with a HTI-96-Min hydrophone. The recording instruments were placed in the same position at depths of 1m, 2m, and 3m for each 3 sites respectively. This is because the sites varied in depth, with the boat site being the deepest and the tourist site being the least deep. The data used for CSE can also be found on Zenodo for others' projects, an open research repository.

Each audio recording was cut into one second clips. The audio was analyzed in two ways. The first was through clustering with PCA and UMAP. These audio clips were transformed into spectrograms, visual representations of frequency that varies with time. These spectrograms were then converted by a Convolutional Neural Network into mathematical values stored in a vector. The paper referred to this step as projecting the audio clips into a multidimensional space, which was done through a mel spectrum, mel-spectrogram, or VGGish embedding. The vector was reduced again via Principal Component Analysis (PCA). Initially, each vector contained a plethora of numbers representing qualities such as pitch and variance. PCA, a dimensionality reduction technique commonly used in machine learning, reduced the number of dimensions of the data by extracting "principal components" from the vector which were axes representing the most significant patterns and variations in the data. PCA was likely used for this step because it can find linear relationships between vectors that didn't have linear relationships. UMAP was then followed as another dimension reduction technique to actually cluster data points onto the 2d or 3d graph, which can be seen via the user interface of the Coral Sound Explorer software. UMAP can plot relatively similar data points closer, and relatively different data points farther apart. From the data generated by PCA, UMAP must retrain the original "local structure" which means that data points generated by PCA that were close to each other will remain close to each other when graphed by UMAP.

UMAP replicates the geometric relationships of the original high-dimensional space in lower dimensions, and it clusters acoustic recordings into points. The other way was through calculating a silhouette index, which quantifies how similar audios are. The closer the silhouette index is towards 0, the more acoustically similar clips are, while the closer it is to 1, the less acoustically similar the clips are. The silhouette index was calculated from "100 3D UMAPS" based on how far points are from each other. The index between a tourist and undisturbed site, for example, could be around 0.3, while the index between an undisturbed site and boat site, which would be a contrast between no noise and very loud vehicle noise, could be 0.75.

CSE was also used to perform unsupervised learning to cluster groups of sounds. When the authors analyzed recordings from Bora Bora, the CSE algorithm came up with 8 clusters. Cluster 0 was made 98.40% by sounds from a boat site. Cluster 1 was made 48.87% by sounds from a tourist site at 49.72% and by sounds from an undisturbed site at. Because 16% of boat site recordings have not been assigned to a cluster (id: -1). This unsupervised learning showed that the boat site was rather acoustically different from the other two sites. Other clusters such as

cluster 2 were similar to cluster one because it was made from boatsites, but with a more narrow frequency, suggesting the model has clustered various types of vehicles. Cluster 6 was made by 55.41% tourist sites and 44.58% undisturbed sites, abundant in low frequency sounds and fish noises. Overall, these modes of analysis were helpful as a preemptive tool in coral health monitoring with clustering providing a way to visualize and separate emergent groups of sounds across sites. The silhouette index offered a numerical measure of how distinct or overlapping those groups are, making it useful for comparing reefs quantitatively over time.

Ultimately, CSE was able to identify disturbances throughout 24 hours, like a period of boating or rain. It also clustered acoustic recordings by patterns that are harder to detect manually, and finally, it saved much time compared to traditional methods of passive acoustic monitoring analysis.

*How does CoralSoundExplorer Compare with traditional PAM ?*

One main drawback of using PAM in coral reef monitoring is that it is difficult to analyze such large amounts of data. CSE makes this process extremely fast through machine learning, but this could limit the information scientists are able to extract if they calculate traditional ecological indices from PAM data. For example, when reviewing studies on PAM used for anuran (a species of frog) conservation , Lassandro et al found that ecological aspects most researched were the calling patterns of the frog (45/72), and species richness of the overall ecosystem (19/72) (Lassandro et al, 2025). CSE derives a richness value for each of the data points as well. This value doesn't completely dictate each data point's position, but it is directly correlated with the species richness of the reef. Additionally, unsupervised learning allows CSE to cluster data points together based on discrepancies in both frequency present in recordings, and the intensity of sound. This would provide insight into patterns like the calling of the frogs, such as periods of shrimp snaps or intense boat traffic.

Some situations in PAM require detecting individual sounds, while others require looking at the soundscape as a whole. For example in situations where vocalization happens via multiple species and it's difficult to pinpoint one species. Also, when studying systems where the source of the sound is unknown, or when the question focuses on the overall community. CSE doesn't enable such precise analysis as traditional eco-acoustic analysis would because the points and values are clustered in respect to each other, making data interpretation inconsistent. However, CSE can visualize the different frequencies within a soundscape. But the result would be mixed - for example, some fish vocalizations and boat sounds may have the same frequency, meaning CSE would cluster those two together. It is known that supervised learning can train models that identify ecological sites from a soundscape, whereas unsupervised learning can provide a greater and more detailed understanding of ecological sites, which is what CSE is based on. But if only one species of fish needs to be identified or the analysis of PAM data must be changed for some purpose, that is where CSE falls short.

Another drawback of CSE may be the presence of anthropogenic noise disrupting PAM monitoring. Although CSE can easily cluster anthropogenic noise and the biophony apart, there

is also a way to limit recording the anthropogenic noise altogether. For example, Elise et al accomplished this in their work (Elise et al, 2019). In both research papers (Elise et al, 2019; Minier et al, 2025), the hydrophone used captures similar ranges. In terms of recording, the HTI-96-Min hydrophone covers a frequency range from 2Hz to 30 KHz, which is more than enough for the reef's soundscape as most organisms fall within this range. For example, pistol or snapping shrimp create sounds from 2-5 kHz. Elise et al 2019 used a RESON hydrophone that captures a frequency range of 30hz to 100kHz. However, within this frequency of 30 Hz to 100 kHz, Elise et al studied four specific bandwidths and specific frequencies which target ecologically relevant frequencies. They targeted and derived traditional ecoacoustic indices from 0.1-0.5kHz, 0.5-1 kHz, 1-2 kHz, and 2-7 kHz which allows the recordings to be primarily dominated by relevant biological sound, as most anthropogenic commercial shipping or seismic exploration fall within 100-500 Hz (0.1-0.5 kHz will capture anthropogenic noise). In classifying reefs' ecological states, Elise et al found that data taken from a frequency that encompasses 2-10 kHz often gave better predictions of a reef's ecoscape as it captures mostly biologically relevant sounds.

In terms of timing and frequency, Elise et al took recordings that could be used to account for large discrepancies in future datasets. They took recordings during the day which is from 2 hours after sunrise to 2 hours before sunset, and at night which is from 3 hours after sunset to 2 hours before sunrise. They did not include dawn and dusk because the soundscape changed too rapidly. They also took into account moon phases and temperature as they found that peak biological activity occurred with every new moon, and the cool season lasted from September to October while the warm season lasted from March to April. This is an important consideration because reef-life is very dependent on those two conditions. For example, coral spawning is heavily influenced by the oceanic temperature and moon. Ultimately, Elise et al found that recording the audio at night was most effective for successfully discriminating amongst reef ecostates as there is less anthropogenic noise. They also found that in total, around 250 minutes across samples and multiple nights allows for a reef to be accurately discriminated among ecostates. In contrast, Minier et al initially analyzed data recorded throughout 24 hour periods in which every 10 minutes, one minute of audio was recorded. So within one day, 144 minutes of audio was recorded. It would be better to spread out this recording so that it's less frequent than every 10 minutes so that 250 minutes of recording can be reached. This would be optimal for classifying reef ecostates, while having the general trend be spread throughout the duration of a week or a month.

Even though it might not be most efficient at finding exact species, CSE is still a great complement as a first step coral monitoring process for its quickness of detection for any changes in a reef's soundscape, both day to day and long term.

**5. The Future of Passive Acoustic Monitoring and CoralSoundExplorer Applications**

Passive Acoustic Monitoring of coral reefs, especially complemented with artificial intelligence tools, such as machine learning, and real time visualization tools such as the

CoralSoundExplorer, offer critical insights into the state of coral reef ecosystems. In particular, the CSE software was designed so that there is no need for the process of extracting traditional acoustic indices. It can be used as a way to gauge the general trend of a reef without extensive surveying. The NOAA's Coral Reef Restoration Project (NOAA Fisheries, 2025) pairs with partners across the united states, and has established the National Coral Reef Monitoring Program. Scientists were sent to perform annual surveys on reefs at American Sāmoa, Hawai‘i, including the Papahānaumokuākea Marine National Monument, the Mariana Archipelago; Guam and the Commonwealth of the Northern Mariana Islands, the Pacific Remote Island Areas: Wake, Johnston, Howland, Baker, and Jarvis Islands, and Palmyra and Kingman Atolls. Their surveys include counting fish and imaging coral. However, the project fails to account for reefs located elsewhere, not in the pacific, and their surveys which are carried out annually may not capture rapidly declining reef health, which can happen due to coral bleaching especially (Watson, 2025). With CSE and PAM, however, scientists can understand a reef's general soundscape trend throughout the year when surveys are not being done, providing important insight on reef changes such as if a new boating route went across that reef. Additionally, this information will be a crucial preemptive measure in preventing a reef's deterioration because of how scalable the process is compared to diver-based methods. PAM is cost effective, and can be deployed in more conditions. CSE makes PAM analysis faster. If any negative trend is detected in the reef's audio through the CSE software, scientists can then conduct further visual and other field surveys because, regardless of the cause, a deteriorating soundscape will negatively impact reefs as reef sounds guide the orientation and habitat settlement of many fish and larvae.

**6. Conclusion**

Passive Acoustic Monitoring (PAM) has become an increasingly valuable tool in assessing coral reef and fish communities. It provides a continuous, non-invasive method of tracking ecological activity. Unlike traditional diver-led surveys, PAM captures the complex soundscape of reef ecosystems, encompassing biophony, geophony, and anthropophony. Through these acoustic signatures, researchers can infer ecological status, biodiversity, and changes over a period of time. Studies have shown that PAM complements visual and environmental data, and enhances predictions of fish assemblage structure and ecological function. However, despite its advantages, PAM also faces challenges, including the difficulty in linking specific sounds to taxa, managing massive datasets, and isolating biological from anthropogenic noise. Nevertheless, its efficiency, and ability to detect temporal and spatial dynamics make PAM an indispensable component of modern reef monitoring strategies.

The integration of Artificial Intelligence (AI), particularly machine learning, has significantly improved the analytical power of PAM. Deep learning techniques, including convolutional neural networks (CNNs), enable automated extraction of meaningful ecological information from raw audio recordings. Supervised learning models can accurately classify reef habitats and site identities. Unsupervised methods such as UMAP uncover ecological and temporal patterns within soundscapes. These advances allow researchers to interpret massive

datasets efficiently and detect subtle ecological signals. It will help to reveal relationships between reef soundscapes and biodiversity. However, AI applications still require rigorous methodological standardization in order to ensure reliable and interpretable results. Addressing these limitations will be essential for large-scale and automated reef monitoring.

Recent developments such as CoralSoundExplorer illustrate the next step in PAM-AI integration. CSE's combination of supervised and unsupervised learning provides rapid visualization and quantification of reef soundscapes. It allows users to detect disturbances and track ecosystem changes over time. Its accessible interface allows both specialists and non-specialists to assess reef conditions quickly. While CSE cannot yet replace detailed ecological indices or species-level identification, it serves as a powerful early-warning and trend-detection system for reef health assessment. As climate change and human activities continue to threaten coral reefs, integrating PAM with AI-driven tools like CSE will be critical for scalable and real-time global reef monitoring.

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# A Novel Approach to Quantum Error Mitigation: Resolving Coherent Errors with Variational Quantum Algorithms and Machine Learning

By Adhit Natla, Sachit Gonur, and Henry Lu

## ABSTRACT

Although quantum computing promises exponential speedups over classical computation, it remains hindered by various forms of errors. Coherent errors, in particular, occur due to miscalibrations in quantum gates, causing slight overrotations or underrotations on the quantum state. Despite being very minor, such errors accumulate over time, deviating the final state significantly. Our research proposes to mitigate such coherent errors through two primary approaches: a mathematics-based calibration model to address static errors, and a machine learning model that addresses time-dependent errors. Our static error correction scheme uses an ancilla-assisted calibration protocol that uses swap gates to account for the deviations in hardware, and then estimates the overrotations via a mathematical model. The model predicts the error within 3 significant figures. For the time-dependent error, we relied on a Long Short-Term Memory model to determine the error based on the time-dependent temperature and resistance. In the paper, we also implemented a polynomial regression model to predict the attenuation and calculate the resulting error. With outliers corrected, we were able to get a training $R^2$ of 0.89 and a cross-validation $R^2$ of 0.44.

**Keywords** coherent errors, gate operations, ancilla-assisted calibration protocol, Long Short-term Memory

## I. INTRODUCTION

Quantum computing is positioned to revolutionize classical computation, including advancements in digital networks, secure communications, cryptography, and complex mathematical calculations. The quantum computing system works via qubits, the fundamental units of quantum information. While classical computers process information through units known as bits, which represent a rudimentary value of either 1 or 0, qubits function based on the principles of quantum mechanics, which allow them to exist in a mixed state known as superposition. [1].

Superposition allows qubits to exist in a linear combination of both 0 and 1 simultaneously, hence allowing quantum systems to process a vast number of tasks in parallel [2]. Additionally, qubits can enter a state known as entanglement, where they are intrinsically linked to another regardless of the distance separating them. This phenomenon allows for theoretical communication methods like quantum teleportation, where two receivers can utilize entangled qubits to send and receive information [3].

Mathematically, such quantum weirdness is best encapsulated by the Copenhagen interpretation, understanding a quantum particle as a mathematical superposition of quantum bases states until a probabilistic collapse at the measurement. With the elegant use of bracket

notation, matrices and imaginary numbers, a quantum circuit can be represented as a series of operators acting on a quantum state.

Moreover, quantum algorithms remain dependent on carefully tuned quantum gates, which manipulate qubit states similar to how logic gates function on classical computers. However the latter lacks the ability to utilize superposition and entanglement limiting it to binary operations. Quantum gates are unitary operations that cause the qubit to rotate a precise amount, which can change the probability amplitude of the qubit's states as well as its phase. [4]. A few examples of these gates include the Pauli-X gate and the Hadamard gate. The Pauli-X gate flips the qubit's state, analogous to the classical NOT gate, while the Hadamard gate creates superposition by rotating the qubit from a deterministic state ($|0\rangle$ or $|1\rangle$) to an equal superposition of 0 and 1. Other more complicated gates include the CNOT gate, which places two qubits in a state of entanglement. Entanglement fundamentally connects two qubits and instantly reflects any change in one in the other. However, in order to maintain the intricacy of these gates, especially in superconducting qubits, there must be a delicate electromagnetic pulse and precise control of the qubit's environment. In reality, however, maintaining an ideal state like this remains a key challenge, as even minute imperfections during gate operations or random noise can introduce errors that collapse the entire system.

Despite the vast possibilities of quantum computing, it remains hindered by various forms of errors because qubits are extremely susceptible to environmental imperfections; errors can fall into one of two categories: incoherent (stochastic) or coherent (systematic) [5]. Incoherent errors are random errors that arise from unpredictable environmental noise, such as temperature beyond the ideal threshold, stray photons from external light, or even electromagnetic radiation [6]. Noise such as bit flips are usually not a big issue, as they tend to average out. However, a breakdown of the superposition or entanglement in a qubit system is a much bigger problem. These various forms of noise can lead to a state known as decoherence, which is when the qubits can no longer maintain foundational states like superposition and entanglement. Without these traits, quantum computing does not have any advantage over classical computing[7]. Another type of error is coherent errors. Coherent errors are repeatable and systematic errors caused by an overrotation when a quantum gate is applied. These can be due to various factors, including faulty hardware and temperature fluctuations. These errors can be extremely pernicious, because they can accumulate and cause larger deviations from ideal states; for instance, a single-qubit rotation intended to be 180 degrees might consistently over-rotate by a small angle which can later lead to a cumulative gap that draws us away from the intended state [8].

Errors are also very dangerous in complicated entangled systems, where a change in one qubit is reflected in the entire system. Coherent errors especially present this problem, because they are not detected in statistical measurements. Coherent errors generally change the phase of a quantum state by a small amount. This means that the measurement of the state remains roughly the same. However, repeated operations by fault gate will have a catastrophic cascading effect on the entangled state.

To mediate these effects, we need to use an algorithm that will account for these faults in current quantum hardware. A great choice for these constraints are Variational Quantum Algorithms, which combine quantum and classical methods for more stable outcomes. Generally, a VQA will define a quantum cost function which will not be possible to calculate on a classical computer and use a classical optimizer to minimize the cost function. This puts most of the training burden on the classical computer, greatly reducing the possibility of errors.

Previous research has already been done regarding how to mitigate coherent errors through calibration techniques. For instance, according to a study conducted by David Mckay in "Efficient Z Gates for Quantum Computing" a similar approach was utilized to calibrate a single qubit gate through randomized benchmarking and an iterative phase estimation in order to determine the magnitude of over rotation [9]. Their methodology is somewhat synonymous with our strategy of addressing gate level miscalibration in qubits. Similarly, according to Lukasz Cincio, a theoretical division scientist in the Los Alamos National Laboratory, he introduced the applicability of a Noise Aware Circuit Learning (NACL), a machine learning system that optimizes variational circuits to reduce quantum hardware noise and coherent errors in multilayered qubit systems [10]. Although both studies utilized a form variational parameter testing and optimization in order to improve gate fidelity, their primary focus was targeted to state preparation and benchmarking rather than analyzing the effects of coherent error on qubits. Our research aims to fill this gap by proposing a scheme that accounts for the hardware in qubits, which can result in different errors under the same circumstances. Our work using ancilla-assisted variational calibration, estimates and compensates for over rotations by using machine learning techniques such as gradient descent and a time series machine learning model.

## II. METHODS / METHODOLOGY

### A. Simulating how errors propagate through a quantum system

We simulated the propagation of a small gate overrotation in a quantum system. We entangled our qubits in a GHZ state, which is a maximally entangled state. This state would have an equal probability of being 0 and 1, and we can represent it as:

$$|\mathrm{GHZ}\rangle = \frac{1}{\sqrt{2}}\left(|0\rangle^{\otimes n} + |1\rangle^{\otimes n}\right).$$

We used 3 and 5 qubits in our GHZ state, but this is not a fixed number and can be changed to anything. The GHZ state is maximally entangled, which makes it very sensitive to any errors. We apply a target rotation angle of $\boldsymbol{\theta} = \frac{\pi}{3}$ and an error ε that varies from $\frac{\pi}{12}$ to $\frac{\pi}{24}$. The rotation gate that we used was an $R_X(\boldsymbol{\theta})$ gate, which is a rotation about the x-axis $\boldsymbol{\theta}$ degrees. We then calculated the fidelity of our error quantum state with respect to our target quantum state. State fidelity is a measure of how similar two quantum states are to each other: 0 means that they are orthogonal, and 1 means that they are identical. The fidelity of pure quantum states is calculated as the magnitude of the square of the inner product of the two quantum states.

$$F(|\psi\rangle, |\phi\rangle) = |\langle\psi|\phi\rangle|^2$$

Finally, we plotted the ε against the fidelity of the state to see how much ε changed the final quantum state.

Our second procedure was repeatedly applying the same erroneous gate to our system of entangled qubits. We applied the gate 1 to 10 times, and calculated the state fidelity of the current state to our original state. We fixed our error at $\varepsilon = \frac{\pi}{12}$.

We then standardized the x-axis of both of these graphs, and calculated their slope. We converted the x-axis of these graphs to z-scores to calculate the standardized slope.

**B. Detecting and correcting static errors in entangled systems**

Static errors are a simplified subset of general coherent errors in quantum systems. They don't change with time, meaning that we can calculate the error at one timestep and apply the correction throughout the entire computation. However, errors are hardware specific, which means that the same fluctuation in a microwave pulse will result in a different error for different qubits. Slight errors in manufacturing will result in different properties, such as junction resistance in superconducting qubits, for each qubit [9]. However, we also want to measure the error qubit without destroying its quantum state, which might be complicated to reprepare. As a result, we proposed two different approaches using an ancilla qubit to measure the error on these qubits.

Our original approach was to use a phase kickback protocol to transfer the error on our target state, which we'll call $|\psi\rangle$, without directly measuring it and collapsing its superposition.

A few notes to consider before our procedure: **(1)** the ancilla also has an error on it, **(2)** we assume that our error was additive, **(3)** in our code we reprepared $|\psi\rangle$ every time we ran our circuit again due to how Qiskit operates, however in a real quantum computer this step is not necessary.

For the circuit we define the following variables:

| | |
|---|---|
| $\|\psi\rangle$ | Target state |
| | |
| **θ** | Target gate angle |
| ε | Constant additive error on $\|\psi\rangle$ |
| $\delta$ | Prediction of ε |
| $\varepsilon_2$ | Constant additive error on ancilla |
| $\delta_2$ | Prediction of $\varepsilon_2$ |

| | |
|---|---|
| n | Number of circuit repetitions |

As we try to rotate a qubit by angle $\boldsymbol{\theta}$, the gate rotates it by $\boldsymbol{\theta} + \varepsilon$ due to the coherent error. $\delta$ is our prediction of the error, which allows for multiple epochs of approximation as $\delta$ refreshes. It is worth noting that while $\delta$ is helpful for the gradient descent, it fails to improve the mathematical relationship since the precision of $\varepsilon$ depends solely on the number of trials done for the probability.

Our first approach was to use a phase kickback circuit to transfer the error on $|\psi\rangle$ to our ancilla qubit. It accounted for the hardware error by determining what the error was on the qubit with $|\psi\rangle$. The errored gate is already applied on $|\psi\rangle$.

Our old steps were as follows:

1. Change $|\psi\rangle$ and the ancilla to the x basis by applying a Hadamard gate
2. Use an $R_Z$ gate to rotate the ancilla by $2\pi$
3. Change the ancilla to the Z basis by applying a Hadamard gate
4. Measure the ancilla and predict what $\varepsilon_2$ is and store in $\delta_2$
5. Change the ancilla to the X basis by applying a Hadamard gate
6. Entangle the ancilla and $|\psi\rangle$ with a CNOT gate($|\psi\rangle$ is control, ancilla is target)
7. Use a CNOT gate to disentangle the qubits($|\psi\rangle$ is control, ancilla is target)
8. Use the $R_Z$ gate to rotate ancilla by $-(\boldsymbol{\theta} + (\delta - \delta_2) + \varepsilon_2)$
9. Apply a Hadamard gate to $|\psi\rangle$ and ancilla
10. Measure ancilla and calculate loss
11. Reset ancilla to 0 and then repeat above steps(recalculating error on ancilla is not needed) until loss is below $10^{-4}$
12. Use the $R_Z$ gate to rotate $|\psi\rangle$ by $-(n * (\boldsymbol{\theta} + \delta) + \delta)$

Unfortunately, this approach had a flaw in that the our $R_Z$ and our CNOT gate did not commute, resulting in a change of $|\psi\rangle$. We also overlooked the fact that $R_Z$ gates aren't actually implemented in hardware as pulses, they are just simulated in software.

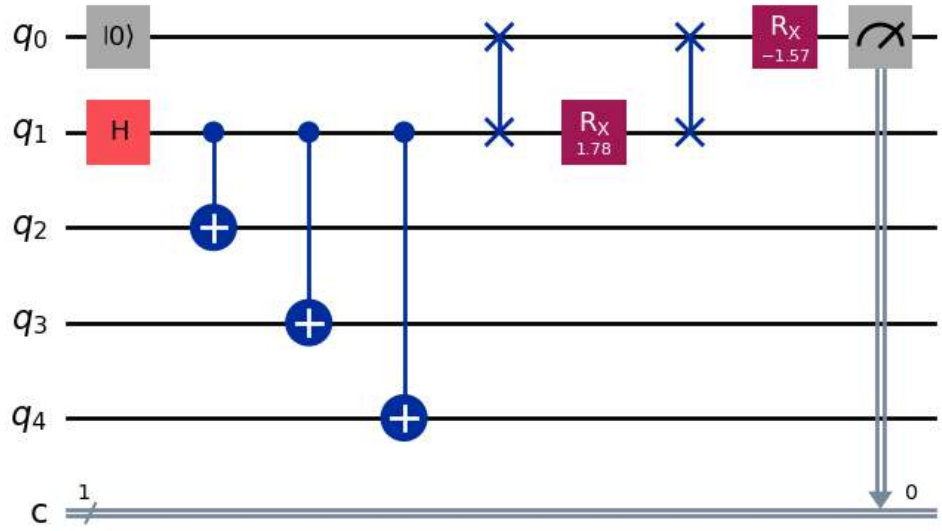
Our second approach was to use a swap gate protocol that swapped our ancilla qubit and $|\psi\rangle$. It was the same idea as our phase kickback circuit, however we didn't need to make sure that any gates commuted because we didn't apply any faulty operations on $|\psi\rangle$. We also used the $R_X$ gate.

The $|\psi\rangle$ state is qubits 1 through 4, and the CNOT gates entangle them together into one quantum state.

Our steps are as follows:

1. Apply a SWAP gate to the ancilla and $|\psi\rangle$

2. Apply an $R_X$ gate to the ancilla and rotate by $\boldsymbol{\theta} + \varepsilon$
3. Apply a SWAP gate to the ancilla and $|\psi\rangle$
4. Apply an $R_X$ gate to the ancilla and rotate by $-\boldsymbol{\theta} - \delta - \delta_2 + \varepsilon_2$
5. Measure the ancilla and calculate the loss




We ran both of these circuits $10^8$ times to get an accurate probability distribution. Initially, we used gradient descent to optimize our function. We numerically calculated the gradient and ran it until the loss dropped under our threshold. However, we were able to find a closed form solution for $\varepsilon$ in terms of $\delta$ and the probability of the ancilla in the $|1\rangle$ state.

We start by defining the notations according to standard quantum computation. The ancilla qubit starts in the 0 state of the computational basis, represented by

$$|0\rangle = \begin{pmatrix} 1 \\ 0 \end{pmatrix}$$

The rotation matrices are defined as followed:

$$Rx(\phi) = cos(2\phi)I - isin(2\phi)X = \begin{pmatrix} cos(2\phi) & -isin(2\phi) \\ -isin(2\phi) & cos(2\phi) \end{pmatrix}$$

In the case of our circuits, the qubit is rotated by $\boldsymbol{\theta}$ plus epsilon and negative $\boldsymbol{\theta}$ minus $\delta$.

$$Rx(\theta+\epsilon) = \begin{pmatrix} cos\frac{\theta+\epsilon}{2} & -isin\frac{\theta+\epsilon}{2} \\ -isin\frac{\theta+\epsilon}{2} & cos\frac{\theta+\epsilon}{2} \end{pmatrix};\ Rx(-\theta-\delta) = \begin{pmatrix} cos\frac{\theta+\delta}{2} & isin\frac{\theta+\delta}{2} \\ isin\frac{\theta+\delta}{2} & cos\frac{\theta+\delta}{2} \end{pmatrix}$$

Therefore, as we perform the operations, the final state of the qubit can be represented in the mathematical notation

$$Rx(-\theta-\delta)\cdot Rx(\theta+\varepsilon)\cdot|0\rangle = \begin{pmatrix} cos\frac{-\theta-\delta}{2} & -isin\frac{-\theta-\delta}{2} \\ -isin\frac{-\theta-\delta}{2} & cos\frac{-\theta-\delta}{2} \end{pmatrix}\cdot\begin{pmatrix} cos\frac{\theta+\delta}{2} & -isin\frac{\theta+\delta}{2} \\ -isin\frac{\theta+\delta}{2} & cos\frac{\theta+\delta}{2} \end{pmatrix}\cdot\begin{pmatrix}1\\0\end{pmatrix}$$

$$= \begin{pmatrix} cos(2\theta+\epsilon)cos(2\theta+\delta)+sin(2\theta+\epsilon)sin(2\theta+\delta) \\ i(cos(2\theta+\epsilon)sin(2\theta+\delta)-sin(2\theta+\epsilon)cos\,(2\theta+\delta)) \end{pmatrix}$$

$$= \begin{pmatrix} cos\frac{\epsilon-\delta}{2} \\ -isin\frac{\epsilon-\delta}{2} \end{pmatrix}$$

According to Born's theorem, we can then derive the probability of the final state collapsing to the $|1\rangle$ state as the norm squared of the second component:

$$P(1) = \left|-isin\frac{\epsilon-\delta}{2}\right|^2 = sin^2\frac{\epsilon-\delta}{2}$$

Reorganizing the components, we can start from a measured probability and an initial guess $\delta$ to find the error epsilon. Of course, this is not an absolute calculation due to the probabilistic nature of quantum computing, but rather allows for accurate estimations of epsilon as the probability is ascertained with multiple trials.

This allowed us to rapidly speed up our algorithm and give us greater precision. Gradient descent is still a viable algorithm, however it may take a very long time to converge.

**C. Coherent errors due to temperature drift**

A more realistic scenario in quantum computers are drifting errors, in which ε can change due to fluctuations in the environment. A very common example of this is temperature drift, where the temperature causes changes in the properties of the hardware. Fluctuations in the temperature can change material properties such as resistance and dielectric loss in the hardware used to send gate pulses, which can then cause an error in the signal sent. This type of coherent error is called attenuation, which is a measure of the loss of a signal.

I. As the temperature fluctuates with time and coherent errors aren't random, we can use a time series model to predict the error. We propose a Long Short Term Memory (LSTM) model, a type of Recurrent Neural Network(RNN). An LSTM would be ideal for this because its long term cell state would prevent our gradients from exploding or vanishing, a common problem with RNNs.

   The LSTM's inputs would be temperature, past errors, and qubit ID as input, and it would then predict the error at some timestep in the future. Our LSTM only focuses on resistive loss.

   The qubit ID input vector was passed in as a parameter, ensuring that the LSTM separately trained weights for each qubit.

Unfortunately, as there was no publicly available dataset, we ended up simulating our data. We broke up our data generation into 3 processes: **(1)** temperature fluctuations through time, **(2)** resistance as a function of temperature, and **(3)** attenuation caused by the resistance.

**(1)** Temperature

To model temperature, we used a sinusoidal function and added random noise. Although temperature in quantum systems is generally random, we use a sinusoidal function to model the fluctuations. Our function also includes a factor for qubit-specific hardware, which we just added as a constant. This can be tweaked depending on the hardware, and will be more complicated than just a simple constant.

Sinusoidal temperature drift:

$$t_0 + A \cdot \sin(\omega t + \phi)$$

Qubit shift:

$$q_f \cdot \sin(\omega t + \phi)$$

We added random noise based off of a normal distribution and scaled it appropriately. $n_l$ is our maximum noise level.

$$\epsilon(t) \sim \mathcal{N}(0, n_l^2)$$

Final temperature equation:

$$T(t) = t_0 + (A + q_f)\sin(\omega t + \phi) + \epsilon(t)$$

**(2)** Resistance

To model resistance, we started off with the Bloch-Grüneisen Law [10]. At low temperatures, this law can be approximated by the following equation, where $T$ is the temperature and α is the temperature coefficient of resistance:

$$R(T) = R_0 + \alpha \cdot T^5$$

**(3)** Attenuation

To model attenuation, we used the formula:

$$\alpha(R) = \frac{1}{l} \cdot \sqrt{R}$$

where $l$ is the length of the cable and $R$ is the resistance[11].

To predict error some timesteps in the future, we use autoregressive inference. Autoregressive inference predicts the next value in the sequence, then appends that value to the training data. It then predicts the next value and continues this process until it gets to the target timestep.

To prevent our model from overfitting, we added a dropout of 0.3, and added 2 layers to the model. We used a batch size of 32 and 50 epochs to train our model. Our optimizer was the Adam optimizer, and we used the MSE(Mean Squared Error) loss function.

II. We wanted to run a regression on real data, however, so we managed to find a small dataset. We were able to get 23 data points connecting temperature, resistance, and attenuation[12]. We analyzed coaxial cables of varying hardware and found a strong square root relationship between them using polynomial regression. To account for these changes in hardware, we used baseline correction to first linearly scale up all of the resistances at 300 K to 100 Ω and used that scaling for 77 K and 13 K, and then subtracted the 300 K value from the others.

## III. RESULTS / ANALYSIS

### A. Simulating how errors propagate through a quantum system

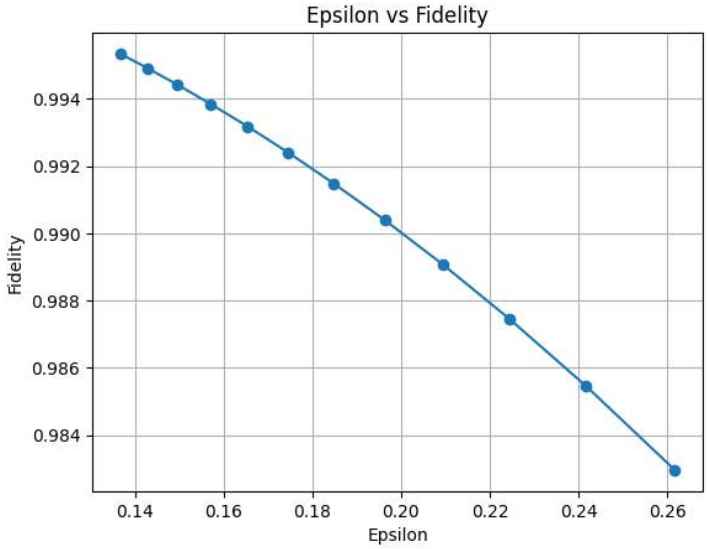



FIG. 1. Error vs Fidelity graph. ε was varied from $\frac{\pi}{12}$ to $\frac{\pi}{23}$, and the fidelity of the resulting quantum state was calculated. The fidelity varied slightly with the error, and the entangled state stayed very close to the ideal state. Running a linear regression on the data gave a standardized slope of -0.003777.

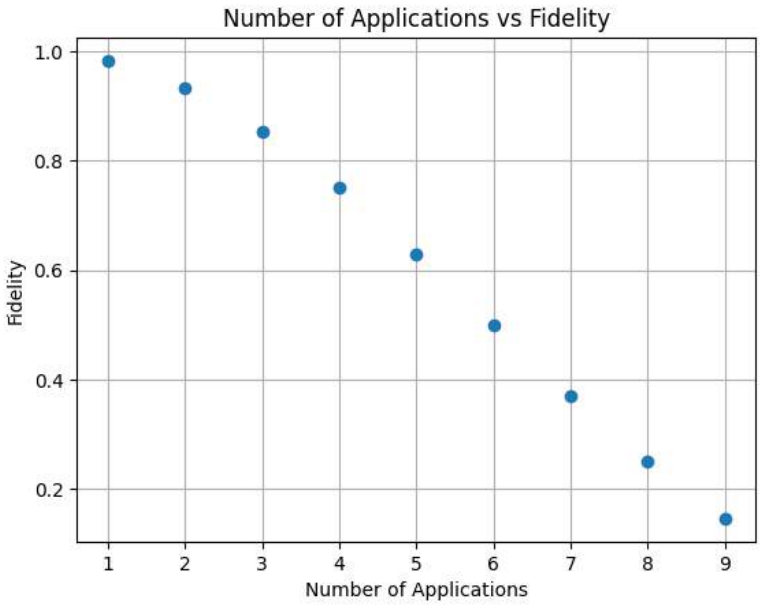



FIG. 2. Number of errored gate applications vs Fidelity graph. The gate applications were varied from 1 to 9, and the value of ε was kept constant at $\frac{\pi}{12}$. The resulting fidelity plummeted with the amount of operations. Running a linear regression on the data gave a standardized slope of -0.2845.

Comparing these two slopes, the number of applications had a far greater effect on fidelity than the actual error value, which tends to be much smaller. As a result, although the actual gate error might not change the entangled state much, the number of applications tends to destroy it much more.

**B. Detecting and correcting static errors in entangled systems**

For our ancilla error over $10^8$ epochs, we predicted it to 3 significant figures. The actual error was $\frac{\pi}{12}$, or ~0.261799, and our predicted error was ~0.26180.

We were also able to predict the target state error to 3 significant figures over $10^6$ epochs. The actual error was $\frac{\pi}{15}$, or ~0.20943, and our predicted error was ~0.20932.

**C. Coherent errors due to temperature drift**

LSTM Results

| Mean Absolute Error (MAE) | Root Mean Squared Error (RMSE) | $R^2$ (Coefficient of Determination) |
|---|---|---|
| 0.0047 | 0.0069 | 0.9981 |

TABLE 1. Three metrics we evaluated our model on. Our model was able to explain 99.81% of the variance in attenuation, and it had very low MAE and RMSE.

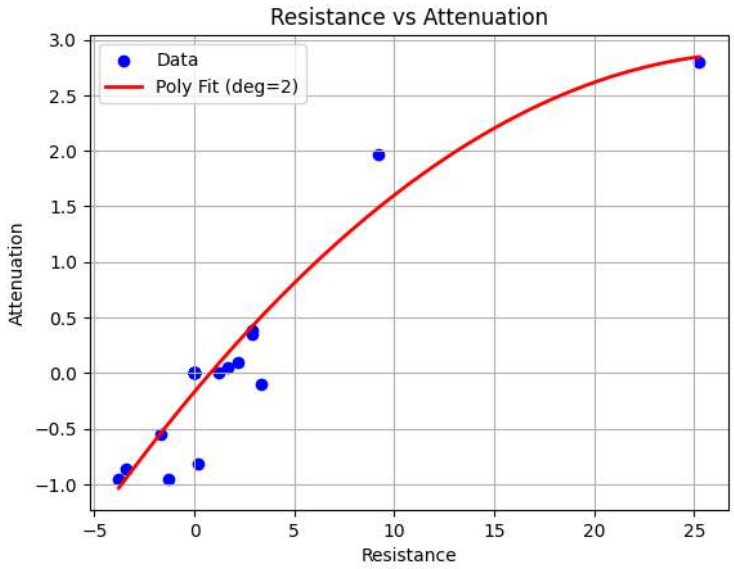



FIG. 3. Resistance vs Attenuation. Describes the relationship between the resistance of the coaxial cables used to transmit the microwave pulse to the qubit and the amount of lost signal in the microwave pulse. The resistance evolves through temperature, and the data was taken at 300 K, 77 K, and 13 K.

For our polynomial regression model, our training $R^2$ was 0.892, and our validation $R^2$ was 0.44. An important thing to note is that our dataset was very small, so we had to remove 2 relative outliers from the validation process. These outliers followed what physics models predicted, a square root law, but we didn't have enough data to model that curve. As a result, they would be taken out for cross validation and would make our $R^2$ incredibly low. These points are indexed 20 and 22 in our code.

Our validation $R^2$ was also significantly less than our training because of our lack of data, which gave those medium outliers significant weightage. The folds in which they were in had a -0.065 and 0.23 $R^2$, which was significantly lower than the others, which had an average of 0.672.

## IV. DISCUSSION / CONCLUSION

Our methodology has a few constraints; namely it needs to be in an environment in which qubits have enough coherence time to last the error computation, but in a quantum system where temperature is the main driving factor for errors. In current quantum systems, especially in superconducting qubits, qubits have a very low decoherence time, meaning that our state will be affected by more than coherent errors. We need a framework in which superconducting qubits can be stable enough to run our computation and correct for the error.

We would also benefit from real data to train our LSTM, instead of hypothetical data that is very easy to train on. Real noise would allow us to make our LSTM more robust, and it would make it much more generalizable.

Our static error correction method could benefit from a phase kickback methodology, which we had tried to implement but did not find a set of commuting gates. A phase kickback circuit would provide a different framework as opposed to using swap gates, and it could use fewer gates than the swap gate circuit. This would simplify it and reduce its energy consumption.

For future works, we can expand the amount of parameters our model takes into, and upgrade our model type. We could switch our model to a transformer, which would have 2 significant benefits. First, it would be able to handle much more data and therefore capture much more complexities in data; secondly, it would be able to perform autoregressive inference in parallel, which would be much faster and require a shorter decoherence time for our qubits.

Our methods also do not correct for the skin effect or dielectric loss, two very big causes of attenuation. Dielectric loss is also caused by environmental fluctuation, which can be modeled by the change in temperature. The skin effect is caused by the frequency of the microwave pulse, which is something that our model cannot fix. Adding a term to account for the frequency in our input could allow us to create a gate specific bias that will allow for our predicted error to be more accurate.

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**AUTHOR CONTRIBUTION STATEMENT** Sachit Gonur built and trained the LSTM, created the data, built the polynomial regression model, and built the original quantum phase kickback circuit. Adhit Natla helped research about the LSTM and worked on the entanglement portion of the quantum swap gate circuit. Henry Lu built the mathematical function and came up with the idea for the SWAP gate quantum circuit.

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# Beyond the Starting Five: A Deep Analysis of Bench Depth and Lineup Consistency in the NBA By Ryan Kim


## Abstract

This research examines the significance of two variables that are impactful yet often overlooked in research on NBA data: the depth of a team's bench and the stability of its lineups, and how they can impact teams' success. Using evidence from recent NBA seasons, this research analyzes the correlation between bench performance and lineup consistency with other measures, including win percentage, offensive and defensive efficiency, and postseason results. This research finds that a well-performing bench enhances team performance during the regular season, while lineup stability correlates more with defensive rating than with team success. This research suggests that winning teams are not only expected to prioritize star players but must also invest in a productive, deep bench while maintaining a stable lineup. Future research could take a step further by exploring additional years, leagues, or variables to determine how consistency and depth contribute to winning basketball.



## Keywords

Bench Depth; Lineup consistency; NBA data analysis; Data science; Sports research;


## Introduction

The National Basketball Association (NBA), consisting of the best basketball players across the world, is regarded as the top basketball league in the world (1). 30 teams compete for a championship each season, strategically planning every move to gain an advantage against other teams in the regular season and ultimately in the playoffs. One of the main factors that team management and coaches struggle with is determining how to construct and utilize their roster (2). A shallow approach to roster building typically focuses more on star players, but most championship-caliber teams also prioritize bench depth and building a well-rounded team (3). Teams do, however, need to achieve the balance between depth and continuity in the lineup if they are going to maximize their success (4).

A deep bench means that a team has solid backup players who can enter the game as substitutes and play when starters are either tired or injured (5). It can be helpful over the course of a long 82-game regular season when injury and fatigue take their toll. It also enables teams to be competitive in back-to-back contests or on long road trips. However, having too many players and frequently switching lineups can sometimes lead to a lack of chemistry and consistency. Players won't feel they have enough time to develop a rhythm or learn to play together. This can lead to confusion on the court and subpar play.

A consistent starting lineup throughout most of the season, conversely, enables players to communicate effectively and build chemistry (6). It can also lead to better offense and defense as players grow accustomed to each other's playing styles. This tactic can be risky, however. If a star player becomes fatigued or hurt, the whole team is affected. If there is no quality bench,

starters may be overused and perform below their usual standard in the middle of the season or in the playoffs. Additionally, relying on star players can also make it easier for opponents to detect patterns and strategies, thereby mitigating the effectiveness of these players.

This research will examine the impact of roster depth and lineup consistency on team performance in the NBA, both during the regular season and the playoffs. It will explore their correlation with regular-season win percentage, playoff performance, injuries, and overall team ratings on both offense and defense. Its purpose is to determine how teams can enhance roster design and execute effective substitution strategies. By answering this question, teams can better manage their rosters and ultimately win more games, both during the regular season and in the playoffs.

**Data and Methodology**

The sample data for this study covers 300 team seasons for all 30 NBA teams over 10 years (2015-2016 to 2024-2025). Each entry represents a team's data for a single season, including roster depth, lineup consistency, injuries, and season results. The data were obtained from the NBA (7) and Basketball Reference (8) and organized in Google Sheets, which together provide complete coverage of each team for each season in the dataset outlined in Figure 1. Together, these variables indicate how roster depth, consistency, and injuries correlate with team performance.

| Category | Variable | Description | Minimum | Average | Maximum |
|---|---|---|---|---|---|
| **Measures of Depth and Consistency** | BENCH_RATE | Plus/minus of a team's bench | –6.3 | –0.47 | +6.2 |
| | BENCH_MIN | Number of minutes played by a team's bench | 1041 | 1442 | 1856 |
| | LINEUP_START | Unique number of starting lineups for a team | 6 | 22.463 | 54 |
| | LINEUP_CONS | Unique number of lineups for a team | 187 | 504.03 | 985 |
| **Performance** | REG_WPCT | Winning percentage in the regular season | 0.122 | 0.4927 | 0.838 |
| | PLAYOFFS | The round that a team makes it to in the playoffs (0=miss, 1=1st round, 2=2nd round, 3=conference finals, 4=NBA finals, 5=win championship | 0 | 0.973 | 5 |
| | INJURIES | Total number of players that got any playing time (more injuries = more unique players) | 16 | 19.087 | 33 |
| | OFF_RATE | A measure of a team's efficiency on the offensive side of the court | 98.4 | 110.7513 | 122.2 |

| | | | | | |
|---|---|---|---|---|---|
| | DEF_RATE | A measure of a team's efficiency on the defensive side of the court | 98.2 | 110.7576 | 120.4 |

**Figure 1:** Variable Definitions and Summary Statistics.

For each team's season, we gathered variables associated with depth and consistency (BENCH_RATE, BENCH_MIN, LINEUP_START, LINEUP_CONS) and performance (REG_WPCT, PLAYOFFS, OFF_RATE, DEF_RATE, INJURIES). Figure 1 provides the category, variable, and a short description, as well as the minimum, average, and maximum values for the entire league across the 10 years.

To measure the relationships between the depth/consistency variables and the performance variables, we calculated correlations between the depth/consistency variables and the performance variables using Fisher's exact test. After gathering the data in Google Sheets, we used the built-in correlation function to calculate the correlation coefficients between the variables. Correlation coefficients ranged from –1 to +1, where values closer to +1 indicated stronger positive correlations while values closer to –1 indicated stronger negative correlations. Values close to 0 indicated weak or no linear correlation. Additionally, correlation values below 0.3 were not analyzed as closely because they are considered weak and less meaningful in the context of this study. These methods enabled us to identify short-term team success during each season. However, the data did not account for every variable that may influence the performance variables, such as coaching decisions, team chemistry, strength of schedule, salary cap structure, etc. Despite these limitations, the dataset provided sufficient information to examine how roster depth, lineup stability, and injuries relate to regular-season and postseason performance for the period.

**Results**

We set out to examine the correlation between factors related to bench depth and lineup consistency and variables measuring team success, injuries, and ratings. To establish the correlation, we gathered data from the 2015-2016 season through the 2024-2025 season on various statistics, including win percentage, furthest playoff stage, net bench rating, number of unique starting lineups, and other factors. To gather the data, we used statistics from the official NBA website (7) and Basketball Reference (8). We used Fisher's exact test to measure the correlation between each variable.

| | REG_WPCT | PLAYOFFS | INJURIES | OFF_RATE | DEF_RATE |
|---|---|---|---|---|---|
| **BENCH_RATE** | 0.781 | 0.474 | -0.394 | 0.518 | -0.457 |
| **BENCH_MIN** | -0.137 | -0.094 | -0.119 | -0.301 | -0.165 |
| **LINEUP_START** | -0.397 | -0.124 | 0.393 | -0.056 | 0.442 |

| | | | | | |
|---|---|---|---|---|---|
| **LINEUP_CONS** | -0.342 | -0.108 | 0.287 | -0.036 | 0.393 |

**Figure 2:** Correlation Results between Depth & Consistency and Team Success, injuries, and team ratings.

Figure 2 provides the complete set of results for the correlation analysis between the four depth and consistency variables and the five performance variables. Several variables showed measurable relationships with roster depth, lineup consistency, and team success. BENCH_RATE showed the strongest correlations with regular-season win percentage. Such correlations suggest that bench rating is a prominent variable regarding team success in both the regular season and the playoffs. BENCH_MIN showed weak or slightly negative correlations with all performance measures, excluding a correlation of -0.301 with offensive rating.

For lineup measures, LINEUP_START showed a strong correlation of -0.397 with regular season win percentage, and a slightly negative correlation for playoff progress that was much weaker -0.124. LINEUP_CONS overall showed nearly identical correlations with the performance variables as LINEUP_START, with differences within ±0.05 for each variable except injuries. LINEUP_START and LINEUP_CONS showed the strongest correlations with defensive rating at 0.442 and 0.393, respectively.

**Discussion**

The strongest correlations are observed between bench net rating (BENCH_RATE) with regular season win percentage (0.781) and offensive rating (0.518). These findings suggest that teams with efficient, reliable players on the bench won more regular-season games and were more effective offensively. It indicates that bench players are more than just placeholders; they are an integral driving force toward success during an 82-game season. Interestingly, BENCH_RATE also exhibited a moderate positive correlation with playoff progress (0.474), indicating that effective second units still matter in the playoffs, though the impact is weaker than during the regular season. This is supported by existing literature and research indicating that depth will be more of a factor in the regular season grind, but can also be utilized to bring stability to the playoffs (9).

On the other hand, bench minutes (BENCH_MIN) were weakly or slightly negatively correlated with every measure of success, meaning that the teams that played their bench more often did not necessarily perform better. In fact, excessive bench use was negatively correlated with offensive rating (-0.301). This suggests that efficiency, rather than minutes played, brings out the full strength of a deep bench. A team might apportion minutes evenly, but if those players are not efficient, the result is negative.

The correlations regarding lineups did not fully support our hypothesis. Starts per lineup (LINEUP_START) were negatively correlated with win percentage in the regular season (-0.397) and positively correlated with injuries (0.393). Teams that had to replace a lot of people in the lineup, typically due to injury, had worse regular-season performance. This supports the value of

continuity: when the same players are on the court all the time, they develop chemistry and have more success. Likewise, the cumulative number of lineups (LINEUP_CONS) also showed a weaker but still negative correlation with win percentage (-0.342), indicating that having too many unique lineups and changes leads to instability rather than flexibility. LINEUP_START and LINEUP_CONS both, however, positively correlated with defensive rating (0.442 and 0.393, respectively). Teams trying various looks may find more success defensively as constant rotations decrease player fatigue and make it harder for opponents to adjust to the defense. LINEUP_CONS also correlated negatively with injuries, suggesting that rotating unique lineups is the best way to prevent injury within the parameters of this database.

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**Research on the Development of Chile's Agricultural and Wine Industry: Geographical Advantages, Trade Challenges, and Coping Strategies By Wumomo Li**

**Abstract**

Chile’s wine and agricultural products hold a significant position in the international trade market. However, the country currently faces various challenges related to export policies, natural conditions, and marketing strategies. This study collects the data from a range of authoritative official sources, including Chile's National Customs and international trade databases, to analyze the industries in Chile. The findings reveal notable shifts in the wine market: the traditional European market is gradually declining, whereas exports to Asia and the United States are increasing significantly. Similarly, agricultural products used in the production of wine, such as cherries and grapes, have experienced growing exports to Asia and North America. To address these trends, the study proposes a series of macro- and micro-level strategies aimed at optimizing Chile’s export performance and market positioning.

**Biography**

Wumomo Li is a high school senior with a strong interest in economics and international trade. She is particularly interested in the global agricultural and wine markets and plans to pursue further studies in economics at university.

**Key words** Economics; Agriculture; International Trade; Geography; Wine

**Introduction**

Chile is a crucial country in South America's economic development with unique geographical characteristics; specifically, a long and narrow territorial shape, the western part with the Pacific Ocean, and the eastern part beside the Andes Mountains. These geographical arrangements provide Chile with a diverse climate, providing a fitting environment for agriculture and fishery development.

Chile demonstrates exceptional performance within the international trading zone. As a country that has a high proportion of exports, including wine, fruit, and seafood, international trade plays a key role in Chile’s economic development. This article aims to analyze and introduce the current development of Chile’s wine industry and its international trade. The first section will discuss the geographical advantages and trade background of Chilean wine production; the second section will analyze key wine varieties and export destinations; and the final section will focus on the economic impacts and challenges facing Chile’s wine trade.

| Industry category | Key data | Economic contribution |
|---|---|---|
| Agriculture | Global share of cherry exports: 38%<br>Global share of Grape exports: 24%<br>Wine exports: $1.6 billion<br>Grape exports: $1.34 billion | Agricultural GDP contribution: 5.2% (national share in 2024)<br>Seasonal employment: 500,000 (agricultural export driven) |

Fig1:Agricultural Economic Contribution
ODEPA; ITC Trade Map; BCCh; SERNAPESCA;

**Agricultural Trade Industry and Geographical Advantages**

Chilean agriculture and fisheries have an important status in the global market, which gives a key perspective to analyze the economic development model. This section focuses on how the unique natural conditions in Chile benefit agricultural development. Analyzing Chile's geographical characteristics is of particular significance, as the country's unique morphology and climatic conditions exert a direct influence on its agricultural production structure and export capacity. These geographical shapes and diverse climate zones enable the cultivation of a range of high-quality fruits and wine-use grapes (Wines of Chile). At the same time, an elongated coastline and well-developed broader facilities provide insurance for exports. An in-depth understanding of these geographical advantages helps to grasp Chilean agriculture's core competitiveness.

In Chile, the Andes mountains and the Pacific Ocean form natural barriers that prevent insects and pests from effectively invading, creating an ideal environment for crop growth. Meanwhile, Chile crosses the northern desert climate zone, the central part of the Mediterranean climate zone, and the southern temperate maritime climate zone. For example, the central Mediterranean climate zone is hot and dry during the summer, while it is temperate and rainy during the winter, which benefits grapes and allows them to accumulate taste and flavor substances. The southern temperate maritime climate zones have a large difference in temperature between day and night, which fits the conditions to cultivate special grapes such as Pinot Noir.

Due to Chile's geographical characteristics, goods exported through its ports can be shipped directly to major markets such as North America and Asia, resulting in higher transportation efficiency. In contrast, road transportation often takes much longer because of Chile's complex and dispersed terrain. For example, transporting goods by land alone from the capital Santiago to northern Chile takes approximately 40-48 hours. If the goods are first shipped by sea to the northern port of Antofagasta (taking only 12-15 hours) and then transferred to short-distance land transport (3-4 hours), the total time is only 15-19 hours, which is more than half shorter than pure land transport (The Paper).




Fig2: Map of Chile (created by the author)

**Analysis of Chile's Agricultural Trade Imports and Exports**

Exports of agricultural products play a crucial role in Chile's economic development. In 2024, Chilean agriculture reached $26.4 billion, $25.3 billion of exports, and employed around 10 percent of Chile's labor force(U.S. Department of Agriculture, Foreign Agricultural Service). This section will analyze the performance of exports from the wine industry. It will detail recent market performance, identify changing trends, and also analyze different marketing strategies in different countries.

**Wine**

The wine industry in different regions of Chile have their own characteristics and demonstrate strong and unique advantages in the global market. Ashe Coquimbo region in northern Chile produces high-sugar Muscat grapes, which are the main source for making fortified wine. The coastal Aconcagua region takes advantage of its cool climate to produce high-quality white wine. Meanwhile the southern region, relying on its unique cool climate, is able to produce high-quality Pinot Noir.

**Economics**

According to the data released by the Chilean Ministry of Agriculture, in 2024, the total value of wine exports reached 1.6 billion dollars (IVINSA 13). Chilean wine regions have built a full product range. Basic wines make up about 65% of exports.  In contrast, Premium reserve wines account for around 20%. This product mix has made Chilean wines more competitive in global markets. The total international competitiveness went up by about 18% (Ministry of Finance, Chile). Chilean wine is mainly exported to three major markets: China, the United States, and the United Kingdom. In 2024, Chilean wine exports reached US$1.6 billion. The Central Valley region made up 90% of the total exports. The main export destinations were China (7.8%), the United States (4.7%), and the United Kingdom (4.3%). The Aconcagua region

also had a good performance, which sent 12.5% of Chilean wine exports to Brazil, 7.8% to the U.S., and 7.3% to the UK. There are no exact numbers for the South Region, but its premium Pinot Noir wines helped increase sales. In the U.S, exports rose by about 15% compared to last year. In Brazil, they went up by around 12%. The total international competitiveness went up by about 18% (Ministry of Finance, Chile)

**Future Wine export trends**

***China***

Several key trends are expected to shape the future of Chilean wine in the Chinese market. Considering the price perspective, $40 to $110 would become the main price range of Chilean wineries to focus on, because this range meets the demand of business banquets in China. This range also sustainably reflects the high-quality advantage of Chilean wine. In 2024, the sales of $40 to $110 for mid- to high-end Chilean wine increased by 18% (Wines of Chile). In addition, the high-end Chilean wines that are priced at more than $110 could satisfy the demand for the gift market and high-end consumption (Wines of Chile; IWSR; Wu); high-end products above $110 have achieved a 25% growth rate in 2024(IWSR).

Considering the category preference trends, Cabernet Sauvignon represents the principal variety in Chilean wine exports. However, Carmenere, a variety unique to Chile, has been attracting a growing consumer preference in the Chinese market (Wines of Chile).

Regarding the layout of the appellation, the traditional high-quality appellation, Maipo Valley, which is located in the Central Valley, is still the main export appellation, while Colchagua Valley and other emerging appellations, relying on their own features, form a differentiated advantage, which gradually wins the Chinese importers' recognition.

It is particularly noteworthy that cross-border e-commerce, live streaming, and other emerging channels are reshaping the traditional import model. It is therefore advisable for Chilean wineries to actively engage with these innovative sales channels, which enable direct and precise access to young Chinese consumers. In the Chinese market, the demand for localization has increased substantially. According to MarketWatch, the result shows that the product’s packaging with a Chinese-style or naming elements with lucky meanings is notable in the market during the traditional festivals, such as the New Year. Therefore, incorporating the Chinese-style on the wines’ package or naming elements with lucky meanings would be a significant marketing strategy for export to China, with the purpose of fitting the local consumers' preferences (China Daily).

***Japan***

The future of Chilean wine also shows several important trends in the Japanese market. Considering the price perspective, the mid-range between $10- $30 wines would be the main price range for Chilean wineries to export to Japan. This range could meet the Japanese consumption customs, such as family dinners and daily drinks, and also maintain a better

price-performance ratio (Ministry of Finance, Japan). The consumers of the Chilean wines that are above $30, mid- to high-end, are mainly premium izakaya, Japanese French restaurants, and the gift market (Rabobank).

Considering the layout of the appellation, Aconcagua and the southern cool region's wine category, Chardonnay and Pinot Noir, are a better fit for the Japanese market's pursuit of an elegant style, while Cabernet Sauvignon from the Central Valley appellation is better suited for the mass catering channel. It is worth noting that convenience shops, supermarkets, and e-commerce platforms are a crucial point for the marketing strategy. To reach this market, it has been suggested that Chilean wineries launch small-bottle wines and canned products to adapt to single-person consumption scenarios. At the same time, it is suggested that Chilean wineries alter their use of oak barrels. By doing this, Gamayna would have the opportunity to open the Japanese wine market (Ministry of Finance, Japan). This adjustment is crucial because Japanese consumers tend to prefer bolder, more refreshing wines. Reducing the use of oak barrels can lessen the intensity of flavors, resulting in a lighter, more refreshing wine overall.

***USA***

The future of Chilean wine has several important trends in the U.S. market. From the price perspective, US$8 to US$15 low- to mid-end products will become the core mainstay, accounting for 72% of Chilean wine exports to the U.S. (Wines of Chile). This price range mainly meets the needs of daily meals and family gatherings. Products in the US$15 to US$25 range are aimed at consumers who care more about quality, and this segment is where Chilean wines can demonstrate their strength in price-performance ratio (Rabobank). Considering the selection of wine categories, Cabernet Sauvignon from the Central Valley remains the dominant variety, accounting for 58% of total exports. It is worth noting that blended wines in large 1.5L bottles may become a popular product in large supermarket chains in the future. For the appellation layout, the Central Valley dominates the mass market with its large-scale production, while new regions like the Moray Valley are winning the favor of younger consumers with their fruity wine styles. Considering sales channels, it is important to note that major retail chains such as Walmart and Costco account for over 60% of Chilean wine sales in the US. At the same time, the DTC (Direct-to-Consumer) model is growing fast, with an annual growth rate of 18%. The U.S. market has a strong seasonal marketing effect, so it is recommended to develop product sets for scenarios such as Super Bowl weekend, the Independence Day barbecue season, and other festive occasions(Rabobank).

**Economic Impacts and Challenges of Chilean Agricultural Trade Imports and Exports**

Although exports of Chilean agricultural products have significant performance, they also face different challenges. According to the data, extreme weather is leading to a decrease in northern Chile's water storage by 30% (Dirección General de Aguas de Chile). In addition,the grape yield in the Central Valley has decreased by 15% due to the downy mildew (Instituto de Investigaciones Agropecuarias de Chile). Meanwhile, because of outdated basic infrastructure,

the usage time for transporting agricultural products increased 18% compared with 2019 (Ministerio de Agricultura de Chile), and the rate of cargo loss reached 3.2% (Asociación de Exportadores de Chile). The international trade environment also puts pressure on Chile. The anti-dumping tax imposed by the United States reached 173.91% (USITC). These problems not only affect the current export revenue but also undermine the competitiveness of Chilean agricultural products in international trade. After figuring out these challenges, it would be easier to formulate more efficient solutions.

**Argument**

Chilean agricultural production is highly dependent on climate conditions. Recently, extreme weather has occurred more frequently, which affects agricultural production in different ways. In northern Chile, long-term drought caused a decrease in water storage by 30% which directly affects the water usage for vineyards and orchards' irrigation (Dirección General de Aguas de Chile). The central region, with a Mediterranean climate that used to have dry weather, in 2024, experienced abnormal heavy rains. This heavy rain triggered the grape downy mildew, leading to a decrease in grape yields by 15% (INIA). Even more worrying are the future trends. According to the predictions by meteorologists, within the next decade, the probability of Chile's main agricultural appellation might increase by 40% (Subpesca), which means the advantages that Chilean agriculture depends on might become risks in the future development.

Chilean agricultural developments are facing multiple challenges,  not only internal challenges but also external pressure. From an internal perspective, the northern region of Chile is continuously facing water scarcity, in addition to the pollution caused by mining activities; these two problems limit agricultural irrigation and crop growth. In addition, its elongated territory shape has limited the delivery system: the transportation cost of agricultural products increases, and during the transportation process, the problem of loss of fresh agricultural products is becoming more and more prominent.

From the industry development cycle perspective, these constraining factors and the external environment create a superimposed effect. In the short term (1-3years), the wine industry will face double pressure; first, the main importing country’s economy is increasing slowly, leading to a decrease in wine demand, which will ultimately be squeezed out of the market by alternative drinks, such as beer; second, the extreme weather happens frequently that the central appellation’s frost and the southern appellation’s heavy rain not only cause the grape yield quality unstable, but also affect the export supply stability directly.

Of greater concern are long-term (3+ years) structural challenges. Because of the aging infrastructure and limited budgets from the government, Chile is facing serious transportation limitations: The aging road network in agricultural areas and inefficient ports have led to a rise in transportation costs. In the wine industry, the average time consumed for transporting wine from the appellation to the ports  in 2024 increased 18% compared with 2019 (Ministerio de Obras Públicas), while the breakage rate has risen to 3.2% (Wines of Chile). Meanwhile, the international market standard has increased consistently, such as the EU's carbon tariff policy

(imposing additional taxes on imported high-carbon products to make the carbon costs of imported products equivalent to those of EU local products), which might bring 8% to 10% of additional export cost(European Commission). These kinds of structural challenges, combined with external pressures, constrained the industry's development; if the infrastructure efficiency is not able to improve through public-private cooperation, the Chilean agricultural product's international competitiveness probably would continue to decrease. Tariffs have a significant effect on Chilean wine exports to the United States. In 2024, the United States levied a 6.64%-173.91% anti-dumping tax on Chilean wine glasses (USITC). This measure directly pushes up costs and squeezes profits, while the price increase further weakens the product's competitiveness in the market. The United States is one of the crucial export destinations for Chilean wine, accounting for approximately 10% of the export of Chilean wine; however, the wine is not a necessity (Wines of Chile). The increase in price has already caused the demand for Chilean wine to decrease; at the same time, the instability of tariff policy also causes the U.S. importers to become cautious during purchasing.

**Challenges and Solutions**

Chilean Agriculture is facing diverse challenges that the country needs to schedule the solution from national policy to specific operations. This section will focus on the wine industry, talking about targeted response solutions, including exploring new markets strategy policy adjustment. These measures are not only able to resolve the current problem, but also enhance the Chilean agricultural products' international competitiveness. Through the research on these solutions, it could help Chilean agriculture to find a better development route, helping their agricultural products stabilize the dominant position in the global market.

**Wine Challenge**

Currently, the Chilean wine industry is facing a serious risk of market concentration that over-relies on the traditional markets, such as Europe and the United States. This kind of structural flaw has led to a significant lack of industry resilience to risk.

**Wine Solution**

***Macro***

From a Macro perspective, this structural overreliance on European and U.S. markets has significantly reduced the risk resistance capacity of Chile's wine industry. To address the issue of over-reliance on European and American markets, the key lies in exploring the Asian market represented by China. From 2006, the China-Chile FTA has formed a mature trade cooperation framework, which not only eliminates 95% of cargo tariffs(MOFCOM), but also establishes supporting mechanisms such as rules of origin and trade remedies. Relying on this agreement, Chilean wine exports to China can enjoy zero tariff treatment; the general tariff rate is approximately 14% (China Tariff Commission). This kind of agreement significantly

decreases the cost of tariffs and breaks through the policy barriers for Chilean wine entering the Chinese market, which effectively enhances the products' price competitiveness. While exploring the Asian market, the Japanese market also has intensive potential. Since 2007, Japan has been working on the signing of the "Chile-Japan Economic Partnership Agreement", as a result the tariffs of Chilean wine entering the Japanese market have gradually declined. This kind of favorable policy engages the proportion of Chilean wine in the Japanese import wine market, which increased from 7.5% in 2007 to above 25% at the end of 2014(JETRO), and this policy promotes the market reform, which laid the foundation for Chilean wine to well-develop in the Japanese market for the future.

***Micro***

From a micro perspective, Chilean wine companies can reduce their dependence on European and American markets by optimizing their products, distribution channels, and marketing strategies. The products need to cater to the taste preferences of Asian consumers. They could develop semi-sweet wines for the Chinese market and launch small package products for the Japanese market. For sales channels, it is necessary to focus on laying out mainstream e-commerce platforms such as Tmall and JD for the Chinese market, and also pay attention to offline retail terminals such as convenience stores. The marketing strategy could cooperate with food bloggers to recommend the wine, which attracts and retains consumers. In addition, the companies should adopt advanced cultivation technology in order to tackle changes in the climate.

**Conclusion**

Chilean agriculture and trade industries rely on their unique geographical conditions and abundant natural resources, and have occupied a dominant position in the international market. The geographical characteristics from the beginning of this article to the specific analysis of each section could easily recognize that Chilean territory's shape, diverse climate conditions, and elongate coastline provide perfect conditions for agriculture and fisheries development. These advantages promote Chile to become a crucial export country for wine, fruit, and fishery products, and it has injected strong impetus into the country's economic growth.

Chilean agriculture faces numerous challenges, such as extreme weather, aging infrastructure, and international trade barriers. These issues not only threaten the current agricultural production and export, but also might affect the Chilean agricultural product competitiveness in the future. This article proposed different solutions from different perspectives, including changing policy from a macro perspective and the innovation of technology from the micro perspective. Specifically, opening the Asian market in order to avoid the problem of over-reliance on European and American markets.

Once these planned solutions are implemented, they will help Chile build a more modern agricultural system, and the experience accumulated from this will also serve as a valuable reference for developing countries facing similar challenges.

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**Development of BCI's By Rhema Yang**

**Abstract**

As Brain-Computer Interfaces (BCIs) transition from experimental to mainstream technologies, their integration into the workplace introduces both transformative potential and complex ethical challenges. This paper examines the implications of BCIs for privacy, discrimination, cognitive enhancement, and employment dynamics. Drawing on insights from Alexandre Gonfalonieri's 2020 *Harvard Business Review* article, "What Brain-Computer Interfaces Could Mean for the Future of Work," it argues that while BCIs can enhance productivity and accessibility, they also raise significant concerns about data ownership, employee autonomy, and equitable access. The analysis highlights the urgent need for comprehensive federal regulations to govern data collection, ensure fairness in BCI application, and protect employees' mental health and intellectual property rights. Methodologically, this paper synthesizes findings from existing literature on neurotechnology ethics, workplace equity, and digital privacy law. Ultimately, it proposes a robust policy framework that balances technological innovation with human rights protection, ensuring that BCIs are deployed ethically, inclusively, and transparently within evolving work environments.

As we approach the end of the 2020s, Brain-Computer Interfaces (BCIs) have undergone a remarkable transformation from experimental technologies to mainstream tools with significant applications in various fields, particularly within the workplace. This technological evolution has been characterized by rapid advancements in both the capabilities and applications of BCIs. The insights provided by Alexandre Gonfalonieri in his 2020 *Harvard Business Review* article, "What Brain-Computer Interfaces Could Mean for the Future of Work," remain highly relevant as they highlight the potential for BCIs to revolutionize workplace productivity and human-computer interaction (Gonfalonieri).

BCIs are systems that facilitate direct communication between the human brain and external devices. The technology functions by translating neural activity into digital signals that can control computer systems, enabling new forms of interaction that bypass traditional input methods such as keyboards and mice. BCIs are typically a combination of hardware (e.g., electrodes or sensors) and software (e.g., algorithms for signal processing and interpretation). Over the past decade, advancements in neuroimaging, signal processing, and machine learning have significantly improved the accuracy and functionality of BCIs (Yuste et al.).

BCIs can streamline workflows by automating routine tasks through direct brain signals, potentially leading to significant gains in efficiency. For individuals with physical or communication impairments, BCIs offer new methods for interaction and collaboration that can bridge gaps in accessibility. Some BCIs are designed to augment cognitive functions such as memory and attention, which could have implications for training and skill development (Lebedev and Nicolelis).

The swift advancement of BCI technology has outpaced the development of regulatory frameworks necessary to address the unique challenges and risks associated with its use. The lack of comprehensive policies has led to several pressing concerns that need to be addressed. BCIs collect and process highly sensitive neural data, which includes personal thoughts, emotions, and cognitive states. The potential for misuse or unauthorized access to this data presents significant privacy and security risks (Ienca and Andorno). Existing data protection laws may not fully encompass the intricacies of BCI data, necessitating the development of new regulations specifically tailored to address these concerns.

Furthermore, the variability in BCI effectiveness among individuals due to differences in cognitive abilities, age, and other factors raises the risk of discriminatory practices. BCIs could inadvertently create or exacerbate disparities in workplace opportunities if not managed carefully. For instance, employees who struggle to produce robust brain signals may face disadvantages, leading to potential marginalization (Nijboer et al.).

The rapid adoption of BCIs in the workplace presents both unprecedented opportunities and significant challenges. As we harness the potential of this technology, it is crucial to develop a robust regulatory framework that addresses privacy, discrimination, and equitable access concerns. By establishing comprehensive policies and safeguards, we can ensure that the benefits of BCI technology are realized while protecting individual rights and promoting fairness in the workplace.

This memo serves as a call to action for policymakers and regulatory bodies to prioritize the development of regulations that address these critical issues and to foster an environment where BCI technology can be used ethically and equitably.

BCIs collect highly sensitive data, including detailed brain activity patterns, cognitive states, and emotional responses. The accumulation and analysis of such personal data raise substantial privacy concerns. The risks of misuse include unauthorized surveillance, data breaches, and the potential for exploitation of personal information (Ienca and Andorno). Federal legislation should establish comprehensive guidelines governing the collection, storage, and utilization of BCI data.

BCIs may exhibit varying levels of effectiveness based on demographic factors such as gender, age, and cognitive differences. This variability could result in discriminatory practices where certain groups are unfairly treated or excluded based on their ability to use BCIs effectively (Nijboer et al.). Federal regulations should require that BCIs undergo rigorous testing for bias and fairness across diverse demographic groups.

The effectiveness of BCIs may vary among individuals, particularly those with learning differences, neurodiverse conditions, or those who are more creative and may not utilize BCIs effectively. This disparity could lead to inequitable access to opportunities and exacerbate existing inequalities in the workplace (Yuste et al.).

The use of BCIs could have unintended effects on employees' mental health and well-being. Continuous monitoring and data collection may lead to increased stress, anxiety, or

feelings of intrusion, potentially affecting overall job satisfaction and productivity (Ienca and Haselager).

BCIs generate data that may be considered proprietary, raising questions about ownership and intellectual property rights. Disputes may arise regarding who owns the data collected through BCIs—the employee or the employer (Gonfalonieri). Establish clear regulations regarding the ownership of BCI data to ensure transparency and fairness.

The adoption of BCIs raises broader ethical and societal questions about the nature of work, personal autonomy, and societal inequalities. The potential for misuse or coercive practices needs to be addressed to ensure that BCIs are used responsibly (Ienca and Andorno).

As BCIs continue to advance and integrate into the workplace, it is imperative that legislation evolves to keep pace with technological progress. By establishing robust privacy protections, fairness standards, and ethical oversight, we can ensure that BCI technologies promote productivity without compromising human rights or well-being.

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# Age and Second Language Acquisition: A Review of Critical Period Effects

**By Sophie Collomb**

## Author Biography

Sophie Collomb is a student at Lick-Wilmerding High School in San Francisco, California. She grew up in a multilingual household speaking French, Chinese, and English, and has long been interested in how age shapes language learning.

## Abstract

The ability to learn language is a defining feature of human cognition, yet it appears to be constrained by biological and developmental factors. The Critical Period Hypothesis (CPH) proposes that a limited window exists during early life when the human brain is particularly receptive to language acquisition. This narrative review synthesizes existing research examining how age impacts first and second language learning, focusing on whether there is a "critical period" for second language acquisition (SLA). Drawing on peer-reviewed articles, books, and meta-analyses, this paper explores the neurological, cognitive, and social explanations behind age-related differences in language learning. Findings indicate that while early learners show native-like proficiency more easily due to heightened neural plasticity, adults can still achieve high competence through different cognitive strategies. The review concludes that while biological constraints influence language learning, motivation, exposure, and cognitive maturity also play essential roles. Understanding these dynamics can inform more effective language education policies and approaches, highlighting the complexity of human learning.
Keywords: *Critical period hypothesis, second language acquisition, age effects, bilingualism, cognitive science*

## Introduction

Language learning is one of the most remarkable human capacities. From the babbling of infants to the fluent conversations of adults, language reflects the brain's ability to link sound, meaning, and structure. Yet, a central question in cognitive science remains unresolved: Is there a critical period for learning languages? Researchers have long debated whether language learning ability declines sharply after childhood or whether age differences can be explained by social and cognitive factors (Lenneberg; Birdsong).

Theories about how age affects the ability to learn a language date back to Eric Lenneberg's seminal work (1967), which introduced the "Critical Period Hypothesis" (CPH). According to this view, humans are biologically primed to acquire language during early childhood, after which neuroplasticity declines, making new languages more difficult to master. While CPH is well established in first language acquisition, its role in second language acquisition (SLA) is less clear. Many adult learners achieve high fluency and even near-native pronunciation, challenging the notion of a strict cutoff. The question, therefore, is not only

whether there is a critical period for language acquisition, but how biological, cognitive, and experiential factors interact across the lifespan.

This paper explores the relationship between age and second language acquisition, examining the evidence for and against CPH. It aims to synthesize existing research on neural plasticity, cognitive mechanisms, and sociocultural influences to determine how age shapes language learning outcomes. Specifically, it reviews evidence on differences between first language and second language acquisition windows, explanations for age-related decline in language learning, and whether early bilingualism supports or hinders additional language acquisition. By synthesizing existing literature, this review will provide clarity on one of the biggest mysteries in psycholinguistics and outline why age continues to be a central factor in theories of SLA.

## Methodology

This narrative review draws on peer-reviewed articles, books, and reviews accessed through Google Scholar, JSTOR, and Cambridge University Press. Key search terms included *language learning*, *second language, language acquisition*, *critical period*, *age*, and *age related effects*. Of the 20 articles reviewed, 16 were included in the results. Sources were selected for their influence and relevance to age-related SLA debates.

## Results

### The Critical Period Hypothesis and Neural Plasticity

Language learning's biological foundations reveal the extent to which development shapes neural organization. Lenneberg (1967) argued that lateralization of language to the left hemisphere, which typically completes around puberty, constrains language acquisition thereafter. Neurological evidence supports this: children who suffer left-hemisphere damage often recover language abilities, while adults rarely regain full function (Newport). Functional MRI studies show that children engage more diffuse neural networks when processing language, suggesting greater flexibility, while adults show more localized, specialized activation (Kim et al.).

This neural "plasticity" is often cited as the biological foundation of the critical period. During early childhood, synaptic connections are highly adaptable, allowing efficient formation of linguistic categories such as phonemes. After puberty, pruning processes reduce this flexibility, making it harder for learners to perceive and reproduce unfamiliar sounds in a second language (Werker and Tees).

### Evidence from Second Language Learning and Differences Between First and Second Language Acquisition

The most cited empirical support for the critical period in SLA comes from Johnson and Newport (2004), who tested Korean and Chinese immigrants to the U.S. on English grammar.

They found a strong negative correlation between age of arrival and grammatical accuracy for participants who arrived before age 15, but no significant correlation for those arriving later—indicating a decline that plateaued after puberty. Their findings suggest that achieving native-like proficiency in a second language becomes exceedingly difficult, and often unattainable, for adult learners.

However, later research found that this relationship is more complex. Birdsong (1998) and DeKeyser (2003) reported that adult learners can achieve near-native proficiency under intensive exposure and motivation, suggesting individual variation rather than a strict cutoff. The critical period may therefore be a "sensitive period"—a time when learning is optimal, but not impossible afterward (Hakuta et al).

While both language 1 (L1) and language 2 (L2) learning rely on similar neural systems, they differ in timing and input. Infants learn language implicitly through immersion, while adults often rely on explicit learning strategies such as rule memorization. Studies using event-related potentials (ERPs) show that adults process grammatical violations differently from children, reflecting a shift from automatic, implicit learning to conscious, controlled learning (Weber-Fox and Neville).

The phonological domain appears most sensitive to age. Flege et al. (2002) found that learners exposed to an L2 after adolescence rarely achieve native-like pronunciation, even after years of practice. Conversely, vocabulary and syntax can remain flexible throughout adulthood, especially with sustained exposure (Birdsong).

**Cognitive and Motivational Factors, and Multilingualism and Cross-Linguistic Influence**

Beyond biology, cognitive differences also influence learning. Adults have stronger metalinguistic awareness and can consciously analyze grammar, which may compensate for decreased plasticity (DeKeyser). Motivation and identity also play crucial roles. Studies by Wolfe-Quintero (2011) show that emotional connection to the target language and culture enhances learning outcomes across all ages.

Interestingly, multilingual individuals often show enhanced capacity for learning additional languages, even in adulthood. Prior experience with multiple linguistic systems can maintain cognitive flexibility and improve phonological awareness (Kroll and Bialystok). This suggests that the brain's capacity for language learning, while constrained, remains adaptable under the right conditions.

**Discussion**

The findings reviewed here suggest that age affects language learning, but not in a strictly deterministic way. Early learners benefit from biological advantages, greater neural plasticity and implicit learning systems, but older learners can draw on cognitive strategies and motivation to compensate.

The CPH thus captures an important trend but oversimplifies a continuum of learning potential. Rather than an abrupt cutoff, age effects are gradual and domain-specific: pronunciation and phonology decline earliest, while syntax and semantics remain flexible longer.

From a neurological perspective, the decline in plasticity may reflect a trade-off: as the brain stabilizes learned categories, it becomes less efficient at forming new ones. Yet this specialization also enables the abstract reasoning and analytical skills adults use in explicit learning (Hartshorne et al.).

Social and emotional factors also mediate outcomes. Children often learn in immersive environments where errors are tolerated and corrected naturally, while adults face social anxiety and reduced exposure opportunities. Language learning, therefore, is both a cognitive and a social process.

This nuanced understanding has practical implications. Language education should adapt to learners' developmental stages: immersive, play-based exposure for children, and metacognitive, structured learning for adults. Programs that blend implicit and explicit methods, such as immersion with formal grammar instruction, may best leverage the strengths of both age groups. From a policy perspective, education systems could prioritize early foreign language exposure in elementary curricula while offering adult programs that emphasize cognitive strategies, metalinguistic reflection, and sustained immersion opportunities. Encouraging lifelong learning and providing institutional support for multilingual education ensures that language instruction aligns with developmental and cognitive realities, rather than assuming a one-size-fits-all approach.

**Limitations**

This review is limited by its narrative nature, relying on secondary analysis of existing studies rather than original data. Moreover, most research on age effects has been conducted in Western, English-speaking contexts, limiting generalizability across languages and cultures. Age of acquisition is often confounded with factors such as motivation, education, and exposure. It is also important to note that correlations found in many age-related studies do not necessarily indicate causation; factors like motivation or opportunity could drive the observed relationships rather than age alone. Future studies should use longitudinal and cross-linguistic designs to separate biological from environmental influences. Advances in neuroimaging may also clarify how neural plasticity changes across different language domains.

**Conclusion**

Age undeniably influences language acquisition, but it does not determine success. While younger learners show advantages in pronunciation and implicit grammar learning, adults retain remarkable capacity for mastering new languages through different cognitive routes. The critical period should thus be viewed not as a rigid boundary but as a sensitive period modulated by experience, motivation, and learning context. Practically, children benefit most from immersive, play-based and communicative approaches that mirror natural language environments, while

adults learn best through structured programs that integrate explicit grammar instruction with real-world communication practice. Understanding how age shapes language acquisition enriches both science and education. It reveals how deeply intertwined biology, culture, and cognition are in shaping one of humanity's defining abilities—the capacity for language.

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**Camels on Fire: Biomimetic Enhancement of Firefighter Protective Apparel via Vasoregulatory and Thermally Insulative Mechanisms: Development of Cost-Effective, Sustainable, PFAS-Free Turnout Gear By Vedika Devarajan**


## Abstract

Firefighters: first-responders, civil workers, heroes. Firefighters risk their own lives to save countless others, yet face devastating consequences. ~72% of firefighters die from occupational cancer, caused not only by smoke inhalation, but also toxic chemicals embedded in their own protective gear. Per- or Polyfluoroalkyl Substances (PFAS) are amphiphilic 'forever' chemicals used in conventional turnout-gear that may trigger thyroid/liver disease and several cancers. To make matters worse, emerging PFAS-free technology contains aramid fibers which can cause internal inflammation. Inspired by natural camel thermoregulation strategies, Camels on Fire investigates a sustainable, non-toxic alternative to PFAS and aramid fibers in hopes of bettering the livelihoods of firefighters globally. Following a criteria-driven selection process, I adopted carbon-felt outer shells and wool-felt thermal liners for all designs, varying only the moisture barrier to deploy 1/2 strategies. Camel vasodilation iterations utilized a semipermeable-fiberglass to increase air flow (analogous to blood flow) and minimize localized trauma. Insulation utilized needle-punched ceramic fiber which can trap air between bonded/unbonded regions. 4 validated procedures: Fourier's Open Flame, Moisture Vapor Transfer Rate (MVTR) testing, Young's-Modulus-inspired Flexibility, and Physical-Properties analysis, evaluated 11 engineering criteria against my designs. Fourier's Open Flame data gave insulation a Thermal-Efficiency-Index of 91.4, while vasodilation scored 157.3. Insulation showcased lower Q/t, but vasodilation demonstrated greater dissipation efficiency. With MVTR data, vasodilation held a 3.08-fold greater slope, compared to insulation which quantifiably resists moisture penetration. In Flexibility, vasodilation demonstrated an optimal mean angle-displacement of 5.33° ± 0.58° and, in Physical-Properties, ideal practicality. Ultimately, vasodilation passed all criteria and beat insulation in ¾ tests. Next steps involve addressing robustness and gauging compliance with NFPA-standards. Combining thermoregulation strategies or implementing new ones (i.e. piloerection) is imminent! These findings redefine protective assurance and enhanced safety for our Nation's Heroes; with Camels on Fire, we can reimagine firefighter gear for today and beyond.


## Introduction

Firefighters, our Nation's Heroes, are faced with carcinogenic chemicals and inflammation-inducing materials day-to-day though their turnout gear. Camels on Fire evaluates a cost-effective, light-weight, and practical replacement by bidding the question: How can the application of camel thermal regulation strategies, specifically insulation and vasodilation, optimize non-toxic firefighter turnout gear?



Fig 1: Powerful Californian Park Fire, portrayed from the side of a road.

Firefighters sustain high survival rates for the civilians they rescued, at 63.7% average, rising to >68% when rescued within 6 minutes of arrival on site. Despite their heroics, first-responder jobs are often combatted with severe mental health trauma. Findings show 18 in 100,000 firefighters commit suicide, compared to 13 in 100,000 for other occupations, with ~20% suffering from PTSD (Post Traumatic Stress Disorder) in their lifetimes. Exacerbating this issue is the threat of occupational cancer. In 2023, ~72% of first responder deaths were due to prostate, testicular, and lung cancers, Non-Hodgkin's lymphoma, and other variations of detrimental conditions. Firefighters have a 14% higher risk of morbidity from cancer than the general public. A variety of reasons causes this, toxic smoke/soot inhalation, diesel exhaust, localized heat stress, exposure to Volatile Organic Compounds (VOCs), and, the focus of study, PFAS (Per- and polyfluoroalkyl substances).

PFAS is a group of more than a thousand synthetic chemicals, composed of strong carbon-fluorine (C-F) bonds. The electronegativity of F creates a dipole of partial ionic character with C allowing for a bond dissociation energy of 531.5 kJ/mol. As this bond is practically impossible to degrade, PFAS substances are denoted as 'forever chemicals', and can accumulate over time. As they are amphiphobic, they are used in a variety of household and industry products, but several scientific studies have noted the severe negative effects of PFAS exposure. PFAS has been linked to endocrine disruption (thyroid hormones), reduced immune response to vaccination, alteration of liver enzymes, increased cholesterol, kidney cancer, testicular cancer, prostate cancer and breast cancer. For generations, PFAS has been used in firefighter turnout gear to repel water/oil and prevent hypothermic reactions. Fluoropolymers (in the outer shell), PTFE (in the moisture barrier) and DWR aqueous emulsions (coating) are all variations and used to enhance gear performance, but instead expose our Hero's with carcinogens.

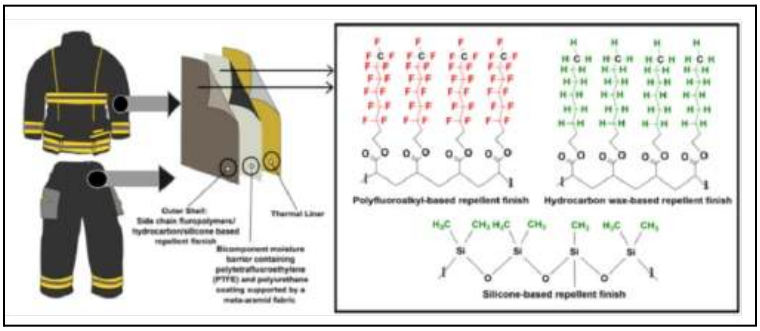



Fig 2: Schematic of firefighter turnout gear and PFAS chemical structures

Current emerging PFAS-free technology, though appears to be a perfect solution, comes with several limitations and repercussions as well. PFAS-free turnout gear typically entails aramid fibers, made with aromatic polyamides with >85% amide linkages attached to aromatic rings. This enables exceptional heat resistance and abrasion resistance capabilities as well as high tensile strength, which is optimal for turnout gear. Devastatingly, recent research has shown such materials have poor UV resistance and inhalation of microfibrils can cause respiratory/mechanical skin irritation as well as lung and transient pulmonary inflammation.

Camels on Fire utilizes camel biomimicry techniques to create a nontoxic PFAS-free, aramid-free turnout gear that does not harm firefighters, is practical, and sustainable. Camels utilize many thermal regulation strategies, but insulation and vasodilation stood out distinctly.

Insulation concerns the outer layer of skin (often voluminous and thick) and the trapping of air molecules in a tightly bound structure hindering their ability to vibrate and pass thermal energy (low thermal conductivity). In camels, vasodilation is the expansion of blood vessels under the skin that increases blood flow and cools the skin by dissipating internal heat.

Turnout gear is primarily composed of 3 layers: the outer shell, protection from flash fire exposure, abrasions and chemicals. Next, the moisture barrier, selectively permeable for acceptance of skin moisture but not for external liquids/chemicals (keeps skin dry). Lastly, nearest to the skin, thermal lining, flexibility, mobility, comfort and moisture wicking ability. The moisture barrier will consist of the application of either insulation or vasodilation principles in the materials/structures selected.

Both design iterations will be evaluated in a series of 4 tests, testing a total of 11 NFPA-inspired criteria: flame resistance, abrasion resistance, water repellency, lightweight, PFAS-free, moisture-wicking capability, insulation, moisture management, mobility/flexibility, practicality, and breathability. The general hypothesis was that vasodilation iterations would allow for better comfort, evaporation of moisture, practicality, and semi-permeable properties compared to insulation. Testing eventually proved the hypothesis correct, vasodilation surpassing insulation in ¾ tests, with a 3.08-fold greater moisture transfer slope, 6.96x rigidity compared to insulation on inverse angle displacement, and greater overall practicality, only underperforming by merely 3.2 J/s in heat transfer testing. Though Camels on Fire tests were designed to be effective, efficient and accurate, testing in more realistic scenarios to gauge compliance with NFPA standards directly is essential. This would mean altering air-quality, chemical exposure levels, mechanical abrasions, gauging long-term durability/repeated usage, etc. Next steps would involve improving the vasodilation design to reach a Q/t value of ≤17 joules/second, potentially evaluating a combination of vasodilation and insulation materials, or even other thermoregulation strategies.

**Results**

To test assembled samples (vasodilation and insulation individually) against the criteria effectively, Camels on Fire's 4 tests are each embellished in detail below, covering procedure, data collection, and more.

Firstly, Fourier's Open Flame involved a 4-inch x 4-inch Neoprene silicone slab (selected for its similarity to human skin thermal conductivity) to 98–100°F to simulate skin surface-temperature. Then placed it over a sample, with the outer shell facing an open flame, and recorded the silicone's temperature change (ΔT) at 30-second intervals for five minutes. Fourier's Law of Thermal Conduction or Q/t = kA(ΔT)/d, relates heat transfer over time (Q/t) to material properties: thermal conductivity (k), cross-sectional area (A), temperature difference (ΔT), and thickness (d). With data, calculated from Q/t values, ≤ 8-17 joules/seconds (second-degree burn tolerance range) indicates an acceptable performance. This test evaluates the criteria flame resistance and insulation.

Moisture Vapor Transfer Rate testing used Lithium Chloride (LiCl), a desiccant that readily absorbs moisture from its surrounding environment. By sealing the sample over a 4-inch-diameter cup containing 10 g of LiCl in a humidity-controlled room, the amount of moisture passed through the fabric and absorbed by the LiCl was measured. The resultant weight gain every 5 minutes for the first 2 hours, then every 30 minutes for an additional 5 hours as the absorption rate decelerated. The rate of absorption (MVTR) was derived from the slope of the sorption data, measured at 30-minute intervals over a 14-hour period. The procedure was replicated under identical humidity conditions using a paper towel to establish an optimal absorbency MVTR threshold of 0.352. The target MVTR for the designs was set marginally lower than 0.352 to ensure a balanced combination of breathability, moisture-wicking, and barrier performance.

Inspired by Young's Modulus static testing, Flexibility was time-dependent and focused on permanent deformations. Each sample positioned as a 45-45-90 triangle against a straight angle initiated the procedure. Each sample was assessed by measuring angle displacement from 180° at 2-, 3-, and 5-minute intervals, where an optimal result of 0° indicated complete malleability and suitability for turnout gear. The average angle displacement across the three-time intervals was calculated to obtain a general consensus for each design.

Physical properties was a computational practicality test with no distinct hands-on component. Metrics were evaluated and compared to industry standards through a linear comparison between the cost ($/in^2), weight (g/in^2), availability and sustainability (origin) of insulation vs vasodilation materials.

Fourier's Open Flame Testing:

During Insulation testing, after approximately 240 seconds, the rate of temperature increase diminished, and the sample approached a thermal steady state at around 132°F. This plateau behavior signifies that the insulation material began equilibrating, where the rate of heat influx through conduction matched the rate of heat dissipation to the environment. Such stabilization indicates the formation of a thermal boundary layer, characteristic of efficient insulating media.

$$k_{total} = 0.045 + 0.05 + 0.06 = 0.2 \text{ W/mK}$$

$$Q/t = kA(\Delta T)/d = (0.2\ W/mK)(0.01\ m^2)(274.261\ K)/(0.03\ m) = 18.28\ joules/second$$

During Vasodilation testing, the sample showed no clear plateau, with temperatures rising steadily to 145°F by 300 seconds. The continuous temperature climb reflects insufficient heat resistance and faster energy transfer through the material. Thus, the plateau in the insulation trial serves as direct evidence of superior thermal stability and controlled heat conduction, characteristics essential for maintaining safe internal temperatures in protective gear applications.

$$k_total = 0.045 + 0.05 + 0.04 = 0.135\ W/mK$$

$$Q/t = kA(\Delta T)/d = (0.135\ W/mK)(0.01\ m^2)(299.817\ K)/(0.01905\ m) = 21.24\ joules/second$$

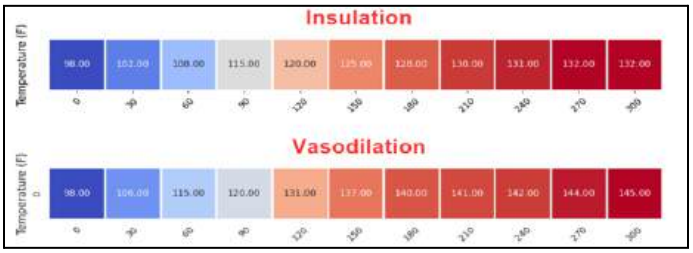



Fig 3: Heatmap representing raw Fourier's Open Flame data over 5 minutes, used for plateau conclusions and Fourier's Law calculations (Insulation: 98°Fmin to 132°Fmax, Vasodilation: 98°Fmin to 145°Fmax, plateau at 3.5, p = 0.02, Figure 1)

An additional calculation computed using collected data, involved the Biot number, a dimensionless quantity in heat transfer that compares internal thermal resistance of a solid to that of its surface. $Bi = \frac{hL_c}{k}$, where Bi is the Biot number, h is the convective coefficient, estimated from flame-air contact, Lc is thickness, and k is thermal conductivity. A higher Biot number exemplifies the external protection layer increasing in temperature, but remaining lower temperatures internally, which is essential for thermal protection necessitated by firefighters. A lower Biot number, showing the opposite properties. For Insulation:

$$Bi_{insulation} = \frac{(25)(0.03)}{0.20} = \frac{0.75}{0.20} = 3.75$$

This design exhibits higher dimensionless thermal resistance ration, indicating enhanced intra-material heat diffusion, optimal for insulation and firefighter turnout gear. For Vasodilation:

$$Bi_{vasodilation} = \frac{(25)(0.01905)}{0.135} = \frac{0.47625}{0.135} = 3.53$$

This design demonstrated lower coefficient, allowing internal conductive responsiveness to be greater, and induces a reduced capacity to spatially confine thermal gradients.

MVTR testing proved vasodilation as a breathable material compared to insulation through steady-state modeling and Fick's law:$W(t) = W_0 + A(1-e^{-k_1 t}) +$ mt, where W(t) is

total weight of the sample at time t, A is transient diffusion amplitude (represents short-term absorption), k_1 is diffusion rate constant ($h^{-1}$), m steady-state MVTR slope (g/h), and W_0 is initial weight. Regression plots were used to estimate curvature data, then demonstrating a k1 value of ~0.0083 for insulation and ~14.321 for vasodilation.

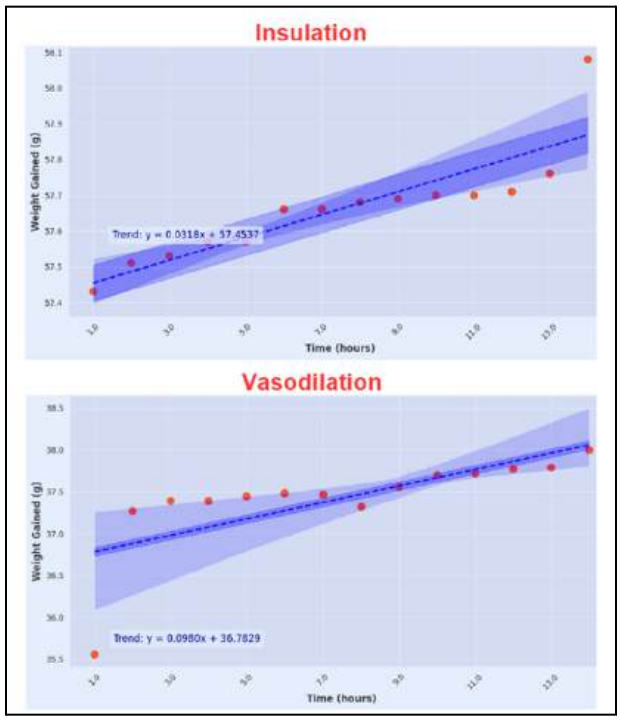



Fig 4: Line of best fit/regression plots for Moisture Vapor Transfer Rate raw data over a 13-hour interval, (Insulation: y = 0.0318x + 57.4537, $R^2 = 0.92$; Vasodilation: y = 0.0980x + 36.7829, $R^2 = 0.89$, $p < 0.05$, Figure 2).

From here, using the diffusion coefficient formula, Fickian diffusion calculations show physical heat transport kinetics, allowing for a $D = k_1 L^2$ more insightful look into MVTR data. For insulation:

$$D = 0.0083 \times (0.03)^2 = 7.47 \times 10^{-6}\ \mathrm{m^2/h}$$

$$D = 7.47 \times 10^{-6}/3600 = 2.08 \times 10^{-9}\ \mathrm{m^2/s}$$

For vasodilation:

$$D = 14.231 \times (0.01905)^2 = 5.16 \times 10^{-3}\ \mathrm{m^2/h}$$

$$D = 5.16 \times 10^{-3}/3600 = 1.43 \times 10^{-6}\ \mathrm{m^2/s}$$

Vasodilation, exponentially, had a steady-state weight gain rate, nearly 3x that of Insulation in identical test conditions. Insulation thus acts as a vapor barrier, with low diffusivity,

it serves optimal for thermal regulation, but detrimental to breathability. Vasodilation promotes vapor migration, diffusing moisture ~700x faster than insulation.

| Test - Insulation | | | Test - Vasodilation | | |
|---|---|---|---|---|---|
| Time (min) | Flexibility (degrees) | Angle Displacement θ | Time (min) | Flexibility (degrees) | Angle Displacement θ |
| 2 | 133.00 | 47.00 | 2 | 175.00 | 5.00 |
| 3 | 142.00 | 38.00 | 3 | 175.00 | 5.00 |
| 5 | 154.00 | 26.00 | 5 | 174.00 | 6.00 |

Fig 5: Raw data compilation of insulation and vasodilation flexibility, angle displacement and time, (Insulation: $\theta(t) = 7.5t + 118$; Vasodilation: $\theta(t) = -0.25t + 175.5$, Figure 3)

During Insulation testing, the measured angle displacement (θ) exhibited a steady increase over the recorded time interval, from 133° at 2 minutes to 154° at 5 minutes. Linear regression analysis of the data yielded: θ(t) = 7.5t + 118, positive slope of 7.5°/min, indicating a progressive reduction in flexibility over time. This trend suggests that the sample's resistance to bending increased as deformation progressed, likely due to intrinsic structural stiffening under sustained loading conditions. The continuous rise in angle displacement signifies that the insulation material offered comparatively less compliance under mechanical stress, limiting its capacity for deformation recovery. Conversely, Vasodilation testing displayed reduced variation in bending displacement, with θ values ranging narrowly from 175° at 2 minutes to 174° at 5 minutes. Linear regression produced the model: θ(t) = -0.25t + 175.5, exhibiting a slightly negative slope (-0.25°/min). The near-zero, marginally decreasing trend in θ indicates that the sample maintained consistent flexibility, effectively resisting angular stiffening over time. The plateau-like behavior of θ under vasodilation treatment demonstrates enhanced mechanical compliance, suggesting a more uniform distribution of strain throughout the material matrix and an improved capacity for bending recovery.

This computational analysis involved a linear comparison between the cost ($/in^2), weight (g/in^2), availability and sustainability (origin) of insulation vs vasodilation designs. At 0.09 $/in^2, 1.06 g/in^2 and high availability/sustainability, vasodilation outperformed insulation.

*Typical Industrialized Turnout Gear:*

Weight: 0.305-0.524 g per in^2

Cost: $0.97-$1.05 per in^2

*Insulation:*

Weight: 2.5 g per in^2

Cost: $0.11 per in^2

Ceramic Fiber: Recycled ceramic fiber is made from natural minerals and doesn't contain asbestos or other harmful substances, readily available.

*Vasodilation*
Weight: 1.06 g per in^2
Cost: $0.09 per in^2
Fiberglass: Recyclable, composed of non-depletable sand (sillica) and production does not require significant time/energy, readily available. (Additional note: sustainable, non-toxic brand acquired.)

**Discussion**

The results of Camels on Fire demonstrate potential of camel-inspired thermoregulation strategies as a sustainable and PFAS-free solution for firefighter turnout gear. Among the two design iterations, insulation and vasodilation, the vasodilation model exhibited superior performance in three of the four tests, suggesting that thermoregulation through enhanced breathability and air permeability offers a more effective approach to comfort and safety than traditional insulation-based mechanisms. Fourier's Open Flame, Moisture Vapor Transfer Rate (MVTR), Flexibility, and Physical Properties testing collectively revealed insights of material behavior, efficiency, and practical applications.

In Fourier's Open Flame testing, insulation demonstrated a thermal efficiency index of 91.4, corresponding to a Q/t of 18.28 J/s, while vasodilation measured 21.24 J/s. Although the insulation design displayed slightly greater resistance to heat transfer, it approached the upper limit of acceptable second-degree burn tolerance, signifying that both materials maintained adequate protection. The plateau behavior observed in the insulation trial confirmed stable heat diffusion through the ceramic matrix, effectively restricting internal temperature rise. However, the marginally higher Q/t in vasodilation suggests increased internal conductivity, consistent with the camel-inspired principle of facilitating controlled heat dissipation. This reflects a thermodynamic balance, vasodilation sacrifices minimal thermal retention in exchange for significant cooling potential and moisture regulation, a critical factor for long-term wear and comfort in firefighting scenarios.

The MVTR analysis provided the most striking contrast between the two models. The vasodilation design achieved a diffusion coefficient (D) of $1.43\times10^{-6}$ m²/s, 700x higher than insulation's $2.08\times10^{-9}$ m²/s. This difference highlights the enhanced permeability and breathability achieved through the semipermeable fiberglass barrier, mimicking the camel's dynamic heat-dissipation mechanism. While insulation served effectively as a vapor barrier, its poor diffusion capacity implies a high likelihood of moisture accumulation during prolonged use. In real-world contexts, this could exacerbate heat stress and increase discomfort, ultimately limiting performance. The vasodilation iteration, on the other hand, maintained a steady-state diffusion rate that supports moisture migration and evaporative cooling, addressing one of the most significant shortcomings of current turnout gear which is poor thermal comfort under prolonged exertion.

Flexibility testing further emphasized the advantages of vasodilation-based materials. The insulation sample showed a steady increase in angle displacement with a positive slope of

7.5°/min, indicating progressive stiffening over time. This rigidity could juxtapose mobility and response efficiency during active firefighting. Conversely, the vasodilation model displayed near-zero angular change with a negative slope of –0.25°/min, showing consistent flexibility and mechanical compliance. This result not only enhances comfort but also implies that stress distribution within the fiberglass matrix remains uniform, minimizing fatigue and the risk of mechanical failure. The superior flexibility, paired with a significantly lower weight (1.06 g/in² compared to insulation's 2.5 g/in²), positions vasodilation as a more ergonomic and sustainable alternative to conventional materials like aramids or fluoropolymer composites.

Physical properties analysis reinforced these findings. Vasodilation proved both cost-effective ($0.09/in²) and sustainable, utilizing recyclable fiberglass derived from nondepletable silica sand. The environmental and economic advantages of this material are substantial, particularly when contrasted with the high cost and carcinogenic legacy of PFAS-based fluoropolymers. Importantly, all materials employed were verified as non-toxic and readily available, enabling realistic large-scale production and adoption. Together, these results validate the hypothesis that camel-inspired vasodilation principles yield improved moisture regulation, flexibility, and sustainability without compromising heat protection.

While the experimental findings were robust, several factors could have influenced the results. Laboratory conditions, such as consistent humidity during MVTR testing and controlled flame exposure during Fourier's analysis, may not perfectly replicate the dynamic environmental stressors firefighters encounter in real-world conditions. The use of synthetic Neoprene to model skin conductivity, while justified for consistency, introduces a simplification that may affect precise thermal correlation to human physiology. Furthermore, limited replications restrict the statistical power of the results. Increasing sample numbers, testing across variable humidity and temperature gradients, and integrating mechanical abrasion and chemical exposure simulations would enhance reliability and external validity.

Although both design models achieved acceptable thermal safety, the vasodilation iteration fell slightly above the optimal heat transfer threshold (21.24 J/s versus ≤17 J/s). Future research should focus on reducing this value while maintaining high MVTR rates. Potential strategies include incorporation of both vasodilation's permeability with a thin insulating sublayer to simulate the camel's multi-tiered skin structure or even to other thermoregulation strategies. Additionally, incorporating dynamic pore architectures using shape-memory fibers or bio-derived hydrogels could enable adaptive heat and moisture regulation. Testing should also be expanded to full-scale turnout prototypes under simulated operational environments, including exposure to flame jets, high-pressure water, and mechanical flex cycles to gauge NFPA standard compliance.

The broader implications of this research extend beyond firefighting. The demonstrated camel-inspired thermoregulation system has potential applications in other high-heat occupations such as welding, aerospace, or disaster response. Its sustainable, PFAS-free composition also contributes to reducing environmental contamination from chemicals aligning with global initiatives to phase out PFAS from industrial production by 2030. Importantly, this work

underscores the value of biomimicry in engineering sustainable safety solutions: by observing how organisms like camels thrive under extreme desert conditions, we can reimagine protective technologies for human use.

In conclusion, Camels on Fire successfully validates the feasibility of camel thermoregulation strategies, specifically vasodilation, as a biomimetic foundation for next-generation firefighter turnout gear. While insulation demonstrated superior static heat resistance, vasodilation achieved greater overall performance in breathability, flexibility, and sustainability, fulfilling the criteria for enhanced safety and comfort. This study establishes a crucial step toward eliminating PFAS and aramid fibers from protective gear, offering a viable, environmentally conscious, and health-oriented alternative. Future work focused on hybrid optimization and large-scale field testing could accelerate the transition toward safer, smarter, and sustainable protection for our Nation's Heroes.

**Materials and Methods**

To investigate biomimetic thermoregulation strategies inspired by camels, two design iterations, insulation and vasodilation, were developed to serve as the moisture barrier in a three-layer turnout gear assembly. The outer shell (carbon felt; Fabrix Co., CF-109) provided flame resistance and mechanical protection, while the thermal liner (wool felt; FeltCo., WF-11) enhanced comfort and moisture wicking. The moisture barrier differentiated the two designs: the insulation model utilized a needle-punched ceramic fiber (ThermoCeram™, CF-30), whereas the vasodilation model used semipermeable fiberglass (AeroGlass™, FG-12). All fabrics were cut into 10.16 cm × 10.16 cm (4 in × 4 in) squares and layered sequentially without adhesive to preserve air permeability. Each composite was designed to replicate the structural layering of modern turnout gear while remaining PFAS- and aramid-free.

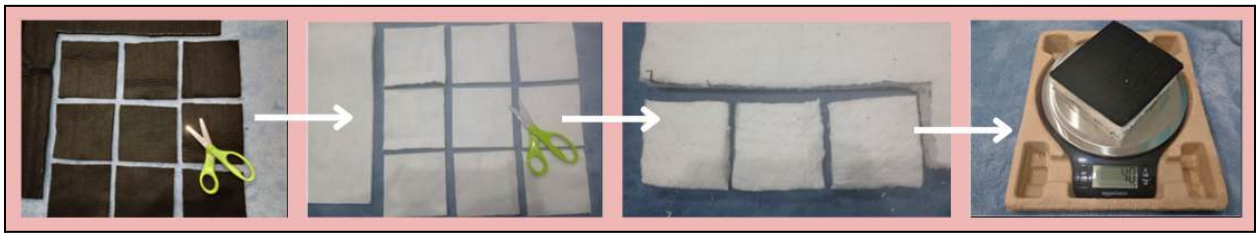


Fig 6: assembly and initial construction/evaluation of samples

Each sample was evaluated against 11 NFPA-inspired criteria encompassing flame resistance, abrasion resistance, water repellency, weight, PFAS-free composition, moisture management, insulation, flexibility, breathability, and practicality. Four tests, Fourier's Open Flame, Moisture Vapor Transfer Rate (MVTR), Flexibility, and Physical Properties, were developed to comprehensively evaluate thermal, mechanical, and environmental performance. All trials were performed under controlled indoor conditions (21 ± 1°C, 45–55% relative humidity).

Fourier's Open Flame Test, (Criteria: Flame Resistance, Insulation), Thermal resistance was measured using a custom setup inspired by Fourier's Law of Heat Conduction, expressed as:

$$\frac{Q}{t} = \frac{kA(\Delta T)}{d}$$

where Q/tis the rate of heat transfer (J $s^{-1}$), kis the thermal conductivity (W $m^{-1}$ $K^{-1}$), Ais the cross-sectional area ($m^2$), ΔTis the temperature gradient (K), and dis the thickness of the material (m).

A 10.16 × 10.16 cm Neoprene silicone slab (McMaster-Carr, 1849K52) was preheated to 98–100 °F to simulate the average skin surface temperature of firefighters. The slab was placed on top of the assembled sample, with the carbon-felt outer shell facing an open propane flame (~1100 °C) from a portable fire pit (Outland Firebowl 870). Temperature change (ΔT) of the silicone interface was recorded using a laser infrared thermometer (Etekcity 1080P) at 30-second intervals for 5 minutes. A steady-state plateau indicated thermal equilibrium and was used to calculate the effective thermal efficiency index. Measurements between 8–17 J/s were considered within the safe thermal tolerance threshold for second-degree burn prevention.

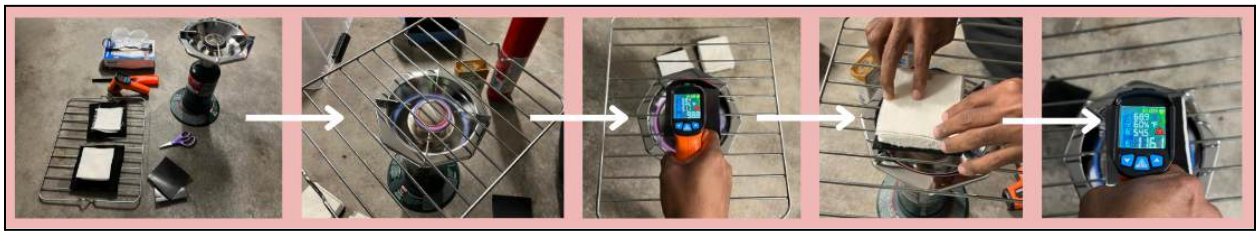


Fig 7: Materials and basic procedure of Fourier's Open Flame Test

Moisture Vapor Transfer Rate (MVTR) Test, (Criteria: Water Repellency, Moisture Management, Moisture-Wicking Ability, Breathability), Moisture permeability was quantified using Lithium Chloride (LiCl; Sigma-Aldrich 793520) as a desiccant due to its strong hygroscopic properties. A humidity-controlled room (48 ± 2% RH) was maintained throughout testing. Each 10 g LiCl sample was sealed inside a 10 cm-diameter glass cup using the turnout gear sample as a barrier layer, affixed with polyethylene film and laboratory-grade tape. The total mass of each cup was measured using a precision microbalance (Ohaus Adventurer AX) every 5 minutes for 2 hours, followed by 30-minute intervals over an additional 5 hours.

Moisture uptake over time followed a transient exponential model derived from Fick's Law of Diffusion: $W(t) = W_0 + A(1 - e^{-k_1 t}) + mt$ , where W(t)represents the cumulative mass at time t, Ais the diffusion amplitude, k_1is the rate constant ($h^{-1}$), and mis the steady-state moisture transfer rate. Diffusion coefficients were subsequently computed as D=k_1 L^2to compare performance across samples. A paper towel control established an optimal MVTR threshold of 0.352 g/h.



Fig 8: Materials and basic procedure of Moisture Vapor Transfer Rate (MVTR) Test

Flexibility Test (Young's Modulus–Inspired), (Criteria: Mobility/Flexibility, Abrasion Resistance), Mechanical compliance and angular recovery were evaluated using a time-dependent adaptation of Young's Modulus testing. Each sample was positioned to form a 45°–45°–90° triangle against a fixed plane. Using a protractor (Fisherbrand 14-687) aligned at the midline, the sample was bent to 90° and held for durations of 2, 3, and 5 minutes. The final angular displacement (θ) was measured upon release to quantify residual deformation.

This experiment emphasized time-dependent plasticity over static elasticity, modeling the degree to which each design maintained structural integrity after bending. A slope of ~0°/min was interpreted as consistent flexibility without stiffening under prolonged mechanical strain.




Fig 9: Materials and basic procedure of Flexibility Test (Young's Modulus–Inspired)

Physical Properties Assessment, (Criteria: PFAS-Free Composition, Lightweight Design, Mobility, Practicality), Physical performance was assessed computationally through a comparative analysis of each prototype's density, cost, and sustainability index. Weight was measured using the same microbalance, and cost per surface area was calculated from supplier pricing (USD/in²). Sustainability scores reflected material renewability and recyclability, with qualitative scaling (1–5).

Typical industry turnout gear weights range from 0.305–0.524 g/in² at costs of $0.97–1.05 per in². Insulation and vasodilation prototypes were benchmarked against these standards to determine feasibility for manufacturing scale-up.

All tests were replicated in triplicate per design iteration (n = 3). Raw data were compiled in Microsoft Excel and analyzed through regression modeling and linear fits to identify diffusion constants, thermal steady states, and angular recovery rates. Graphical visualizations (Figures 2–4) were generated using Python (v3.12; Matplotlib). No external code was employed beyond standard data visualization scripts.

**Acknowledgements**

All experiments were conducted at my home laboratory under safe and controlled conditions. Appropriate personal protective equipment (PPE), including masks, gloves, and goggles, was worn as required for each experimental procedure. Comprehensive stand-by safety measures were implemented to ensure a secure testing environment during all stages of experimentation.

I extend my sincere gratitude to my parents for their exceptional support throughout Camels on Fire. They provided essential materials, assisted with the procurement of fabrics, and supervised higher-risk experiments, including Fourier's Open Flame and Moisture Vapor Transfer Rate (MVTR) testing. I am deeply thankful to Dr. Aruna Turaga, my external science mentor, for her guidance on evaluating practical metrics and elucidating the biological and environmental implications of PFAS. I also acknowledge Ms. Kendall Campana, Ph.D. student, California Coast University, for her mentorship in adapting the engineering design process to my research framework. Additionally, Anna E. Lindell and Jessica Warren of the anti-PFAS startup in Denmark, Cambiotics, met with me and helped me refine my experimental research.

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