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Plant-Based Vascular Grafts for Space Medicine: Quantifying and Enhancing Durability under Simulated Spaceflight and Aviation Conditions By Sanha Kang

Abstract

Long-duration spaceflight exposes the cardiovascular system to hypobaric pressure, fluid redistribution, and elevated core temperature, collectively impairing vascular function and accelerating remodeling. These challenges highlight the need for vascular materials that can maintain biological stability under space missions. Plant-based vascular grafts offer a sustainable and biocompatible alternative to synthetic scaffolds. Their intrinsic cellulose-based microchannels mimic human vasculature, promoting endothelialization and nutrient transport. Despite growing interest in sustainable biomaterials, their potential in space medicine has not been investigated. This study pioneers the application of plant-derived vascular grafts within simulated spaceflight environments, integrating bioengineering and human health in space. Plant-based vascular grafts were synthesized with fresh Viburnum rhytidophyllum leaves that were decellularized using SDS–Triton protocol and rolled into tubular grafts stabilized with gelatin–glutaraldehyde crosslinking. Endothelial cells were seeded onto the luminal surface to approximate physiological vessel conditions. Finished grafts were then placed in a custom bioreactor generating perfusion flow of culture medium to simulate the environment inside vascular grafts. Simultaneously, tested grafts were exposed to thermal cycling of 37 °C–41 °C, reflecting the "space-fever" phenomenon observed in microgravity, and to hypobaric pressure of 0.39 atm, simulating depressurization scenarios relevant to space missions. Mechanical characterization revealed quantifiable degradation in tensile and burst strength following simulated space stressors, allowing direct measurement of the extent of structural compromise. Heat exposure and pressure cycling caused moderate declines; all grafts, however, maintained factors of safety above two relative to physiological pressures. Complementary experiments tested applying chemical crosslinkers and concentrations to plant-based grafts to identify optimal reinforcement strategies that enhance durability under these conditions. Crosslinking significantly improved tensile and burst performance, with 18.75% formaldehyde and 2.5% glutaraldehyde producing the strongest reinforcement, revealing a previously unreported strategy for stabilizing plant-based scaffolds in low-pressure, high-temperature space environments. Microscopic imaging confirmed that endothelial cells remained adherent and viable following combined stress exposure. This work establishes the first demonstration of plant-based vascular grafts engineered for spaceflight resilience, advancing regenerative biomaterials for sustaining human health during extended space missions.

1. Introduction

Long-duration spaceflight and high-altitude aviation environments impose significant physiological challenges on the cardiovascular system. Cardiovascular deconditioning, specifically, is triggered by dramatic fluid shifts and reduced vascular loading, perturbing hemodynamics and accelerating vascular remodeling, which collectively increase long-term

disease risk for mission crew members. Effects include increased heart rate, decreased cardiac output and stroke volume, and expanded jugular vein and carotid artery cross-sectional areas due to microgravity-based fluid redistribution. These findings underscore the urgent need for biomedical interventions capable of preserving vascular integrity under extreme aerospace conditions, where conventional medical support may be lacking.

Furthermore, astronauts routinely experience a sustained elevation in resting core body temperature of approximately +1 °C during the first two to three months of missions, a phenomenon often called "space fever." Recent findings document an average increase in resting body temperature to about 38 °C (100.4°F), even greater during physical exertion, where internal body temperature may reach or exceed 40 °C (104°F). These temperature changes unique to space conditions are attributed to impaired convective heat loss, inefficient sweating, and altered fluid redistribution unique to microgravity. In addition, elevated core body temperature during spaceflight may accelerate mechanical degradation of native vascular tissues, potentially compromising the long-term durability of grafts astronauts already possess.

Conventional vascular grafts, a staple of surgical repair, are poorly suited for these environments. Synthetic grafts such as expanded polytetrafluoroethylene (ePTFE) and polyethylene terephthalate (Dacron) demonstrate durable performance in large-caliber vessels but show reduced viability in small-diameter applications, with five-year patency rates frequently ranging only from 44% to 62% despite aggressive anticoagulation therapy. Their long-term durability is undermined by thrombosis, intimal hyperplasia, and mechanical compliance mismatch, all common causes of graft failure. Additionally, most current graft sources are derived from non-degradable synthetic polymers or animal tissues, raising concerns about sustainability and medical ethics. The growing demand for biocompatibility and environmental stewardship highlights that existing graft solutions fall short of meeting the challenges posed by both clinical and extraterrestrial contexts.

Plant-derived vascular grafts have recently emerged as a promising alternative. Decellularized leaf scaffolds provide a renewable, low-thrombogenic, and structurally adaptable platform that has been shown to support endothelialization and maintain mechanical strength in biomedical settings. Beyond their clinical potential, such scaffolds align with environmental engineering principles by leveraging sustainable biomass rather than animal-derived or synthetic materials. However, despite these advantages, plant-based grafts have not yet been evaluated under aerospace-relevant stressors such as hypobaric pressure and thermal cycling, which are conditions that astronauts and high-altitude pilots frequently encounter.

The present study aims to address this gap by assessing the structural and biological durability of plant-based vascular grafts exposed to hypobaric and thermal stressors that reflect real-world aerospace scenarios. In addition, a supplementary investigation was conducted to optimize crosslinking strategies, testing different agents and concentrations to enhance mechanical reinforcement of the scaffolds. By applying a validated bioengineering platform to the context of aerospace medicine and framing it within the paradigm of environmental

sustainability, this work offers a novel perspective at the intersection of engineering, medicine, and planetary health.

While plant-based scaffolds have been validated for terrestrial biomedical use, their potential in environments characterized by hypobaric pressure, thermal dysregulation, and microgravity remains unexplored. In such contexts, both the structural stability of acellular grafts and the biological tolerance of cell-seeded grafts become critical factors in determining feasibility. By subjecting engineered vascular conduits to conditions that approximate those encountered in spaceflight and high-altitude missions, this study seeks to bridge the gap between theoretical material suitability and real-world physiological demands. Evaluating grafts not only mechanically but also in the presence of living endothelial cells provides a more comprehensive perspective on how sustainable, lightweight, and easily fabricated biomaterials might integrate with living systems under aerospace-relevant stress: qualities especially valuable in settings where conventional medical infrastructure and supply chains are absent.

2. Related Works

Long-duration spaceflight presents significant cardiovascular challenges, including cephalad fluid shifts that redistribute 1.5 to 2 liters of blood to the upper body, leading to cardiac deconditioning and reduced orthostatic tolerance (Hughson et al., 2016; Arbeille et al., 2017). Astronauts also experience elevated core temperatures of 0.5 to 1.0°C above baseline and exposure to hypobaric conditions as low as 0.3 to 0.4 atm during extravehicular activities (Stahn et al., 2017). These stressors accelerate vascular aging and endothelial dysfunction, with microgravity conditions reducing nitric oxide production and impairing vasodilatory capacity (Versari et al., 2013). Traditional vascular grafts including autologous vessels and synthetic polymers like PTFE are impractical for space missions due to limited availability, poor small-diameter performance, and extensive fabrication requirements (Pashneh-Tala et al., 2016; Vara et al., 2020; Lawson et al., 2015).

Recent advances in plant-based tissue engineering offer a promising alternative. Decellularized plant tissues preserve native cellulose matrices with vascular architectures that mirror mammalian capillary networks (Gershlak et al., 2017). Spinach and apple-derived scaffolds have successfully supported human endothelial cells and demonstrated excellent biocompatibility (Gershlak et al., 2017; Modulevsky et al., 2014, 2016). Chemical crosslinking with glutaraldehyde can enhance mechanical properties and resistance to degradation (Hickey et al., 2018). However, no studies have evaluated plant-based vascular grafts under space-relevant conditions such as thermal stress, hypobaric pressure, or combined environmental stressors. This study investigates decellularized Viburnum rhytidophyllum leaf-derived vascular grafts under simulated space mission conditions, including thermal cycling (37–41°C), hypobaric pressure exposure (0.39 atm), and endothelial cell culture. This work establishes the first empirical foundation for plant-based vascular grafts as a sustainable solution for cardiovascular health during extended spaceflight missions.

3. Methods

3.1 Leaf Preparation

All experimental procedures were conducted following the protocol established by Merna et al. (2023).

Fresh leatherleaf viburnum (*Viburnum rhytidophyllum*) leaves were selected as the model plant source due to their superior mechanical integrity and suitable dimensions for fabricating small-diameter grafts, consistent with previous reports. Immediately after collection, leaves were rinsed thoroughly with deionized (DI) water to remove residual soil and surface contaminants.

Decellularization was performed using a sodium dodecyl sulfate (SDS)-based protocol adapted from previously optimized methods developed by the Merna Laboratory. Leaves were immersed in a 70% SDS solution prepared in DI water until complete loss of pigmentation was observed. Following SDS treatment, scaffolds were transferred into a clearing solution consisting of 0.1% Triton X-100 and 10% bleach, which facilitated removal of residual cellular debris and enhanced optical transparency. To eliminate detergent residues, samples were rinsed extensively in DI water until no visible foam was observed.

Sterilization was achieved by immersing scaffolds in 70% ethanol for 1 h, followed by rinsing in sterile phosphate-buffered saline (PBS). Decellularized and sterilized scaffolds were stored at 4 °C in sterile PBS until further use. This workflow was not newly developed in this study but was adapted from standardized and validated decellularization protocols reported by Merna and colleagues, ensuring reproducibility and allowing the platform to be applied to the aerospace-relevant stress conditions investigated herein.

3.2 Tubular Graft Fabrication

Decellularized leaf scaffolds were cut into rectangular strips of uniform dimensions (57.25 mm × 24 mm), with care taken to maintain consistent thickness across samples. Each strip was rolled tightly around a cylindrical stainless-steel mandrel (diameter ≈ 1 mm) such that the adaxial surface was oriented toward the lumen, reproducing the anisotropic structural alignment of natural vasculature.

To stabilize the tubular configuration and provide mechanical reinforcement, a crosslinking adhesive solution was prepared by combining bovine gelatin (50% w/v, pre-warmed to 55 °C) with glutaraldehyde (25% stock solution) in proportions previously described. The mixture was applied evenly across one edge of the scaffold strip to serve as an adhesive interface. The strip was then rolled around the mandrel and held in place for ~1 min to permit crosslinking. Following fixation, constructs were incubated at 37 °C in sterile PBS for 4 h to ensure complete stabilization of the tubular geometry.

The resulting tubular grafts approximated the dimensions of small-caliber vessels and were suitable for subsequent stress testing under aerospace-relevant conditions. This fabrication process closely follows established methods previously standardized by the Merna et al.,

ensuring structural reproducibility while enabling direct application of the platform to the novel context of hypobaric and thermal stress simulations performed in this study.

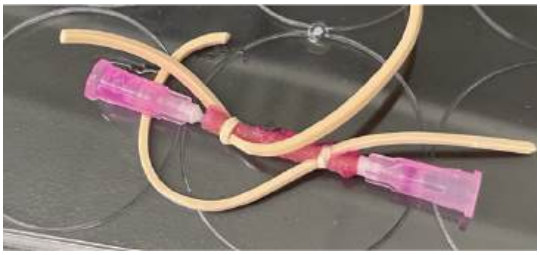


Figure 1. This image reveals the finished plant-derived vascular graft seeded with endothelial cells and cannulated using 20-gauge needles for perfusion and flow conditioning.

3.3 Graft Seeding and Cellular Evaluation

To extend the study toward more physiologically relevant conditions, endothelial cells were introduced onto the luminal surface of the plant-derived grafts to assess biological compatibility and viability under simulated aerospace environments. SDS-decellularized *Viburnum rhytidophyllum* scaffolds were sterilized in ethanol, coated with fibronectin (10–20 μg/mL), and seeded with endothelial cells (~8×10^5 cells/cm²) using a syringe to achieve uniform luminal coverage. The grafts were rotated 90° every 15 min for 3 h to promote even adhesion and incubated for 24 h at 37 °C, 5% CO_2 to permit attachment and spreading.

After incubation, fluorescence images were obtained to assess cellular coverage, and nuclei were quantified in three representative regions per graft using ImageJ to calculate mean endothelial cell density. The seeded constructs were subsequently exposed to hypobaric pressure in a custom bioreactor, enabling dynamic simulation of aerospace-relevant stressors while maintaining cell viability.

Confocal fluorescence imaging was performed on endothelialized grafts that underwent hypobaric pressure exposure using an Olympus FV3000 laser scanning confocal microscope equipped with a 10× objective (UPLXAPO10X, NA 0.4). Samples stained with Hoechst 33258 were excited with a 405 nm laser (7% transmission), and emission was collected at 411–480 nm using a photomultiplier tube detector (500 V). Images were acquired at 2048 × 2048 pixels (0.621 μm/pixel), covering a 1.27 × 1.27 mm field of view with a 12-bit depth.

3.4 Stress Simulation Protocols

To replicate the environmental stressors most relevant to long-duration spaceflight and high-altitude aviation, plant-based vascular grafts were subjected to controlled thermal cycling and hypobaric pressure exposure. These simulations were designed to reproduce physiologic stress conditions that astronauts and aircrew are known to encounter during missions.

3.4.1 Thermal Cycling

Grafts were exposed to cyclic temperature changes between 37 °C and 41 °C to mimic the range of human internal core body temperatures observed in space environments. Under terrestrial conditions, core temperature is tightly regulated at ~37 °C; however, microgravity induces impaired heat dissipation and altered circulatory dynamics, resulting in a persistent elevation in core body temperature: a condition termed "*space fever*." During exercise aboard the International Space Station, astronauts have been documented to reach internal temperatures as high as 40–41 °C, reflecting the combined effects of microgravity, fluid redistribution, and limited convective heat loss. These findings justify the use of 37–41 °C cycling as a physiologically relevant stressor for graft evaluation. In the laboratory, grafts were submerged in sterile phosphate-buffered saline (PBS) within a temperature-controlled beaker placed on a hot plate. The temperature was increased from 37 °C to 41 °C, maintained at 41 °C for 40 min, and then reduced back to 37 °C. Each sample underwent two complete cycles, with a total exposure duration of approximately 2 h.

3.4.2 Hypobaric Pressure Exposure

In parallel, grafts were exposed to hypobaric stress to simulate the pressure conditions that may occur during unregulated high-altitude flight or contingency depressurization events in spacecraft. Commercial and military aircraft routinely operate at cabin pressures equivalent to 0.6–0.7 atm (~8,000–10,000 ft), and unpressurized environments at extreme altitude or equipment failure can expose tissue to pressures as low as 0.3–0.4 atm. Similar low-pressure exposures have also been associated with increased cardiovascular strain and endothelial dysfunction in both aviation and spaceflight research. To simulate these scenarios, grafts were submerged in sterile PBS within a sealed acrylic pressure chamber. The chamber was connected to a vacuum line, reducing the internal pressure to 0.39 atm (≈ −9 psi) and maintained for 3 hours. This condition reflects the lower bound of pressures that astronauts or aviators might realistically encounter in emergency or depressurized operations.

Together, the thermal and hypobaric regimens were selected to approximate real-world physiologic stressors encountered in aerospace environments, thereby providing a relevant context to evaluate the durability and biocompatibility of plant-based vascular grafts under extreme conditions.

3.5 Mechanical Testing

Mechanical evaluation of grafts was performed to determine their structural resilience following exposure to thermal cycling and hypobaric stress. Two complementary assays—burst pressure testing and uniaxial tensile testing—were employed to characterize failure thresholds and load-bearing capacity, respectively.

3.5.1 Burst Pressure Testing

Burst pressure testing was conducted to evaluate the ability of tubular grafts to withstand intraluminal pressure, a critical determinant of vascular safety during implantation and function.

Grafts were cannulated at both ends with barbed syringe adapters and secured using sterile ligatures to prevent leakage. Sterile PBS was infused at a constant rate until catastrophic rupture occurred. Burst pressure was defined as the maximum internal pressure recorded immediately prior to graft failure. This method provides a direct measure of the factor of safety of each graft relative to physiologic blood pressures and has been widely adopted as a benchmark for engineered vascular conduits.

3.5.2 Tensile Testing

To assess the intrinsic material properties of the decellularized scaffolds, strips were excised longitudinally from graft walls and trimmed into dog-bone geometries to standardize sample geometry and minimize stress concentration at the grips. Samples were mounted onto a uniaxial tensile tester equipped with pneumatic grips and a calibrated load cell. Each sample was elongated at a constant strain rate until rupture, and force–displacement data were recorded. Ultimate tensile strength and elastic modulus were calculated from stress–strain curves. This analysis provided quantitative insight into scaffold stiffness and mechanical degradation following exposure to simulated aerospace conditions.

Together, burst pressure and tensile testing enabled comprehensive evaluation of both whole-graft functionality and intrinsic material performance. These assays ensured that observed changes in graft mechanics could be directly correlated with the imposed thermal and hypobaric regimens, providing a rigorous framework for assessing durability under conditions relevant to aerospace medicine.

3.6 Crosslinking Optimization

In addition to the primary stress-testing protocols, an independent set of experiments was conducted to evaluate the potential of chemical crosslinking to enhance scaffold durability. This investigation aimed to explore whether modulation of crosslinker type and concentration could provide a tunable method to improve mechanical reinforcement of the decellularized plant-derived grafts. While crosslinking is an established strategy in scaffold engineering, the systematic application of multiple agents at varying concentrations to this specific plant-based platform represents a novel extension of existing approaches.

For these experiments, tubular grafts were immersed in either glutaraldehyde or formaldehyde solutions at defined concentrations: 2.5%, 11.25%, and 25% for glutaraldehyde, and 10% and 18.75% for formaldehyde. Samples were placed on an orbital shaker to ensure uniform exposure and incubated in each solution for 10 minutes. Following crosslinking, grafts were rinsed four times in deionized water to remove residual reagents and were subsequently stored in sterile PBS until further use.

This additional optimization study was designed to provide preliminary insight into how targeted crosslinking chemistries could augment the structural integrity of plant-derived vascular grafts. By varying agent and concentration, this experiment offered an initial framework for

tuning scaffold performance in a controlled manner, extending the applicability of the platform beyond baseline stress tolerance testing.

4. Results

4.1 Overview of Experimental Groups

Four experimental groups were established to evaluate the performance of plant-derived vascular grafts under aerospace-relevant stressors: (i) an untreated control group, (ii) a heat-stressed group subjected to cyclic exposure between 37–41 °C, (iii) a pressure-stressed group exposed to hypobaric conditions at 0.39 atm, and (iv) an additional crosslinker-treated group maintained under baseline conditions to explore the effects of chemical reinforcement.

Across these groups, burst pressure testing was performed to assess intraluminal failure thresholds, and uniaxial tensile testing was conducted to quantify intrinsic material properties. Fluorescence imaging was additionally conducted to evaluate endothelial cell morphology and coverage following hypobaric exposure.

4.2 Burst Pressure

Burst pressure testing demonstrated clear differences among groups (Fig. 2). Control grafts exhibited the highest rupture thresholds (mean 6.95), while pressure-stressed grafts showed slightly reduced values (mean 6.10). Heat-stressed grafts displayed a pronounced decline in rupture strength (mean 4.80), representing ~70% reduction relative to controls.

Even with these reductions, all groups maintained factors of safety (FoS) greater tan 2 when calculated against physiological arterial pressures. Specifically, mean FoS values were ~2.6 for the heat-stressed group, ~2.1 for the pressure-stressed group, and ~3.0 for controls.

Thus, while thermal cycling produced the most severe degradation, the scaffolds remained structurally adequate under baseline vascular loading.

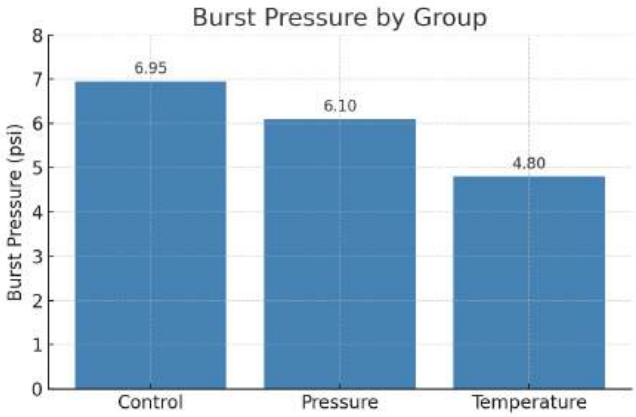


Figure 2. This image reveals the comparative burst pressure performance of plant-derived vascular grafts under different stress conditions. Control scaffolds maintained the highest rupture threshold (6.95 psi), followed by pressure-stressed grafts (6.10 psi) and temperature-cycled grafts (4.80 psi). The decline in burst strength with increasing stress severity demonstrates that both hypobaric and thermal exposures weaken graft integrity, though all groups remained above physiological safety limits.

4.3 Uniaxial Tensile Testing

Uniaxial tensile testing was conducted to evaluate ultimate tensile strength (UTS), elastic modulus, and strain-to-failure of scaffolds across control and stressed conditions.

Control grafts exhibited the highest tensile strength (mean ultimate load ≈ 1.47 N), while temperature-stressed grafts showed marked reductions (mean ≈ 0.83 N). Pressure-stressed grafts demonstrated intermediate values (mean ≈ 0.44 N).

Elastic modulus followed a similar trend, with controls demonstrating the highest stiffness (mean ≈ 4.06 MPa). Both temperature- and pressure-stressed grafts exhibited significantly reduced values (means ≈ 2.96 and 3.03 MPa, respectively).

Together, these results indicate that both heat and pressure stresses diminish the tensile properties of plant-derived vascular grafts, with pressure cycling exerting the most pronounced reduction in UTS.

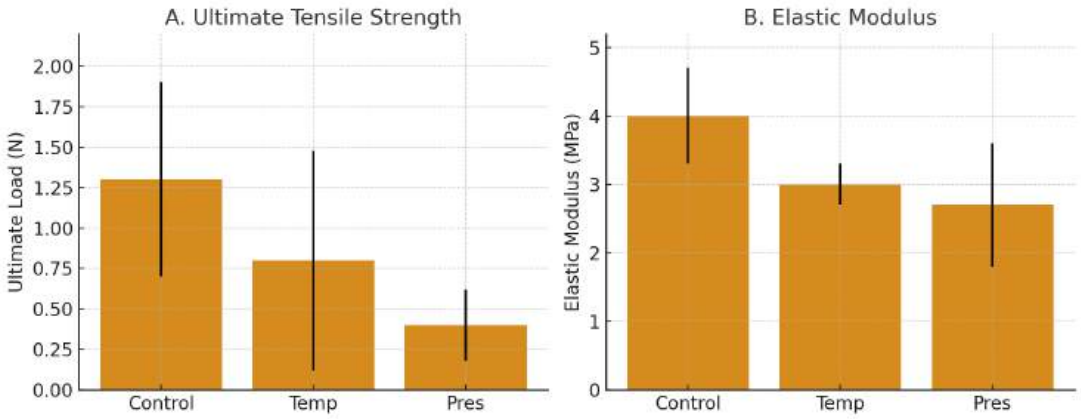


Figure 3. This image reveals the comparative mechanical performance of plant-derived vascular grafts subjected to simulated aerospace stressors. (A) Ultimate tensile strength decreased under both thermal and hypobaric conditions, with the pressure-stressed group showing the most pronounced reduction in load-bearing capacity. (B) Elastic modulus measurements showed a similar trend, indicating loss of stiffness and structural resilience following environmental stress exposure. Together, these results demonstrate that both temperature and pressure variations compromise mechanical integrity relative to controls.

4.4 Cell Viability under Hypobaria

Confocal fluorescence imaging was performed on endothelialized grafts that underwent hypobaric pressure exposure using an Olympus FV3000 laser scanning confocal microscope equipped with a 10× objective (UPLXAPO10X, NA 0.4). Samples stained with Hoechst 33258 were excited with a 405 nm laser (7% transmission), and emission was collected at 411–480 nm using a photomultiplier tube detector (500 V). Images were acquired at 2048 × 2048 pixels (0.621 µm/pixel), covering a 1.27 × 1.27 mm field of view with a 12-bit depth.

Cell density was quantified using ImageJ software (v0.6.0, ImageJ.JS). Images were converted to 8-bit grayscale and a threshold was applied using the Default method with manual adjustment (lower threshold: 7, upper threshold: 9) to isolate Hoechst-positive nuclei from background. The thresholded images were converted to binary masks using the 'Convert to Mask'

function. To separate touching nuclei, the 'Watershed' algorithm was applied to the binary image. Individual nuclei were then counted using the 'Analyze Particles' function with appropriate size exclusion criteria to eliminate debris and clumped cells. Cell density was calculated from the summary statistics and expressed as cells per mm².

Quantitative analysis identified 8,056 nuclei across a total imaged area of 45,494 μm², corresponding to 17.4% surface coverage. The consistent nuclear distribution and fluorescence intensity indicate that endothelial cells remained well attached and morphologically intact following hypobaric exposure.

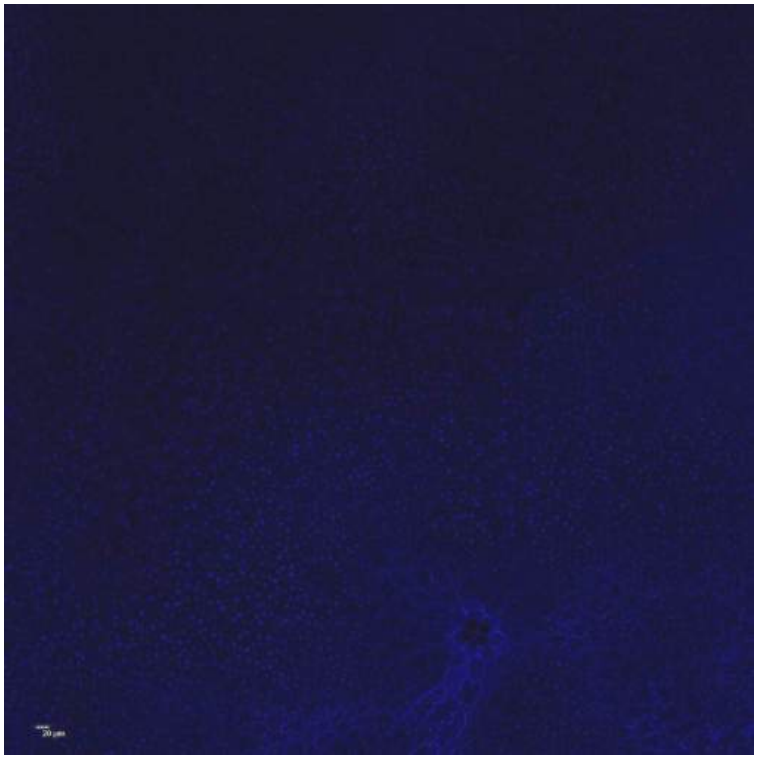


Figure 4. This image reveals the confocal fluorescence image of endothelialized plant-derived vascular grafts following hypobaric exposure. Hoechst-stained nuclei (blue) demonstrate uniform distribution and strong fluorescence intensity, confirming that endothelial cells remained adherent and morphologically intact under reduced pressure. Quantitative analysis identified 8,056 nuclei across a 45,494 μm² region (17.4% surface coverage), indicating sustained cell viability and attachment after hypobaric stress. Scale bar = 20 μm.

5. Discussion

5.1 Summary of Main Findings

This study examined how hypobaric pressure and thermal cycling affect the mechanical and biological performance of plant-derived vascular grafts. Both stressors caused comparable degradation, with thermal cycling reducing burst pressure more severely and hypobaric exposure more strongly affecting tensile strength. Confocal imaging confirmed that endothelial structure remained intact, indicating that mechanical rather than cellular components were primarily

compromised. Crosslinking enhances stability beyond baseline, demonstrating that while the grafts remain functionally resilient under stress, targeted reinforcement can further strengthen their performance.

5.2 Interpretation of Results

The observed mechanical degradation under aerospace stressors, while statistically significant, does not appear to compromise the fundamental suitability of plant-derived grafts for vascular applications. The retention of adequate safety margins suggests that these scaffolds possess sufficient structural resilience to withstand environmental challenges encountered during spaceflight operations. The preservation of endothelial functionality despite scaffold weakening indicates that biological integration capacity remains independent of moderate mechanical decline: a dissociation that may prove advantageous for aerospace medical applications where environmental control is necessarily imperfect.

These findings establish proof-of-concept that plant-derived vascular grafts represent a viable approach to addressing critical gaps in aerospace surgical capability. Current spaceflight medical systems lack validated solutions for vascular repair despite documented cardiovascular risks during long-duration missions. Conventional tissue-engineered alternatives require infrastructure incompatible with spacecraft resource constraints, whereas plant-based scaffolds offer a low-resource fabrication pathway amenable to prefabrication and shelf-stable storage. This work represents the first experimental demonstration that such scaffolds can maintain functional performance under space-relevant environmental conditions.

The preservation of biological functionality under hypobaric stress extends the operational envelope for these devices beyond nominal spacecraft conditions to include emergency depressurization scenarios and reduced-pressure planetary environments. This capability is particularly relevant for future Mars missions and lunar operations where atmospheric pressure deviates substantially from terrestrial norms yet medical evacuation remains infeasible. The ability to optimize mechanical properties through controlled crosslinking further enhances mission-readiness by enabling targeted reinforcement against specific environmental threats.

While clinical translation will require validation through microgravity testing and in vivo performance assessment, this study establishes foundational evidence that plant-derived grafts merit consideration as candidate technologies for extraterrestrial vascular surgery: a capability increasingly critical as human spaceflight extends beyond low Earth orbit.

5.3 Limitations

Several methodological constraints warrant consideration when interpreting these findings. The relatively preliminary sample sizes (n = 5–6 across experimental groups) limit statistical power and preclude definitive characterization of variance within treatment conditions. While the observed effects achieved statistical significance in primary comparisons, replication with larger cohorts would strengthen confidence in effect magnitudes and enable detection of

subtler differences among treatment groups. Additionally, the experimental design simulated aerospace stressors sequentially under controlled laboratory conditions rather than the combined, dynamic exposures characteristic of actual spaceflight environments. Grafts in operational contexts may experience pressure variations, radiation exposure, and microgravity, which are interactions that may produce synergistic degradation effects not captured by isolated stressor testing.

Importantly, this work should be viewed as pioneering proof-of-concept research that establishes foundational feasibility rather than definitive clinical validation. As the first systematic investigation of plant-derived vascular grafts under aerospace-relevant conditions, this study necessarily prioritizes breadth of initial characterization over depth of mechanistic interrogation. The value lies not in providing flight-ready devices, but in demonstrating that botanical scaffolds warrant serious consideration as candidate technologies for space medicine: a possibility previously unexplored in the literature. By identifying both the promise and the constraints of this approach, the present work creates a framework for subsequent investigations that can address the limitations identified here through targeted experimentation, ultimately advancing the field toward viable aerospace vascular grafts for future deep-space exploration missions.

6. Conclusion

This study demonstrates that plant-derived vascular grafts maintain structural and biological functionality under aerospace-relevant environmental stressors, establishing proof-of-concept for their potential deployment in spaceflight medical applications. Despite measurable degradation under thermal cycling and hypobaric conditions, all scaffolds retained adequate factors of safety while preserving endothelial cell viability. Chemical crosslinking emerged as a viable strategy to enhance mechanical resilience, providing targeted reinforcement against stress-induced weakening. Beyond biomedical performance, this work validates the Merna platform as a dual-purpose innovation: functioning simultaneously as a high-performance biomaterial and a sustainable aerospace resource. The convergence of environmental sustainability with aerospace health represents a paradigm shift wherein resource-efficient terrestrial materials can be repurposed for extraterrestrial medical applications, challenging conventional assumptions that space-grade medical devices must derive from energy-intensive synthetic manufacturing or animal sources.

As pioneering proof-of-concept research, this work bridges established bioengineering principles into an entirely new, high-need domain. As human spaceflight extends toward lunar bases and Mars exploration, the absence of validated vascular repair solutions becomes increasingly critical. This study provides the first experimental evidence that plant-based grafts merit consideration for aerospace medical kits, offering an alternative to conventional tissue-engineered constructs. While further validation through microgravity testing and in vivo assessment remains necessary, the present findings establish a foundation for future research that

could ultimately equip astronauts with vascular capabilities where terrestrial medical evacuation is impossible.

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Neurobiological Underpinnings of Borderline Personality Disorder: Brain Structure, Early Trauma, and Therapeutic Implications By Ishita Jaiswal

Abstract

Borderline Personality Disorder (BPD) is characterized by severe emotional dysregulation that impacts relationships and increases suicide risk. This review examines the neurobiological basis of BPD's core features focusing on brain structures implicated in underlying biology and current therapeutic approaches. Advanced studies using neuroimaging reveals three critical alterations: hypoactivity in the prefrontal cortex, reduced hippocampal volume, and amygdala hyperreactivity. These neurobiological findings explain BPD's characteristic symptoms of emotional instability, impulsivity, and interpersonal difficulties. In addition, adverse childhood experiences, particularly emotional abuse and invalidation, appear to shape these neural differences during critical developmental periods, with different trauma types potentially influencing specific symptom manifestations. While there is no approved pharmacotherapy for BPD, the current clinical approach is focused on psychotherapy. Understanding BPD through this neurobiological lens not only advances scientific understanding but also offers hope for targeted interventions addressing the specific brain systems involved in emotional dysregulation. By recognizing BPD as a disorder with clear biological underpinnings, we can move toward more effective treatments and greater compassion for those affected.

Introduction

Borderline personality disorder (BPD) is a chronic, heterogenous and disabling mental health condition that affects emotional regulation, intrapersonal relationships, and external connections, stemming from a deep-rooted fear of abandonment or rejection (1, 2). Emotional dysregulation, which is the inability to manage and resolve intense emotional experiences, is a core feature of BPD. People with BPD often experience emotions more intensely than others, and when triggered, these feelings evolve into erratic behaviors, including impulsive decisions, self-harm, and suicidal behaviors (3). Though once debated, BPD is now recognized by mental health professionals as an actual and well-founded diagnosis, even among adolescents. Studies estimate 1.6% to 3% of the population, and 80% of suicidal youths have BPD (3). 10% of those with the disorder die from suicide (4). Due to its intensity and frequent association with self-harm and suicidal thoughts, BPD is considered one of the most dangerous personality disorders.

Emotional dysregulation is considered the root cause of BPD. It consists of many challenges, such as emotional vulnerability, extreme and fast mood swings, and a lack of effective strategies to return to stability (3). Instead of healthy coping skills, people with BPD resort to harmful behaviors, such as substance abuse, eating disorders, or self-harm, to escape overwhelming emotions (5). According to psychologist Marsha Linehan’s biosocial theory, BPD originates from a person with high emotional sensitivity who grows up in an environment that ignores, invalidates, or punishes their feelings. This causes people with BPD to perceive ordinary

events as unbearable, triggering emotional breakdowns or suicidal actions. The cycle of emotional pain and poor coping becomes embedded, making it extremely difficult to recover without help (6).

Despite its severity, BPD remains one of the most misunderstood mental health disorders, by both general society and medical professionals (7). Recent studies, however, have begun to understand the underlying biology of the BPD. For example, magnetic resonance imaging (MRI) and PET (positron emission tomography) scans show the differences in activation status of brain regions associated with emotional regulation systems in those with BPD when compared to healthy controls (2). This has helped counter harmful stereotypes and introduce a more science-based understanding of the disorder by emphasizing the influence of biology and environment on one's brain.

This review aims to provide an overview of existing literature on underlying mechanisms to help us understand BPD more deeply, beginning with emotional dysregulation that defines the disorder. It will then analyze the brain structures involved in emotional regulation, including the amygdala, hippocampus, and prefrontal cortex, as well as the impact of early trauma. It will also explore the current therapeutic strategies.

Emotional Dysregulation

Emotional dysregulation refers to the inability to effectively manage emotions, causing individuals to experience situations with overwhelming intensity, react with heightened responses, and struggle to return to a stable emotional state. It involved difficulty calming down, maintaining consistent moods, and regaining balance after being triggered. This is a root symptom of BPD and manifests through constant, intense mood swings, rage episodes, and chronic emptiness. Emotional dysregulation also underlies other symptoms: unstable relationships, marked by shifting between idealization and devaluation, impulsive behaviors used to escape or numb emotional pain, and identity instability as fluctuating emotions influence self-image (3, 8, 9).

Our emotional processing systems involve two key components: emotional reactivity and emotion regulation. Emotional reactivity is the automatic response to emotional stimuli, affecting our subjective feelings, behaviors, and physical state. In contrast, emotion regulation refers to how we manage these emotions (10). People with BPD experience intense emotional reactions (hyper-reactivity) and struggle to manage them effectively. They typically lack healthy coping strategies while relying on harmful ones, like self-harm, to handle overwhelming emotions (11). While several factors such as genetic and adverse childhood experiences may contribute towards emotional dysregulation, the diagnosis of BPD involves longitudinal observation of a patient's behaviors.

Brain Structures Involved in Emotional Regulation

With advancements in the field of neuroradiology, the cutting-edge tools have uncovered important structural and functional differences, providing visible evidence of the long-term

neurobiological changes associated with BPD. The following section describes the major changes in prefrontal cortex, hippocampus, and amygdala.

Prefrontal Cortex

The prefrontal cortex, specifically the dorsolateral prefrontal cortex (DLPFC), plays an important role in emotional regulation, executive control (regulating thoughts/actions to achieve goals), and inhibiting impulsive behaviors. When functioning properly, the DLPFC allows for effective regulation, restraining excessive emotional reactivity from limbic regions, a complex network of brain structures responsible for emotions, memory, motivation, and behavior (12, 13).

However, in individuals with BPD, neuroimaging studies reveal both hypoactivity and structural changes in the DLPFC. For example, BPD patients show reductions in DLPFC gray matter volume compared to healthy controls, suggesting weakened regulatory control. Functional imaging studies, which reveal the activity or function of an organ, show impaired activation, or hypoactivity, of the DLPFC during tasks involving aggression control and cognitive flexibility. These findings suggest that in emotionally intense situations, the DLPFC in people with BPD responds more slowly and weakly, leading to difficulties in regulating the overactive emotional parts of the brain (14, 15).

This dysfunction explains why individuals with BPD often experience rapid mood swings and impulsive actions. Instead of efficiently calming down heightened limbic activity, the delayed response creates a gap in regulation, allowing emotions to escalate. Consequently, behaviors such as aggression, self-harm, or rash decision-making may occur before regulatory control takes effect. The prefrontal cortex's impaired timing and inefficiency contribute to the core challenges of BPD: heightened emotional intensity, impulsive behaviors, and chronic instability in relationships and self-image (15, 16).

Hippocampus

The hippocampus is another critical brain structure in BPD, best known for its role in learning, memory, and stress regulation. In healthy brains, the hippocampus stores past experiences and retrieves them to regulate the body's stress response through the hypothalamic-pituitary-adrenal (HPA) axis, preventing the overactivation of emotional circuits.

Neuroimaging consistently shows that individuals with BPD have a smaller hippocampal volume, especially those with histories of childhood trauma, indicating that early distress may impair development. These structural differences correspond with traits such as impulsivity, irritability, and aggression, suggesting that a smaller hippocampus reduces the brain's ability to manage high emotions and stress effectively. In other words, reduced hippocampal volume represents more than a structural change; it also has functional consequences for emotional regulation (17, 18).

The connection between trauma, hippocampal changes, and BPD symptoms highlights the impact of early stress on the brain. Consistent activation of stress pathways, such as the HPA axis, may damage or shrink hippocampal tissues over time, leaving individuals more vulnerable

to emotional dysregulation. With a smaller, less efficient hippocampus, stress responses become exaggerated, memories of negative experiences dominate, and recovery from emotional turmoil weakens (19). These changes interact with dysfunction in other brain regions, like the prefrontal cortex and amygdala, creating a cycle of poor regulation, heightened emotional intensity, and impulsive behavior. Understanding these interactions helps explain why BPD symptoms persist and why treatment often requires approaches that target multiple brain systems simultaneously (18).

Amygdala

The amygdala is a key structure in the limbic system that detects threats and processes emotions such as fear, anger, and happiness. In a normal brain, the amygdala functions as an early warning system by quickly analyzing sensory input for danger and producing appropriate emotional and physiological responses. It interacts closely with regions like the prefrontal cortex and hippocampus, ensuring that emotional reactions remain appropriate to context. This collaboration enables humans to respond effectively to stress while maintaining control once the threat has passed (20).

In people with BPD, neuroimaging studies consistently show heightened amygdala activity, especially during tasks involving negative emotional stimuli. Unlike the stable regulation seen in healthy brains, the amygdala in BPD patients often becomes hyperactive, responding more strongly and frequently to perceived threats. This hyperactivity may also be linked to structural alterations such as increased gray matter volume or irregular connectivity with the prefrontal cortex, which together contribute to exaggerated emotional responses and difficulties in calming down once triggered (21, 22).

These differences in amygdala function help explain some of the hallmark symptoms of BPD. When the amygdala is overly reactive, even minor stressors or ambiguous social cues may be perceived as threats, leading to intense fear, anger, or feelings of rejection. Because the hyperactive amygdala overloads the brain's regulatory systems, emotions escalate quickly and persist, often seen through mood instability, hypersensitivity, and impulsive behaviors. In this way, amygdala hyperactivity not only reflects brain alteration but also illustrates the severe difficulties with emotional regulation and stable relationships seen in BPD (21, 22).

Together, dysfunctions in the prefrontal cortex, hippocampus, and amygdala create a neural environment in BPD that predisposes individuals to intense emotions, impulsive behaviors, and difficulty maintaining stable relationships, underlying the important connection between structure, function, and early life experiences.

Adverse Childhood Experiences

In BPD patients, adverse childhood experiences are not only more common but are also more strongly tied to the disorder than in many other clinical conditions. Early childhood trauma has an especially prominent influence on how the brain develops, and this influence is central to understanding BPD. In fact, individuals with BPD are reported to be thirteen times more likely to

have experienced childhood trauma compared to people in both healthy control groups and other psychiatric conditions (23, 24). These adversities include emotional, physical, and sexual abuse as well as neglect and chronic invalidation. What makes BPD stand out is that emotional abuse and neglect are consistently the most influential risk factors. While physical and sexual abuse also play a role, emotional forms of trauma appear to have the strongest and most direct association with the emotional instability and relational difficulties that define BPD (25, 26).

While not all forms of trauma contribute in the same way, emotional abuse has been shown to predict borderline symptoms most clearly and sexual abuse is more specifically connected to dissociation. The distinction helps explain why BPD can look so different from one patient to another: the type of trauma a person experienced may shape the cluster of symptoms they develop. For example, someone exposed primarily to emotional invalidation may struggle most with emotion regulation and unstable self-image, while another person with a history of sexual abuse may display more dissociative symptoms. This variability is consistent with BPD's heterogeneity, where the same diagnosis can include very different patterns of suffering (23).

From a developmental perspective, trauma disrupts the normal trajectory of brain development and maturation which can interfere with the emotional regulation, identity formation, and stable interpersonal functioning. Because brain structures like the amygdala, hippocampus, and prefrontal cortex are still developing throughout childhood and adolescence, they are especially vulnerable to toxic stress. Prolonged adversity during these periods can alter connectivity and create long-lasting vulnerabilities in self-regulation. In BPD, this is reflected through the chronic difficulties in calming emotional responses, integrating memories of trauma, and maintaining consistency with self-image and relationships (23, 27).

In addition, an abusive childhood shapes long-term functioning by leaving lasting imprints on emotional regulation systems. This reflects the growing evidence that trauma not only affects psychological coping but also becomes embedded in the body and brain. Processes such as epigenetic modification explain how early experiences change gene expression without changing the DNA sequence itself. Chronic abuse and neglect can establish dysregulation by altering the functioning of stress-related systems over time. These biological imprints help explain why the effects of trauma often persist even when circumstances change and why symptoms in BPD can feel so enduring and resistant to quick solutions (2, 28).

Timing is another factor that plays a critical role in the impact of trauma. The sensitive periods of brain development make children especially vulnerable to the damaging effects of adverse childhood experiences. Prolonged and repeated trauma during these stages has far greater consequences than isolated events. In BPD, this is seen in the way chronic exposure to invalidating environments during childhood compromises the development of adaptive emotional regulation. Furthermore, symptoms may overlap with complex PTSD, which also involves emotional dysregulation, a negative self-image, and relational disturbances. This highlights how timing and chronicity of trauma interact with neurodevelopment, leading to different but related clinical outcomes (23, 28).

Treatment of BPD

In the last couple of decades, substantial progress has been made towards understanding the underlying mechanisms of BPD and its clinical heterogeneity. As a result, the therapeutic management of BPD has also significantly improved. The major therapeutic interventions that are currently used in BPD management include psychotherapy, pharmacotherapy and neuromodulation.

Psychotherapy

The first line of treatment for managing BPD is psychotherapy. Several randomized clinical trials have shown that psychotherapy is associated with benefits for patients with BPD. Among various psychotherapy approaches, dialectical behavior therapy (DBT) is the most widely used and considered as the gold standard treatment for BPD, offering a comprehensive approach that combines cognitive behavioral techniques with mindfulness practices. The treatment typically involves both individual and group skills training sessions, allowing patients to learn new strategies while receiving personalized support for their unique circumstances. Several clinical studies have shown that DBT treatment successfully decreased activation of the amygdala, which correlated with improved emotional regulation (29). A recent study reported that DBT treatment led to normalization of neural activity in the left amygdala in response to attachment-related stimuli suggesting a potential improvement in social relationship (30). Another study reported that a shorter (10 week) DBT intervention was effective in normalizing neural activity in amygdala associated with negative bias in response to varying facial expression suggesting an improved emotional regulation (31). Duration of DBT intervention also plays an important role in determining clinical outcomes, particularly a lengthy intervention can create accessibility issues and poor patient-adherence. While a shorter and more condensed (8 week) DBT intervention showed efficacy in improving emotional regulation, depression, and distress tolerance like a 16-week DBT intervention, it was not effective against suicide risk and anxiety (32-33). A meta-analysis of 28 clinical trials reported that psychotherapy is ineffective in about half of the participants suggesting that further research is needed to have a better understanding of which BPD patients are likely to benefit from psychotherapy approach (34).

Pharmacotherapy

Although no approved drugs have been approved by US Food and Drug Administration for use in BPD, the pharmacological interventions can help in managing specific neuropsychiatric symptoms. Pharmacological interventions such as antidepressants can be helpful in reducing comorbid depression in BPD patients. Therefore, antidepressants such as selective serotonin reuptake inhibitors (SSRIs) are commonly recommended in BPD patients (35). However, SSRIs lack evidence for effectiveness against core BPD symptoms and suicidal tendencies (36). A recent study suggests that serotonin receptor antagonists and reuptake inhibitors (SARIs) may be a better approach for treating depression in BPD as they are believed to target nearly all relevant neurotransmitters (37).

There is insufficient evidence of effectiveness of anticonvulsants and antipsychotic in managing BPD (38-39). In addition, according to 2024 American Psychiatric Association (APA) practice guidelines for BPD, any psychotropic medication treatment of BPD be time-limited, aimed at addressing a specific measurable target symptom, and adjunctive to psychotherapy. APA also recommended that a patient with BPD receive a review and reconciliation of their medications at least every 6 months to assess the effectiveness of treatment and identify medications that warrant tapering or discontinuation to limit polypharmacy and prolonged treatment with medications.

Neuromodulation

Due to lack of effective pharmacotherapy and lengthy psychotherapy, novel neuromodulatory approaches such as transcranial magnetic stimulation (TMS), neurofeedback, and transcranial direct current stimulation (tDCS) are being tested for the treatment of BPD. TMS uses magnetic impulses to stimulate specific brain regions associated with mood regulation, emotional regulation and depressive symptoms (40-42). Whereas neurofeedback training teaches patients to monitor and modify their own brain activity patterns to regulate their emotions through real-time feedback. This involves measuring brain waves and receiving either visual or auditory feedback signals (43). Another neuromodulatory approach being tested in BPD is tDCS, which delivers a mild constant electrical current to specific brain regions to modulate neural activity to a patient's emotions (44). These neuromodulatory approaches are still being studied for their long-term efficacy and optimal application in BPD treatment.

Conclusions

Borderline Personality Disorder is marked by emotional dysregulation that affects every part of a person’s life, from their relationships with themselves to relationships with others. This review has shown that emotional dysregulation is not simply a matter of being “too emotional” or “overreacting” but is rooted in significant differences in brain structure and function. The prefrontal cortex, hippocampus, and amygdala (regions central to regulating, storing, and interpreting emotions) work differently in individuals with BPD. A weakened prefrontal cortex leaves emotions unregulated; a smaller hippocampus reduces the ability to manage stress and recall experiences in balanced ways, and an overactive amygdala intensifies emotional reactions to even minor threats. When combined with the lasting impact of early trauma, these neurological differences create the unstable emotions, impulsivity, and fragile self-image that defines the disorder.

Understanding these findings is crucial not only for the medical community but also for society as large. For decades, BPD has been one of the most stigmatized mental health conditions, often dismissed as untreatable. Patients are too often misunderstood, blamed, or pushed aside because their struggles are seen as intentional rather than biological. Yet, neuroscience clearly demonstrates that BPD is not a choice, it is the result of complex interactions between brain biology and lived experiences. Ultimately, greater awareness of the

neurological and developmental roots of emotional dysregulation can shift the conversation about BPD from blame and hopelessness to empathy and progress.

Due to high clinical heterogeneity and frequent comorbidities, BPD is very hard to treat mental health conditions. While pharmacotherapy mainly manages comorbidities with limited efficacy, DBT remains the most effective approach for managing BPD. There is an urgent need for research to better understand the mechanism underlying BPD to develop an effective therapeutic approach.

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The Impact of Prenatal Substance Exposure on Neonatal Opioid Withdrawal Syndrome: Treatment Strategies, Environmental Factors, and Developmental Outcomes

By Saanika Shirgur

Abstract

Neonatal Opioid Withdrawal Syndrome (NOWS) is a multisystem condition, caused by the sudden withdrawal of substances that the infant was exposed to in utero, and poses a significant risk to infant neurodevelopment and health. With continued opioid use among pregnant individuals, there is an urgent need to investigate how different treatment strategies for NOWS influence infant development outcomes. Pharmacologic treatments such as morphine, methadone, and buprenorphine are used widely, but their long-term impact on cognitive, behavioral, and sensory development is unknown. The goal of this research is to determine how different medication and treatment strategies influence the long-term neurodevelopmental outcomes of infants with Neonatal Opioid Withdrawal Syndrome, while also considering the role of environmental and genetic factors. A review of existing literature, developmental studies, and treatment comparison trials was done to find trends in data. The factors of early intervention, parental involvement, socioeconomic status, and genetics were examined as well. Results suggest that both the type and timing of treatment play a critical role in shaping long-term outcomes. Infants who received individualized treatment plans showed improved long-term neurodevelopmental outcomes compared to those who received standard treatment protocols. The results suggest that individualized treatment approaches for NAS may improve long-term neurodevelopmental outcomes and support more effective, targeted care strategies.

Introduction

"The rising incidence of NOWS has resulted in increasing admission rates to NICU, from 7 per 1000 to 27 per 1000 cases" (Anbalagan, et al.). Neonatal Opioid Withdrawal Syndrome (NOWS) is a multisystem condition, caused by the sudden withdrawal of substances that the infant was exposed to in utero (Falkowitz et al.). This condition not only requires immediate treatment to manage withdrawal symptoms but also raises concerns regarding the long-term impact on infant neurodevelopment. Pharmacologic treatments, such as morphine, methadone, and phenobarbital, help manage withdrawal symptoms but early opioid exposure can interfere with brain development. However, treatment for NOWS also includes non-pharmacological treatments to soothe withdrawal symptoms and improve overall infant health and well-being. This combination of both pharmacologic and non-pharmacologic approaches is essential in providing comprehensive care for neonates affected by NOWS. Neonatal Opioid Withdrawal Syndrome is influenced by multiple factors, including environmental factors and genetics, and plays a critical role in shaping the development for these infants. Despite these interventions, the long-term neurodevelopmental outcomes for these infants remain a concern due to factors such as type of treatment, length of hospital stay, environment, and many more factors (Shaw et al.). Studies have also found that infants who experience NOWS are at a higher risk of cognitive

impairments, delayed motor skills, and behavioral disorders later in life. By addressing motor, cognitive, and language deficiencies, therapies can improve brain development (Khurana et al.). Early intervention of these therapies can lessen the effects of cognitive and developmental deficits brought on by prenatal opioid exposure (Conradt). Medication and treatment strategies in neonates with Neonatal Opioid Withdrawal Syndrome (NOWS) can significantly impact withdrawal symptoms, highlighting the need for early intervention and developmental therapies to minimize long-term cognitive and behavioral challenges for healthy overall development.

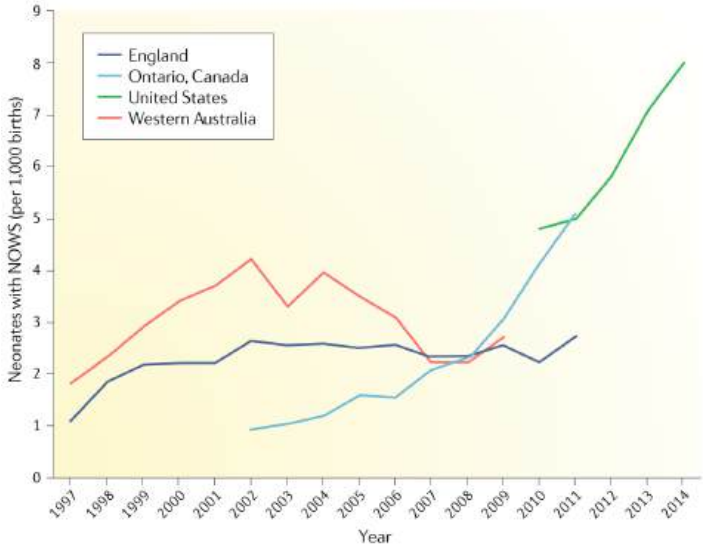


Fig 1: Increasing trendline of neonates with NOWS per 1000 births

Impact of Prenatal Drug Exposure on Withdrawal Symptoms

Prenatal Drug Exposure, including untreated addiction, opioid use, and medications to treat opioid use disorder significantly increases the risk of Neonatal Opioid Withdrawal Syndrome and its adverse neonatal outcomes. “Stimulant use during pregnancy increases obstetric complications for the mother, increases the rate of preterm birth, and decreases birth weight, length, and head circumference for the exposed infant” (Wouldes et al.). The severity of these symptoms and their long-term effects depend on various factors, including the type of substance, dosage, and duration of exposure.

When opioids such as heroin, oxycodone, and methadone cross the placenta, it leads to fetal dependence and NOWS which can show a variety of symptoms. (Committee on Obstetric Practice). These symptoms can include tremors, irritability, high-pitched crying, seizures, frequent yawning and sneezing, poor feeding, and uncoordinated, constant sucking. Additionally, other complications like diarrhea, vomiting, poor weight gain, and dehydration are common in infants with NOWS. Infants experiencing NOWS often require specialized medical care, including pharmacological interventions and supportive therapies, to manage their symptoms and ensure proper growth and development. Beyond opioids, stimulant exposure during pregnancy also poses significant risks to neonate health. The interaction of multiple substances in the

neonatal system creates additional complications, leading to different withdrawal symptoms and developmental challenges. Additionally, higher levels of substance exposure often lead to more severe withdrawal symptoms, prolonged hospital stays, and extended recovery periods. The amount of the substance used by the mother is also connected to how intense the withdrawal symptoms will be. Generally, the larger doses lead to more intense and harder symptoms. Furthermore, different drugs impact the developing body of the baby differently. For instance, the opioid drug heroin or oxycodone mainly impacts the central nervous system and leads to such problems as irritability, trembling, and feeding difficulty. Many factors can contribute to how severe the NOWS is in infants.

In many cases, infants are exposed to multiple substances in utero, and this polysubstance abuse further complicates withdrawal symptoms and long-term health outcomes. These substances interact in complex ways within the neonatal system. Beyond substance exposure, prenatal care access and maternal health also play critical roles in mitigating withdrawal severity. Limited access to medical care can lead to worsened outcomes, while proper prenatal nutrition is essential in reducing the risk of preterm birth and other complications (Wang).

Neonatal Opioid Withdrawal Syndrome (NOWS) severity may be assessed using the Finnegan Scoring Tool, which evaluates a variety of withdrawal symptoms, including neurological, gastrointestinal, and autonomic responses. “The severity of Neonatal Opioid Withdrawal Syndrome (NOWS) may be assessed with the Finnegan scoring tool. Since the Finnegan scoring tool is laborious and subjective, alternative ways of assessment may improve quality of care” (Rech et al.). The eat, sleep, console approach places a main focus on three aspects of an infant’s well being: their ability to eat, sleep, and be consoled (“Caring for infants and families affected by neonatal abstinence syndrome”). This approach has gained popularity due to its focus on infants' abilities rather than individual symptoms. “The new program, Eat, Sleep, Console, is a simplified approach to monitoring and treating newborns with NOWS” (“Eat, Sleep, Console: A Better Way to Help Newborns in Withdrawal”). It has shown a shift towards better outcomes and drastically reduced hospital stays (Matthew Grossman, 2019 40:35-41:33). As a result, ESC is now used more often than the Finnegan Neonatal Scoring Tool.

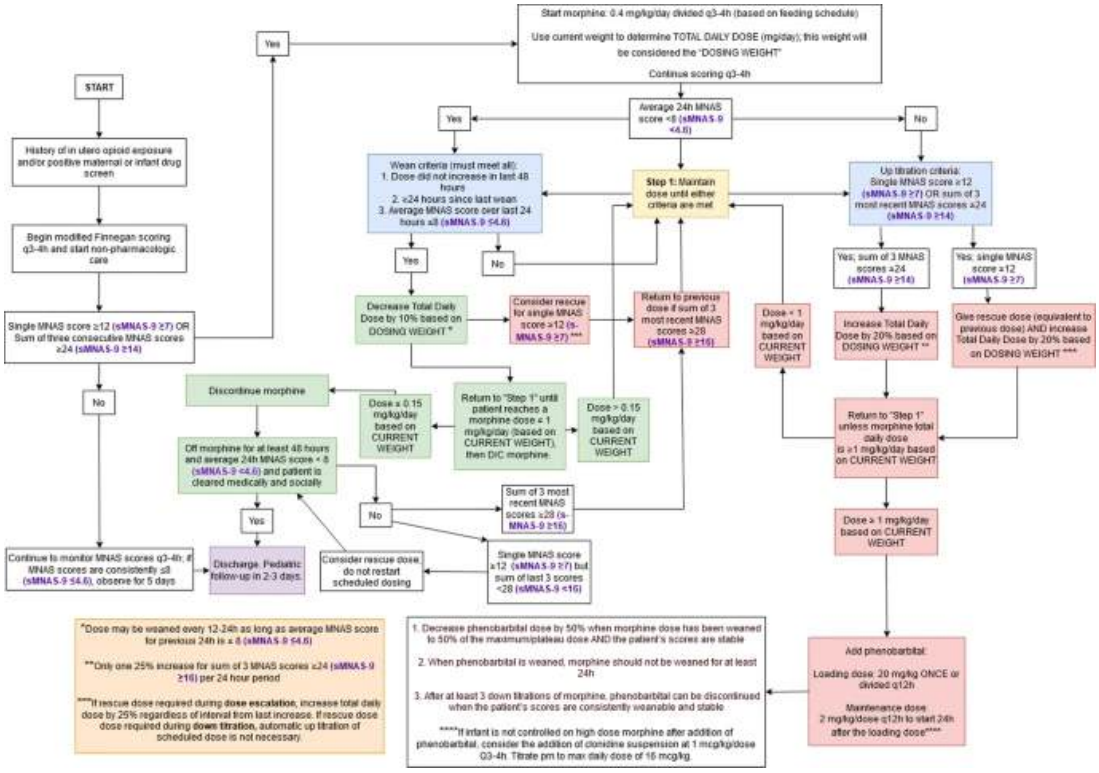


Fig 2: Algorithm for morphine treatment of NOWS based on full MNAS scoring and respective sMNAS-9 cutoff scores (purple, bolded)

While neonatal withdrawal and early interventions are important aspects of care, the long-term effects of prenatal substance exposure also depend on multiple factors. The brains of some infants with in-utero substance exposure develop more slowly, leading to decreased cognitive performance. Infants can often experience developmental delays due to the direct neurotoxic effects of these substances on the developing brain, interfering with normal brain functions. “Prenatal substance exposure is a significant risk factor for poor neurodevelopmental and mental health outcomes in early childhood” (West et al.). Children exposed to substances prenatally are at a higher risk for developing cognitive deficits, such as learning disabilities. All of these factors contribute to the severity of withdrawal symptoms and neonatal development.

The Role of Different Treatment Strategies on NOWS

The role of different treatment strategies in managing Neonatal Opioid Withdrawal Syndrome (NOWS) includes both pharmacological and non-pharmacological approaches. Non-pharmacologic treatments play a crucial role in alleviating NOWS symptoms. These measures provide comfort to the infant by mimicking a womb-like environment, which helps reduce symptoms such as irritability (Non-Pharmacologic Treatment Guidelines). Studies suggest that these methods can be as effective as morphine in managing symptoms while

avoiding the side effects associated with medication. Swaddling has been shown to provide comfort and reduce stress in infants experiencing NOWS. Additionally, breastfeeding is widely used as the optimal method of feeding infants, and has shown that infants who are breastfed or fed their mother's own breast milk experience less severe withdrawal symptoms, have shorter hospital stays, and are less likely to require medication for withdrawal (Bogen et al.). These non-pharmacologic treatments are considered a first-line approach in managing NOWS and can often reduce the need for pharmacologic intervention.

Pharmacologic treatments are commonly utilized to manage NOWS by gradually weaning infants off opioids to minimize withdrawal symptoms. Morphine and Methadone are very frequently used medications as pharmacologic treatments to treat NOWS. However, these medications require careful dosing and monitoring due to potential side effects and the risk of prolonged hospitalization. Studies have shown that morphine treatment typically has a longer duration compared to methadone, but it allows for more individualized symptom-based dosing (Mascarenhas et al.). In contrast, "methadone's longer half-life makes it more challenging to adjust dosing based on symptoms, though it is often more effective for severe withdrawal cases" (Mascarenhas et al.). Buprenorphine is used as an alternative pharmacologic treatment for NOWS, as it does not have any known neurodevelopmental consequences, unlike other opioid-based treatments. Research suggests that buprenorphine may reduce the duration of therapy and hospital stays; however, "its sublingual administration contains a high ethanol (30%) content, which presents additional considerations" (AAP). The potential long-term effects and neurodevelopment of pharmacologic treatments remain a concern and in some cases, adjunct medications, including phenobarbital and clonidine, are used in severe NOWS cases where opioid therapy alone is insufficient. Phenobarbital is often utilized when infants have been exposed to opioids for an extended period, as it can be easily weaned and is particularly beneficial in cases involving polysubstance exposure (Mangat et al.). "Phenobarbital, as adjunctive therapy, led to significantly shorter duration of morphine therapy, inpatient adjunctive days, and length of stay compared with clonidine." (Brusseau, et al.). Overall, phenobarbital is a valuable adjunctive treatment and has many benefits compared to morphine, methadone, buprenorphine, and clonidine however it still poses some risks.

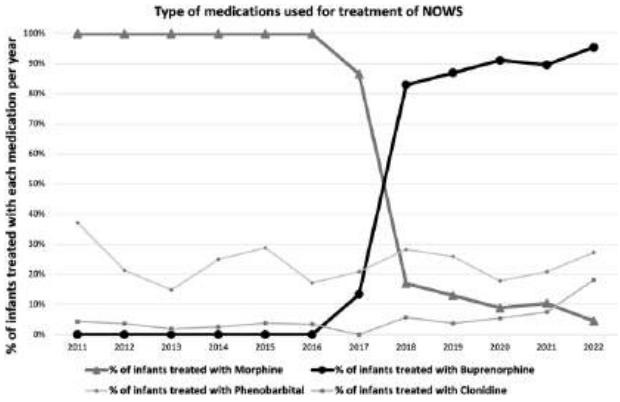


Fig 2: Comparison of Popularity of Pharmacological medications over time

In my interview with Dr. Davida Schiff, she emphasized that "non-pharmacological treatments, such as the Eat, Sleep, Console approach, are increasingly recognized for their ability to reduce opioid use and promote quicker recovery." She also stated, "By focusing on an infant's ability to eat, sleep, and be consoled, we can minimize the need for medications and reduce potential developmental impacts." Nonpharmacologic methods can significantly reduce hospitalization duration while promoting mother-infant bonding and supporting breastfeeding, contributing to overall infant well-being (Koukou et al.). Although pharmacologic treatments remain essential for severe NOWS cases, effectively controlling withdrawal symptoms and preventing complications, their use can prolong hospitalization and pose potential neurodevelopmental risks. Non-pharmacologic treatments, while generally safer, are often integrated alongside pharmacologic interventions to optimize treatment outcomes, and a combination of both is the most effective strategy for managing NOWS.

The Role of Other Factors Influencing the Development of NOWS in Infants

Beyond prenatal drug exposure, several external factors contribute to the severity and outcomes of Neonatal Opioid Withdrawal Syndrome (NOWS). These include environmental stimuli, maternal mental health, socioeconomic conditions, nutrition, and genetic influences. "Early intervention programs in Neonatal Intensive Care Units (NICUs) correspond to these uni- or multi-sensorial solicitations aiming to prevent and detect complications in order to support the development of preterm infants."(Séassau) Excessive environmental stimuli, such as bright lights and loud noises, can exacerbate withdrawal symptoms in affected infants. The Neonatal Intensive Care Unit (NICU) environment plays a crucial role in managing NOWS, as early intervention programs focus on sensory regulation to support infant development. Strategies such as minimizing noise, dimming lights, and providing a quiet, dark space can significantly reduce withdrawal severity and promote recovery. Non-pharmacological interventions that address sensory overstimulation have proven to be essential in NOWS management.

Mothers of infants with NOWS often experience higher rates of mental health disorders, including depression, bipolar disorder, and schizophrenia. "In multivariable analysis, mothers of infants with NOWS and LTPOE had approximately twice the depression risk as controls, while mothers of infants with LTPOE had 2.2 times the bipolar disorder risk and 4.6 times the schizophrenia risk as controls" (Faherty et al.). Poor maternal mental health can lead to inconsistent prenatal care, increased substance use, and higher stress levels, all of which can worsen NOWS severity. Addressing maternal mental health through comprehensive prenatal and postnatal care is crucial in improving both maternal and neonatal outcomes.

Maternal nutrition is another critical factor influencing NOWS severity. Poor maternal health, inadequate prenatal nutrition, and insufficient access to postnatal feeding options can worsen withdrawal symptoms. Maternal factors such as overall health, nutrition, and prenatal care influence fetal development and the severity of NOWS symptoms. Infants with NOWS often experience feeding difficulties, which can lead to further complications such as

malnutrition and poor weight gain. Ensuring that both mother and infant receive adequate nutritional support can significantly improve health outcomes and recovery rates.

The socioeconomic environment of the mother significantly impacts the risk and severity of NOWS. Severe stress, limited access to health care, and poor nutrition can severely worsen withdrawal symptoms and complicate the recovery process. Also, in my interview with Dr. Schiff, she said "others facing hardships are at higher risk for inadequate prenatal care, leading to undiagnosed or untreated substance use disorders". In addition, socioeconomic disadvantage frequently results in polysubstance misuse, thus further complicating the withdrawal process and increasing the likelihood of long-term developmental issues. Improvement of such difficulties by increased access to health care and social support networks can mitigate some of the adverse effects associated with NOWS.

Genetic factors also play a role in determining the severity of NOWS symptoms. "Examination of maternal genetic and epigenetic profiles may assist in prediction of NOWS severity" (Wachman). Variations in the OPRM1 gene, which encodes the mu-opioid receptor, have been linked to differences in hospitalization outcomes for infants with NOWS (Wachman). Additionally, maternal genetic and epigenetic profiles may influence how infants metabolize opioids, impacting the severity of withdrawal symptoms and recovery time. Understanding these genetic markers can aid in predicting NOWS severity and personalizing treatment strategies for affected infants. Addressing these factors through improved maternal healthcare, early intervention programs in NICUs, nutritional support, and personalized treatment approaches can enhance outcomes for infants affected by NOWS. The complexity of neonatal withdrawal can be influenced by individual genetic factors and maternal health conditions, which can influence both the severity of symptoms and the effectiveness of treatment strategies.

The Potential Long-term Neurodevelopmental Consequences of NOWS

NOWS infants are at risk for long-term neurodevelopmental challenges, including cognitive, motor, and sensory impairment. Prenatal opioid exposure disrupts the critical processes of brain development and normal brain function, leading to developmental delays that could go into childhood. The direct neurotoxicity of opioids on the developing brain impacts can shape the development of the brain so that it is more likely to have long-term cognitive and behavioral difficulties. NOWS-exposed children are at higher risk for cognitive and language delay. "Merhar et al found significantly lower cognitive, language and motor scores", in children with NOWS (Mills-Huffnagle et al.). These delays may result from opioid-induced disruptions in neural development, affecting brain areas responsible for memory, problem-solving, and communication. The severity of these impairments can depend on the type of opioid exposure, duration of maternal drug use, and environmental influences. Without proper treatment, such delays can impact children later in life, and therefore, early developmental screening is so important.

Sensory and motor challenges are also common in children with NOWS. These impairments can impact routine activities such as grasping, walking, or balance. Additionally,

neuroimaging research has established that children with NOWS have structural differences in their brains. “Exposure to opioids in utero may alter connectivity in an area of the brain that regulates emotion” (“Prenatal Opioid Exposure May Alter Brain Function in Babies”, 1). These structural changes can cause increased rates of ADHD, anxiety, and behavioral problems. Early diagnosing and intervention are essential in addressing these potential challenges and supporting long-term development.

Early intervention is crucial to providing a healthier future to infants suffering from NOWS. Identifying infants with NOWS and referring them to early intervention programs can address symptoms earlier and possibly help with developmental outcomes. Early intervention programs can support children with their cognitive, motor, and behavioral issues, and can help children reach their developmental milestones. Ensuring that infants receive appropriate medical, therapeutic, and social support is essential for minimizing the long-term effects of NOWS and promoting healthier developmental outcomes.

Conclusion

Neonatal Opioid Withdrawal Syndrome continues to be a significant issue with “about 1 baby diagnosed with NOWS every 24 minutes in the United States, or more than 59 newborns diagnosed every day” (About Opioid Use During Pregnancy, CDC). Understanding the treatment of NOWS and the neurodevelopmental consequences that could accompany it is essential to both the infants and the mothers who are struggling, as it ensures that infants are effectively treated now and in the future. There have been infants exposed in utero, which has resulted in delayed brain development, and this has led to impaired cognitive function later in life. The treatment of NOWS is crucial and involves a combination of pharmacological and non-pharmacological approaches, both with varying advantages and challenges. Pharmacological treatments such as morphine, methadone, and buprenorphine are commonly used to manage withdrawal symptoms in infants with NOWS by gradually weaning them off the medications. Although these medications effectively address withdrawal symptoms, they also come with risks, including increased hospital stays, dependency, and potential long-term neurodevelopmental consequences. Since these pharmacological treatments alone are not enough to fully support the neurodevelopmental outcomes of the infants, non-pharmacological approaches play an important role in treatment. Non-pharmacological treatments including skin-to-skin contact and developmental care plans have also been shown to have significant benefits in reducing withdrawal severity and improving cognitive and behavioral outcomes. Through the use of pharmacological treatments that wean the infants off medication and non-pharmacological treatments with developmental therapies, infants with NOWS can be treated in a way that decreases the effect of withdrawal symptoms and also promotes better long-term development.

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Lyrics—Accompanying Music or Driving Our Behavior? By Raima Choudhary

I was eight when I first listened to *Pillowtalk* by Zayn Malik. My Directioner heart broke after One Direction's breakup, so my coping mechanism became looping any new releases from the members for days on end. Except, this song was particularly scandalous for my eight-year-old self. It had a bad word. But I didn't have to say it; I could control my tongue. Being the singer that I am, as I randomly hummed to the song, I accidentally said the f-word while my parents were sitting right next to me. The next fifteen minutes went by with my parents asking where I learned such a word, which I failed to dodge. To me, it didn't matter as much that I said the word. What was concerning was that I couldn't control my thoughts and words as much as I thought I could. Did the song take that away from me?

Music isn't just an ethereal experience; it quite literally rewires the brain. It activates different parts at once: the frontal lobe for decision-making, the temporal lobe for sound, the amygdala for emotions, the nucleus accumbens for reward, all in sync. Perhaps the most striking are the effects on the hippocampus, a region that forms and retrieves memories. Studies show music can even promote neurogenesis to improve memory in the hippocampus. Patients with Alzheimer's who can't recall the faces of loved ones because of hippocampal dysfunction can remember a melody they played on the piano decades ago.

But that isn't all. With rewiring, the brain comes conditioning, including our thoughts and behaviors. Studies from Iowa State University and the American Psychological Association link exposure to sexually explicit or violent lyrics in music with increased likelihood of mental health issues, suicidal or homicidal thoughts, among others. Similarly, according to a 2011 review by Dr. C. Anderson from Iowa State University, vulgar music lyrics that promote racial slurs or violent imagery correlate to heightened aggression. As we subconsciously keep humming the songs, our brains program themselves to adhere to the tone without us realizing it.

Now, I can't deny I love some Drake, The Weeknd, and Post Malone, but I have to accept explicit lyrics as part of the music industry nowadays. The culture has shifted from rare instances of profanity in music to most of the Top 50 songs having a clean version to them because the original needs "parental advisory". And there is a saying as old as time: whatever your idols do, you follow. Professor P. Cougar Hall of Brigham Young University fears that teens will "confuse the lyrics of popular music with social norms." I surveyed 44 of my peers about their listening habits and noticed a pattern in their responses: "listening to loud/violent music makes me happy" one says, and "I don't like to listen to bad music. I'm not a baby though," the other clarifies. We, as a generation, have found our new normal. With the amount of profanity I hear in a day, I sometimes think this is our new approach to conversing: when in doubt, shuffle a list of curse words and pick a couple. We've started equating explicitness with "expressing ourselves" when, truly, we've just lost the ability and vocabulary to say what we actually feel.

What if you just don't pay attention to the lyrics? According to a Lutherwood Mental Health article, young listeners may not understand the lyrics, but still absorb the message. Conditioning doesn't stop, whether we tune it out or not. Radio host Bobby Holiday once said,

“When it seems like there’s a curse word every third or fourth word… then you’ve lost me because I want to hear a good song and good lyrics that tell a story.” Our generation follows the same speech pattern. We use a curse word for every occasion: “F***, I just crashed my car” or “F***, my favorite artist dropped new music!” That’s the textbook definition of a filler word: something that has no purpose, just fills the gap between thoughts. But what we treat as filler words still molds our brains. Some of my peers admit, “It makes my mind more messed up than it already is”, and “It ends up poisoning my mind and what I think”. Others see it as a channel of catharsis for lyricists. Either way, all that we hear leaves an imprint that ultimately shapes the quality of our lives. Clean lyrics may be harder to find, but they bring us a step closer to a healthier mind.

Social media certainly doesn’t quell the trend; it amplifies it. The endless reels and shorts with explicit background music reinforce the normalcy of the words. More than the meaning of the words themselves, what concerns me is our shrinking vocabulary. Have we truly run out of ways to express ourselves? Music can shape how we feel—nostalgic, heartbroken, inspiring, exhilarated. But maybe we are losing that vast spectrum to repetitive profanity and sameness in music, replacing it with a singular feeling: uniformity. And it seeps into every thought we think and every sentence we say. Music not only reflects the true states of our minds but also who we are becoming as a society. I’m not arguing for censorship. Rather, I’m arguing for having the awareness to question when listening to explicit music: what are we conditioning ourselves to become, and are we in control of it? My eight-year-old self learned she had less control than she thought. Maybe that’s where our focus must be: if we’re not paying attention to what we are absorbing, we’re letting someone else’s words think for us.

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How Can Businesses Leverage Rising Youth Interest in Traditional Vietnamese Art to Build Culturally-Driven Brands and Products? By Quang Pham

Abstract

This paper examines how businesses in Vietnam leverage the rising youth interest in traditional Vietnamese art to build culturally-driven brands and products. Nowadays, with continuous modernization and globalization, many of the Vietnamese younger generation are seeking traditional art forms to reconnect with their history and culture. Businesses have seized these opportunities as a culturally meaningful endeavor with a mission to find the roots for Vietnamese youth. Furthermore, this paper describes how local businesses like Tired City, La Sonmai, and Du Nhien reinterpretation through authenticity and creativity; blending history with commerce, these businesses have demonstrated how tradition can eternally remain alive without being 'outdated'.

Introduction

Vietnam, a country with over 100 million people, is located on the Southeast Asia Coast, shaped by mountains and deltas. Throughout history, Vietnam has endured colonization, war, and reunification. From standing up and fighting back against the Chinese dynasties for thousands of years to surviving the devastation from colonization and the Vietnam War and colonization, the Vietnamese people today represent pride and resilience (Nguyen).

Vietnamese culture is reflected in its history. It lives up to the day like Tết, a traditional holiday marking the start of a new year, when people of all ages share and celebrate with each other, such as through football matches, which bring together people of all ages. Cultural expressions can be seen almost everywhere in Vietnam, from rural areas to tourist attractions, with traditional clothing like the áo dài and nón lá adorning the heads of farmers everywhere. These things are not just culture; they are the stories of who the Vietnamese people are and where they came from.

Among all of these cultural items, there are the traditional art toys. Toys such as Tò he, star lanterns, and bamboo dragonflies are attached to the Vietnamese Gen Z childhood. They are the products that represent a slice of memory in the young generation. As the youth start to seek meaning and identity through history, businesses can respond by turning these cultural symbols into accessible products.

History of Vietnam

Vietnam has a rich cultural history dating back thousands of years. To understand why cultural products matter so much to the younger Vietnamese generations, it is necessary to consider the context of the nation’s history. For more than a century, the Vietnamese endured colonization under Chinese rule, adopting different countries' cultural elements in their own language and customs. In the mid-19th century, French colonization brought to Vietnam Western education, Catholicism, and infrastructure that made the country's culture more diverse.

Buildings and infrastructure such as the Hanoi Opera House or the Long Bien Bridge are heavily predicated upon French architecture. Those architectural landmarks, surprisingly, have become among the most significant tourist destinations in Vietnam nowadays. Then, around the 20th century and years of hardship, Vietnam entered the Đổi Mới ("Renovation") era in 1986, marking a major transition to a market economy. This flip has unleashed rapid growth and international trade, but it has also brought significant cultural changes, such as technology, famous brands, and a growing consumer culture surging into the market (Pham). Among the Vietnamese youth, these significant changes have planted the seeds for rediscovering their own country's culture, sparking the revival of interest in traditional art toys and cultural symbols (Tran).

Consumption patterns

In recent years, Vietnamese Gen Z has grown increasingly interested in consuming products that reflect their identity and cultural values, from the eco-friendly magnet to the items that celebrate national pride. Cultural products , such as Ao Dai (Vietnamese traditional clothing) or collectible toys that exemplify the country's pride, appeal to the younger generations by the sense of style and the desire to rediscover the roots in Vietnamese tradition. This trend has created opportunities for entrepreneurs to recognize and take up the opportunity to turn cultural heritage to accessible products.

Case study #1



"Young people come to the exhibition "Drawing the Dragon" organised by Tired City in collaboration with the Centre for Cultural and Scientific Activities at Van Mieu - Quoc Tu Giam" (Nhan Dan).

Tired City is a creative brand founded in 2016 by Nguyen Viet Nam with a mission of turning Vietnamese cultural symbols into accessible products for the younger generation. Starting from a small gift shop in Hanoi, Tired City has grown into a business chain with more than ten stores by 2024. Their featured products include apparel such as T-shirts and sweatshirts, accessories like tote bags, hats, and keychains, as well as stationery, including notebooks. These

items are mainly produced in collaboration with local artists. The founder, Nguyen Viet Nam, originally an architecture student, was inspired by Hanoi's unique blend of art and culture through modern life. In addition, Nam believes that effectively blending cultural elements into specific products not only increases appeal but also promotes history and cultural beauty. His vision has been embedded into each product category, with each item—a shirt decorated with street vendor illustrations or a notebook featuring nostalgic childhood toys—interpreting Vietnamese cultural symbols.

Tired City's design collections have brought fresh energy to heritage styles. For example, the "Traditional Melodies" fashion line features playful illustrations on t-shirts, sweatshirts, and tote bags, each incorporating dozens of unique art designs about performance arts such as chèo opera, tuồng theater, and ca trù singing. These traditional arts—often perceived as "for the olds"—are reimagined in cute chibi-style graphics, making them more accessible for younger generations. This is evident in a Gen Z interview: "These designs are so unique," said a university customer about her sweatshirt featuring a Vietnamese ca trù singer. Likewise, the "Thirty-Six Streets" collection reinterprets Hanoi's historic neighborhoods in modern styles. Every day, urban culture is in the spotlight: a series of art that depicts the iconic streets such as Hang Quat, Hang Dao, Hang Than, and Hang Long.

Most importantly, Tired City has found a mission and has taken a big step up to start the process. The company often hosts exhibitions and design contests to foster a community that is interested in Vietnamese art. They are also a partner of Hanoi's Temple of Literature, both organizing a "Folk Art in Gen Z" exhibition in 2024 to showcase how illustrators show their talents. Through so much effort, Tired City has produced hundreds of design collections that are inspired by Vietnamese history, turning creativity into tangible products. What began only in a small shop has grown into a sustainable business model. Tired City's success has also proven that the Vietnamese culture could be cleverly remixed to access the younger audiences ("Cultural Industry Through the Lens of Traditional Materials").

Case study #2

Founded in 2017 by two young entrepreneurs, La Sonmai has pioneered the fusion of an ancient Vietnamese painting art form, lacquer painting, with tech accessories like phone cases. Co-founders Lê Xuân Trường and Vũ Anh Đức first sparked their idea while Trường was studying abroad and noticed the Western customers' willingness to pay high prices for handmade goods. He was determined to develop a Vietnamese handicraft once he returned home, teamed up with Đức, who is a classmate from the FPT business school, to find an idea, until they visited Hoi An, which is where they found what they were looking for: "lacquerware" (Vietnam News). They had discovered that Vietnamese sơn mài has great potential to be a source for creating their own products. After their discussion, they decided to create luxury phone cases that are handmade and consider them mini artworks that represent Vietnamese culture.



From the beginning, the company has committed to authenticity. The founders immersed themselves in learning the lacquer technique, seeking out masters, and attempting to create their own unique images. They believed that finding 100 percent traditional methods and natural ingredients would make them stand out in the market. What's more interesting is that they will always say "no" to mass production, focusing on quality rather than quantity. Therefore, by weaving smartphone cases with heritage symbols in delicate lacquer art, La Sonmai allows young customers to carry a small piece of Vietnamese history with them everywhere.

In the larger context, their strategy is to attract more Gen Z customers. Additionally, to maintain creativity and exclusivity, they released limited editions, thereby categorizing their products within the luxury goods sector. Despite offering the top prices for generic cases that people normally use, La Sonmai still attracts a group of customers, including Vietnamese and international buyers, who value the story and effort behind each piece. Notably, the Vietnamese celebrity musician Hồ Hoài Anh and actor Thành Lộc became La Sonmai customers, boosting their brand's profile. In the end, by carefully weaving old lacquer techniques with modern phone fashion, La Sonmai has done far more than promote Vietnamese culture alone; they also make each of their products to spark people's curiosity ("Vietnamese Lacquer Is Business Inspiration for La Sonmai").

Case study # 3



In 2024, 22-year-old young woman Tran Minh Nhi, with a mission to revive Vietnamese silk for the younger Vietnamese generation, launched her business, Du Nhien, a boutique shop. Silk is one of the oldest representatives of Vietnamese crafts, but Nhi observed that many Gen Z consumers are viewing silk as a “luxurious, expensive, and sometimes old-fashioned”, something that their grandmothers usually wore. With her eternal love for Vietnamese silk, Nhi set out to change Gen Z's perspective by blending traditional handmade techniques with her own creativity. The idea for the name “Du Nhien” originated after Nhi visited the Nha Xa village and was drawn to the sight of local woven silk drying in the sun. The term “Du Nhien”, meaning naturally, also deeply resembles her creativity in art, aiming to start a brand that could bring silk closer to the young customers while also supporting the artisans who make it.



A woman who is wearing a Du Nhien product (Du Nhien Facebook)

From the start, Nhi has already woven her own cultural story into her brand products. She spent months travelling to villages learning to create her products directly from the masters at Nha Xa. She said, “We want to create a new creative space for Nha Xa and Vietnamese silk. We strive to preserve age-old weaving techniques while integrating modern designs to produce unique and innovative silk products. By doing so, we maintain the inherent beauty of silk while meeting contemporary aesthetic demands.” (Nhan Dan).

The biggest challenge the business faced was how to make silk affordable and still appealing to students or tourists, since silk can be very costly. Nhi has overcome this obstacle by offering small items made of silk— scarves or accessories— so as to make it more attractive to a younger niche. In her words, she founded Du Nhien to bring together Gen Z youths who share a passion for preserving traditional craftsmanship while embracing youthful creativity”, and that is exactly what her brand has been doing (“Gen Z Aspires to Elevate Vietnamese Silk”).

Cultural significance

The above three case studies have demonstrated that Vietnam’s youth market is not just about economic growth. Rather, they have also shown that Vietnamese businesses are making constant efforts to revive youth interest in history and cultural continuity. In each case, traditional art forms are incorporated into art products to lend a touch of history to each piece, making them not only valuable in terms of financial worth but also culturally rich. Furthermore, traditional art forms, once “old-fashioned,” are now reimagined into fresh and stylish products for younger audiences.

For young Vietnamese people, whose lives are lived anywhere in the world and are constantly shaped by other factors, reconnecting with their roots is not simply a nostalgic endeavor. Surrounded by famous brands, social media, and western fashion, many teenagers or students find a lacquer-painted phone case or a silk áo dài with a lotus, a chance to express their gratitude for Vietnam. Cultural products have become personal symbols, enabling young people to style themselves with pride while being part of a larger national narrative.

In short, the cultural significance of these studies lies in the demonstration that culture and business are not opposing forces. Instead, when history is interpreted through great design, marketing, and entrepreneurship, it can blossom in modern markets. Every woven scarf, every lacquered phone case, or every collectible toy represents more than just a product itself. They are a sense of identity, a celebration of a whole nation's history, and a reminder that culture will never be forgotten (Pham 2025).

Conclusion

This research examines how businesses can leverage young people's rising interest in traditional Vietnamese art to create culturally inspired products. The key is to combine Vietnam’s history and culture with the creativity of the younger generation. With a history of resilience and pride, Vietnam now faces the challenge of preserving its identity. For Gen Z, connecting with

their heritage through toys, clothing, or accessories creates both nostalgia and a sense of belonging.

The case studies of Tired City, La Sonmai, and Du Nhien all illustrate how culturally driven products can thrive through the reinterpretation with creativity, artistry, and authenticity. These business ventures have shown that tradition is not a burden but rather an asset. When it is transformed through artistic design and branding, it can captivate any audience.

All in all, the revival of interest in traditional art among Vietnamese youth is not just a sudden event that happens overnight, but it is a significant cultural movement that has steadily grown year by year. By continuing to embrace creativity, highlighting authenticity, and engaging with young people, businesses can create products that honor their past while shaping the future.

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wExploring the Determinants of INR Depreciation: A comparative Analysis of Macroeconomic Indicators Pre and Post COVID By Aryan Iyer

Abstract

Exchange rate movements play an extremely significant role in determining the position of a country's macroeconomic fundamentals, including influencing inflation, trade balances, interest rates, and investor confidence. Historically, the INR has showcased increased sensitivity to global macroeconomic and financial shocks due to a consistent current account deficit financed by foreign portfolio investment. The study analyzes the key variables that have contributed to the INR's depreciation in relation to the USD, between two different periods of time, pre-COVID (2015) and post-COVID (2020-2024), to understand what effect the pandemic had on the INR's value and whether or not there is a difference in underlying reasons for the INR's depreciation. Secondary data were sourced, and multiple regressions were performed for both time periods, using net FPI flow, change in foreign exchange reserves, inflation (CPI), and interest rate differential between India and the USA as independent variables. It was found that net FPI flows remained a significant predictor of INR depreciation, emphasizing India's vulnerability to US policy alterations and global investor sentiments driving capital flows. This confirms India's low exchange rate pass-through and the fact that global financial cycles outweigh domestic macroeconomic indicators in influencing INR depreciation, offering important insights for policymakers and investors in crafting efficient currency risk management and macroeconomic balancing frameworks.

Introduction

Exchange rates are one of the most crucial macroeconomic fundamentals for a country. The management of the exchange rate contributes to a country's ability to hold out against domestic or international economic shocks as it influences price levels, interest rates, inflation expectations and investor confidence. All these factors are extremely important determinants of the stability of a country. As discussed by Feldstein, an ineffectively run exchange rate can result in currency crises, balance sheet mismatches, and capital flight due to loss of investor confidence, as cited in ("Impact of Exchange Rate Regimes…").

In a study (Fraj and Maktouf), investigating the role of the exchange rate regime on political stability and economic growth found that the same characteristics of an exchange rate have different effects on a country depending on whether the country is developing or developed. The study found that exchange rate flexibility disturbs economic growth for developing countries, while the same proves to be a stimulant for economic growth in developed countries.

The Indian economy has historically been sensitive to global economic shocks like the 2008 housing crisis (Kumar and Vashisht). The Indian economy was not significantly affected by the sub-prime mortgage crisis which started in 2007, in the USA. The RBI (Reserve bank of India) was cutting interest rates till august of 2008, aimed at slowing down the economic growth

rate which had gone above the rate of potential output growth and was resulting in an increase in inflationary pressure.

Later, when the Lehman Brothers filed for bankruptcy, the US financial crisis marked the beginning of a global economic collapse, and the Indian economy felt its impact instantly. Due to the liquidity squeeze experienced by global banks, foreign investment to India abruptly stopped. After performing well for the last 5 years, capital flight became commonplace. From a net inflow of US$20.3 billion in FY2007–08, there was a net outflow of US$15 billion from Indian markets during FY2008–09 as foreign portfolio investors sought safety and allocated resources to their parent companies to strengthen their balance sheets. Therefore, Equity markets ended up losing over 60% of their index value, which translates to about 1.3 billion USD, following a peak index of 21,000 in January 2008 to 8,867 by March 20, 2009. This further resulted in domestic banks having insufficient liquidity and being unable to satisfy domestic demand for money, which led to the money market interest rate rising to 20% and remaining there for a month before decreasing.

Recessions abroad resulted in a drop in external demand for India's exports, and a consequent 2% drop in India's GDP growth rate during the second half of FY2008 - 2009. The conditions also instigated a loss of confidence and resulted in banks becoming more risk-averse, so much so that the non-food credit expansion during the last five months of FY2008–09 contracted by more than 68% when compared with the same period in the previous financial year.

Crude oil prices also appear to significantly influence India's macroeconomic position, as India imports 80% of its oil demands from OPEC nations and hence any movement in the prices of crude oil is closely linked to variations in India's economic activity. This leaves India extremely sensitive to any volatility in crude oil prices (Jain). Historical data denotes that there has been a constant inflationary trend in India due to crude oil price shocks, which has a regressive effect on India's citizens (Varghese).

The Indian rupee has historically showcased heightened vulnerability against the US dollar ("Why Is the Indian Rupee Falling Against the US Dollar?"), owing to structural factors such as persistent inflation differentials, a chronic current account deficit, and heavy dependence on external capital flows. India has experienced a continued current account deficit, meaning India spends more on imports than it earns from exports. The higher trade volume of imports results in greater demand for the USD and greater supply for the INR, which directly weakens the INR in the foreign exchange market. Furthermore, this constant Current account deficit can also contribute to a depletion in foreign reserves and exert downward pressure on the INR.

India faces a consistently higher inflation rate than the USA, which leads to a fall in purchasing power of the INR to outpace that of the USD. Foreign Interest rates also play a significant role in weakening the INR when the interest rates in the USA rise. Global investors re-allocate capital in pursuit of higher returns on investment, resulting in a huge outflow from the Indian economy, which exerts downward pressure on the INR due to the increase in supply. Moreover, this effect is amplified when uncertainty and pessimism prevail globally, which results

in investors moving their assets to “Safe haven” currencies across the world, every significant one of which is the USD. This triggers massive swings of capital flow globally, and hence India also ends up experiencing huge amounts of outflow. This also weakens the INR in the sense that it is highly vulnerable to very volatile changes in value due to the scale of capital flows.

India is highly dependent on crude oil imports, and these imports are paid for in USD, suggesting that price spikes in crude oil will increase dollar demand, as India will have to pay more dollars for the same amount of crude oil, which weakens the INR. Lastly, certain policy decisions by the RBI to pursue certain objectives through allowing wider trading access or shifting its stance can suggest different things to investors, which results in a jump in INR volatility instead of fixing the underlying problem.

There have been a multitude of factors responsible for the INR’s consistent depreciation in relation to the USD. These factors differed pre-COVID-19 and post-COVID-19. Before the pandemic existed multiple factors were responsible for the depreciation of the INR. Firstly, the demand and supply rule (Mittal et al.), There has historically been more demand for the USD owing to the USA’s economic position as a prime exporter of multiple goods such as telecommunications, chemicals, automobiles, and aerospace. These industries are the base for the other industries; hence, the USA can affect the demand and supply for different currencies around the world when deciding to participate in trading activities.

The USD’s nature as a “safe haven” has resulted in the appreciation of the USD in relation to the INR (“Why Is the Indian Rupee Falling Against the US Dollar?”). Volatility in crude oil prices also reflects in the factors resulting in the depreciation of the INR. A sudden increase in the price of crude oil will require India to pay and demand more USD, resulting in the depreciation of the INR in relation to the USD. India’s widening current account deficit resulting from imports of crude oil and electronic goods also contributes to the depreciation of the INR as more USD is demanded and more INR is supplied.

Post the pandemic, in 2021-2022, there were serious impacts on economies worldwide. It triggered huge equity sell-offs in India due to uncertainty (Mittal et al.), and furthermore, this result was amplified due to interest rate hikes by the Federal Reserve Bank, resulting in capital inflows to the USA and outflows from India. These factors, along with a global economic downturn, resulted in the widening of the CAD, resulting in the depreciation of the INR during and post-COVID.

The purpose of this study is to analyze the determinants of the depreciation of the INR in relation to the USD before and after the global pandemic of COVID-19. The research also examines the role of global factors in driving volatility and their implications for investors and policymakers in India. This study provides a more comprehensive understanding of forex volatility in India, offering new insights into risk management and policy implications in emerging markets.

While previous studies have studied the impact of economic variables on the exchange rate, few have compared the significance of these factors before and after the COVID-19 pandemic. This study closes that gap by analysing the effect of net FPI flow, change in forex

reserves, inflation CPI, and interest rate differential on INR depreciation in both time periods to examine which factors remained statistically significant and which turned insignificant, revealing the dynamic balance of the influences of domestic and global factors on the INR's depreciation. This dual-period approach is a novel contribution, as prior work such as (Mittal et al.) and (Varghese) primarily assessed short-term correlations, while this study empirically validates how these relationships changed through global macroeconomic transitions, specifically the COVID-19 global pandemic.

Methodology

Research Aim and Data Characteristics

This study aims to analyze and understand the factors resulting in the depreciation of the INR against the USD, including global and domestic factors, and how they might vary between the selected time periods. It utilizes the dataset sourced from Kaggle titled "Analysing the Drivers of INR Depreciation: A Reproducible Study". The data provides a monthly average for the INR-USD exchange rate from 2014 to 2025. The study provides insight into the depreciating INR to USD value, filling the existing knowledge gap and presenting insights into the identification of risks and policy interventions in the market. The data consists of monthly observations for the entirety of the year, providing 12 observations per independent variable per year, resulting in a total of 5,540 data points, allowing for a clear analysis. The dataset consists of data for crude oil price, FPI flow, Forex reserves, Repo rate, Fed rate, Inflation consumer price index, Volatility index (VIX), GDP growth rate, and political and geopolitical stability.

Data Analysis Procedure

The data will be analyzed by separating it into 2 five-year periods: pre-COVID (2015-2019) and post-COVID (2020-2024). Descriptive and inferential statistics will be carried out for the analysis. The software "Stats.blue", along with Excel, will be used for conducting statistical analyses. A multiple regression will be conducted to understand how the interplay of a multitude of factors can affect the INR-USD exchange rate. A Welch's t-test will be performed to gauge whether or not a statistically significant difference exists between the exchange rates of the 2 periods.

Results and Discussion

This section presents the results of the analysis, consisting of multiple regression models for both time periods, pre-COVID (2015-2019) and post-COVID (2020-2024), and Welch's t-test to compare means of the variables between the 2 time periods. Comparisons of structural factors between the 2 periods are presented, and findings are interpreted in that respective context. Then, the implications for investors and policymakers are summarised.

Table 1: *Regression Analysis between Net Foreign Portfolio Invest Flow, Change in Forex Reserve, Inflation CPI, Interest Rate Difference % with % Change in USD-INR for 2015-2019*

Predictor	*B*	SE B	t	p
Constant	0.002	0.01	0.36	0.72
Net FPI flow	0	0	-3.12	0.00*
Change in forex reserve	-0.0002	0	-1.07	0.29
Inflation (CPI)	0.001	0	0.71	0.48
Interest rate differential %	-0.001	0	-0.20	0.84

**p<0.05*
B = Coefficients
SE B = Standard Error

Table 1 shows the results of the multiple regression which was carried out with the foreign portfolio investment flow, change in foreign exchange reserves, inflation CPI (consumer price index), interest rate difference % (Repo rate - fed rate) as the independent variables and the natural log of the % change in the USD-INR exchange rate as the dependent variable for the period of *2015-2019*. The predictive effect of net foreign portfolio investment flows was confirmed, $b = 0$, $t(55\ DOF) = -3.12$, $p < 0.05$. However, change in forex reserves, $b = -0.0002$, $t(55\ DOF) = -1.07$, $p > 0.05$; inflation (CPI), $b = 0.001$, $t(55\ DOF) = 0.71$, $p > 0.05$; Interest rate difference (%), $b = -0.001$, $t(55\ DOF) = -0.20$, $p > 0.05$ did not have a statistically significant impact on the INR depreciation value. The model has an overall coefficient of determination of $r^2 = 0.4008$ and an F-statistic = 9.1968.

Table 2:*Regression Analysis between Net Foreign Portfolio Invest Flow, Change in Forex Reserve, Inflation CPI, Interest Rate Difference % with % Change in USD-INR for 2020-2024*

Predictor	*B*	SE B	t	p
Constant	-0.0003	0.008	-0.03	0.97
Net FPI flow	0	0	-2.33	0.02*
Change in forex reserve	-0.0001	0.0001	-0.90	0.37
Inflation (CPI)	0.002	0.0014	0.58	0.56
Interest rate differential %	-0.0002	0.0012	-0.15	0.88

**p<0.05*
B = Coefficients
SE B = Standard Error

Table 2 shows the results of the multiple regression, which was carried out with the foreign portfolio investment flow, change in foreign exchange reserves, inflation CPI (consumer price index), interest rate difference % (Repo rate - fed rate) as the independent variables, and the natural log of the % change in the USD-INR exchange rate as the dependent variable. The predictive effect of net foreign portfolio investment flows was confirmed, $b = 0$, $t(55\ DOF) = -2.328$, $p < 0.05$. However, change in forex reserves, $b = -0.0001$, $t(55\ DOF) = -0.9038$, $p > 0.05$; Inflation (CPI), $b = 0.0008$, $t(55\ DOF) = 0.5834$, $p > 0.05$; Interest rate difference (%), $b = -0.0002$, $t(55\ DOF) = -0.1544$, $p > 0.05$ did not have a statistically significant impact on the INR depreciation value. The model has an overall coefficient of determination of $r^2 = 0.1725$ and an F-statistic = 2.867.

Table 3: *t-test Analysis assuming unequal variances between Net Foreign Portfolio Invest Flow, Change in Forex Reserve, Inflation CPI, Interest Rate Difference % with % Change in USD-INR for (2015-2019) & (2020-2024)*

Variable	Categories	Mean	SD	t	p
Net FPI flow	2015 to 2019	4928.33	1902.88	-0.37	0.70
	2020 to 2024	7054.35	38321.45		
Change in forex reserve	2015 to 2019	4.64	9.96	-0.28	0.78
	2020 to 2024	5.25	19.72		
Inflation (CPI) %	2015 to 2019	4.17	1.20	-8.45	0*
	2020 to 2024	5.89	1.01		
Interest rate differential %	2015 to 2019	5.28	1.26	11.07	0*
	2020 to 2024	2.78	1.21		
Natural log of % change in USD-INR	2015 to 2019	0.00	0.01	-0.36	0.72
	2020 to 2024	0.00	0.01		

*p<0.05

Table 3 depicts that there is a difference between the inflation (CPI) % between the period of 2015-2019 (M= 4.173, SD= 1.202) and the period of 2020-2024 (M=5.887, SD= 1.013) given t(114)= -8.447 and p<0.05. Similarly, the Interest rate differential % has no difference between the period of 2015-2019 (M= 5.280, SD= 1.262) and the period of 2020-2024 (M=2.783, SD= 1.207) given t(114)= 11.074 and p<0.05. Conversely, the difference in the Net FPI flow was not significant between the period of 2015-2019 (M= 4928.333, SD = 19102.877) and the period of 2020-2024 (M= 7054.350, SD= 38321.453) given t(86)= -0.385 and p>0.05.

Similarly, the change in forex reserve has no significant difference between the period of 2015-2019 (M= 4.640, SD= 9.964) and for the period of 2020-2024 (M= 5.251, SD= 19.715) given $t(177) = -0.276$ and $p>0.05$. Furthermore, the dependent variable, the natural log of the % change of the USD-INR exchange rate, also does not have a significant difference between the period of 2015-2019 (M= 0.00214, SD= 0.0128) and the period of 2020-2024 (M= 0.00292, SD= 0.0107), given $t(114) = -0.363$ and $p>0.05$. This shows that inflation and the interest rate differential exhibit significant changes between the pre- and post-COVID periods, while net FPI flows, changes in forex reserves, and the exchange rate volatility itself remain largely similar across the two time frames.

In the first multiple regression analysis conducted, only the net FPI flow emerged as a statistically significant predictor for the depreciation of the INR in relation to the USD, likely because the analysis is focused on short-run impacts on the exchange rate. The net FPI flow directly determines the value of the INR in relation to the USD due to the demand and supply rule (Mittal et al.). The amount of inflow/outflow directly influences the supply and demand of the rupee, resulting in immediate reflections of changes in the exchange rate. Furthermore, in the 2010s, India had a wide current account deficit, which was financed by foreign portfolio investments. Later, when expectations of tapering and monetary tightening rose by the Federal Bank (Eichengreen and Gupta), India experienced strong reversals in FPI flows as USA based assets became more attractive and capital was allocated accordingly. This highlights the sensitivity of emerging economies like India to US policy alterations. According to Patnaik (Patnaik), the RBI intervenes during periods of high INR volatility to smooth out the crests and troughs of the USD-INR exchange rate and to protect the INR from extreme volatility, outlining why a change in forex reserves was a statistically insignificant predictor. For inflation,(Ghosh and Rajan) argue that changes in exchange rates do not directly manifest in consumer prices when periods of low and stable inflation exist, which was the case in India in 2015-2019. The channels through which changes in inflation reflected in the exchange rate are indirect, as they reflect in the exchange rate after a considerable amount of time has passed, explaining why inflation emerged as a statistically insignificant predictor for INR depreciation. (Rey) argues that the traditional transmission cycle, in which interest rate differentials determined FPI flows, changed after the 2008 global financial crisis, suggesting that FPI flows are rather determined by U.S. monetary policy and global risk sentiment, explaining why the interest rate differential was a statistically insignificant variable in predicting INR depreciation.

The second multiple regression conducted yields the same results with FPI flow as the only statistically significant predictor. However, the predictive power of the model as a whole decreased. The results indicate that the predictive power of each variable decreased, as inferred from the rise in p-values throughout the variables. The FPI flows' predictive power decreased post-COVID due to structural changes in the behaviour of FPI flows (Chinn). The sensitivity to global uncertainty increased regardless of whether or not the country in question has strong macroeconomic fundamentals, explicitly domestic yields, pointing out that the interest rate differential stayed statistically insignificant in the post-COVID multiple regression results (Rey).

This weakened the predictive power of the net FPI flows and interest differentials. For inflation and change in forex reserves, the explanations of their statistical insignificance remained the same, owing to the indirect channels of transmission in the exchange rate (Ghosh and Rajan) and the defensive intervention by the RBI (Patnaik) opposed to intervening to cause major changes in the exchange rate, respectively.

For the t-test, results show that inflation (CPI) and the interest rate differential changed significantly between the pre- and post-COVID periods, while FPI flows, forex reserves, and exchange rate volatility remained broadly unchanged. These results confirm the findings of the multiple regressions, where, despite significant mean differences in inflation and interest rate differential, neither variable emerged as a significant predictor for the depreciation of the INR in either period. This confirms that while macroeconomic conditions shifted structurally after COVID, their direct influence on the exchange rate remained statistically insignificant. Inflation's rise post-COVID is due to global supply shocks and higher commodity prices, resulting from the pandemic, but as explained by (Ghosh and Rajan), India's exchange rate pass-through remains weak due to time lags, keeping inflation's short-run impact statistically insignificant. Similarly, the sharp drop in the interest rate differential reflects U.S. monetary tightening, also because (Rey) showcases, global financial cycles are a stronger influencer of FPI flows than domestic interest rate gaps. The consistency of FPI significance across periods highlights India's enduring sensitivity to capital flow volatility as the primary determinant of INR movements.

The results of this study lays out valuable information for policymakers and investors. The prevalence of consistent influence of FPI flows on INR depreciation, even though inflation and interest rate differential underwent significant variability post-COVID, implies that the INR is largely determined by global economic conditions rather than domestic macroeconomic fundamentals. For policymakers, this underscores the significance of implementing macroeconomic frameworks that safeguard the INR from extreme volatility owing to unfavourable global macroeconomic conditions, such as a flexible yet credible monetary policy. For investors, the results outline that changes in the values of currencies are determined more by global uncertainty and consequent investor sentiment rather than domestic fundamentals like changes in inflation or the interest rate, to enable better and more favourable investment decisions.

Previous studies, like (Ghosh and Rajan) and (Patnaik), focused on examining singular determinants such as inflation or central bank interventions in explaining INR volatility. However, these works found partial or inconsistent relationships resulting from a single-period analysis approach. This study, however, utilizes a bi-period regression analysis framework along with a Welch's t-test confirmation to isolate and better examine structural shifts in the independent variables of net FPI flow, change in forex reserve, inflation (CPI), and interest rate differential across two very different macroeconomic conditions. Thus, the finding that solely net FPI flow was a statistically significant predictor during both periods demonstrates greater explanatory uniformity than the aforementioned literature which produced varied results. This

improvement is due to the fact that both domestic and global factors have been taken into account, and the study's extensive data coverage of the two time periods (2015-2019 & 2020-2024). Moreover, since the study focuses on comparative inference rather than sole statistical correlation produced results that are more reliable in context of global shocks such as the COVID-19 pandemic.

Conclusion

The aim of the study was to analyze the variables responsible for significantly driving INR depreciation and how these factors themselves varied between the 2 time periods, pre-COVID (2015-2019) and post-COVID (2020-2024). Furthermore, it evaluates how global and domestic factors affect exchange rate behavior. It was found that only net FPI flows were a significant predictor of INR depreciation across time periods, emphasizing India's consistent dependence on global capital flow swings and sensitivity to investor sentiment. On the contrary, inflation (CPI), change in forex reserves, and Interest rate differentials remained statistically insignificant across time periods, highlighting that global macroeconomic factors override domestic economic fundamentals in determining the short-run value of an exchange rate. The study is still limited due to its reliance on secondary data, and the fact that other variables that also affect forex volatility have not been considered, including geopolitical risk variables, trade balances, and commodity price shocks. The consideration of the inflation (PPI) (producer price index) instead of the (CPI) might have yielded better results owing to the inclusion of goods that influence macroeconomic positions to a greater extent, like commodities (crude oil). Future studies can focus on capturing higher frequency data to record real-time fluctuations, compare India's forex volatility to another emerging country, and include more variables that affect the exchange rate mentioned above. Overall, the study highlights the importance of global financial conditions as opposed to domestic economic fundamentals in determining the trajectory of the INR's value.

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Development of pH-Responsive Smart Polymer Films Based on PVA/CMC/PEG Systems for Food Packaging Applications By Ratmir Tsoy

Abstract

Smart polymers provide hope in dealing with the food waste crisis that amounts for 1.05 billion tonnes each year and contributes 8-10% of greenhouse gas emissions. In this work, the authors discuss the preparation and properties of pH-sensitive smart films made of PVA, CMC, and PEG systems containing the natural pH indicator Curcumin for food packaging applications. Unlike other smart polymers that use toxic cross-linkers like glutaraldehyde, this work only uses food-grade materials that are approved in European food additive legislation (E-numbers), in combination with calcium ion (Ca^{2+}) cross-linking of the CMC-Ca^{2+} egg-box structure. Two different versions of the film were prepared: one that is only cross-linked by calcium ions and another that is borate-cross-linked for added rigidity and toughness. pH sensitivity of the films in the range of pH values 4 to 9 is observed, showing visual changes in color from yellow (below pH 6), then to orange-red (from pH 7 to 8), and finally to brownish-red (above pH 8.5), covering the pH range in which food turns rotten. Results of swelling properties indicated that the film had controlled swelling of 15 to 35% weight gain in deionized water at 25°C in 24 hours, showing no breakdown of structure. However, applying food-grade protective wax coatings of 0.5-1.5g/m² substantially lowered the swelling ratio of 40-60% while still taking only 2-5 minutes to respond. Results of mechanical properties indicated that the borate-cross-linked film had higher values of 15-25% for the storage modulus (target range of 300-600 MPa), albeit lower values for the elongation at break (only 3-5% compared to 5-8% for the calcium-cross-linked film), suggesting that the increased stiffness comes at lower flexibility. Results of pre-migration tests in food simulants indicated that there are no discolorations in food simulents, showing low leaching of the pH indicators. Critical validation steps include quantification of migration, testing of resistance to light exposure in food packaging applications at retail light conditions, mechanical properties testing at thermal cycling, and obtaining government approval for approval for food contact uses despite many current drawbacks, this work provides insights for preparation of passive freshness indicators that use only food-grade materials for safer and more eco-friendly alternatives for current smart food packaging technologies. Presently, the materials are in the active testing phase of their potential at the laboratory level and indicate the viability of ionic cross-linking methods in making pH responsive films that can be utilized towards lessening food waste and conserving food safety standards.

Introduction

Smart polymers, self-referred to as stimuli-responsive polymers, are a class of materials that exhibit physical or chemical property variations due to external signals like pH, temperature, ionic strength, light and redox condition [1]. These materials have attracted wide attention for their promising use in food packaging, medical devices, sensors and environmental monitoring system [11]. The worldwide smart packaging market is currently seeing a steady growth, and it

has been estimated that by the year 2025, up over 25% of food packaging will be installed with such technologies [2]. In food packaging, smart polymers exhibit an attractive solution as they enable passive monitoring with no electronic part [3]. They can provide immediate real-time visual information about food freshness when pH-responsive indicators respond to changes that occur due to chemical reactions caused by the growth of bacteria on foods or from spoilage of the food. This function solved the fatal problems of food packaging by general packages which can not inform the inside state of foods. According to the United Nations Environment Programme (UNEP) Food Waste Index Report 2024, the world wasted 1.05 billion tonnes of food in 2022, amounting to 19% of food available to consumers being wasted at retail, food service, and household levels [4]. This waste generates 8-10% of global greenhouse gas emissions, nearly five times the total emissions from the aviation sector [4]. Smart packaging technologies offer potential solutions to reduce this massive waste by providing consumers with accurate real-time information about food quality beyond printed expiration dates.

Smart Polymers and Their Responsive Mechanisms

Smart polymers can change properties such as color, fluorescence, swelling, and permeability when exposed to certain environmental stimuli. Emerging applications of pH-sensitive freshness indicators based on natural colorants are very promising for tracking packaged food products. However, the large potential benefits accrue for materials that can be responsive to the ambient conditions, can be tracked in the absence of any electronic device, and are compatible in aqueous chemistry and bio-based applications. Here, we review pH-sensitive polymers that employ visual indicators such as curcumin to respond to changes in ambient acidity conditions.

Smart polymers' fundamentals include the use of pH as the stimulus that causes changes in the acid–base properties of the added indicators. Curcumin, derived from the spice turmeric, changes color in response to pH when added to films of biopolymer materials, turning yellow in acidic environments and red in basic environments. The mechanism of this color change is that phenoxide ions are generated in the reaction of phenolic hydroxy groups and hydroxide ions. Curcumin has been shown to be antioxidant, antibacterial, antiviral, and anti-inflammatory.
In this work, the polymer matrix is a combination of polyvinyl alcohol (PVA), carboxymethyl cellulose (CMC), and polyethylene glycol (PEG). Some current developments indicate that PVA/CMC films cross-linked with organic acids exhibit improved properties in terms of both biodegradability and mechanical strength for food packaging applications. PVA contributes to the strength, transparency, and barriers, while CMC contributes to biodegradability, viscosity during processing, carboxyl functionality for ionic cross-linking and control of swelling, and PEG functions as a plasticizer, improving flexibility and resistance to brittleness and affecting the binding of water. Cross-linking of these materials can be achieved using calcium ions to develop “egg-box” structures of CMC-Ca2+, and borate cross-links lead to dynamic PVA-B-PVA bridges at higher pH values to impart rigidity and thermal resistance.

Previous Approaches to Smart Polymer Development

In past smart polymer applications, other methods may have relied on the use of the cross-linker glutaraldehyde. GA cross-links well in polymers bearing amines, whereas it is less optimal for PVA/CMC due to it being largely hydroxyl-based and requiring strong acid catalysis, which can be toxic for food-contact applications. Non-toxic catalysts such as lactic and oxalic acid have been tested for cross-linking films of such biopolymers. Fluorescein probes have also been utilized as pH indicators, though it is light-sensitive and requires storage in the dark. Curcumin has better color differentiation in the range relevant to the products' spoilage (about pH 6-8), together with better lightfastness when exposed to normal lighting conditions. Curcumin can be utilized in different hosts like polyethylene, PLA, gelatin, and PVA-based films in smart packaging applications [11],[16].

The Food-Grade Approach

The project uses food-grade materials, with approved components for food contact in Europe (E-numbers): PVA (food grade), CMC (E466), PEG (E1521), calcium chloride (E509), curcumin (E100), glycerin (E422), and food wax (E903). In borate cross-linking, boric acid (E284) and sodium bicarbonate are required, though borate-free alternatives are preferred for boron migration issues.

In contrast to toxic GA, this approach employs $Ca2+$ ionic cross-linking for the construction of CMC-$Ca2+$ egg-box frameworks. $Ca2+$ ionic cross-linking is mild and has been very successful in many types of biopolymers. In the case of the egg-box model, dimers are formed between the opposing polysaccharide chains and $Ca2+$, which assemble laterally in multimers.

Curcumin is used as the pH indicator, and it changes color from yellow at $pH \leq 6$, to yellow-orange at pH 7, and finally to orange-brown or brownish-red at $pH > 8.5$ [7], [21], [22]. Curcumin-based intelligent films have been successfully used in the freshness tracking of poultry products, fish, shrimps, and pork. There is also a protective layer of wax (0.5–1.5 g/m^2) on one or both sides of the film that inhibits solubility in water and maintains swelling and pH responsive properties [8],[23]. The role of this protective layer is to ensure that the film is water resistant and still permits diffusion of ions between the sensor and the analyte for detection.

Current Project Status and Scope

Currently, this project is ongoing in the validation phase in the lab. These materials are considered to have limited solubility and controlled swelling in model conditions. In addition, it can be noted that such materials are still in the process of validation for commercial food contact applications and need comprehensive validation of safety, including migration testing and mechanical testing under conditions of use, in addition to validation of photostability and regulatory approval for food contact use.

Methodology

The experimental approach is structured around careful material selection, precise formulation development, controlled synthesis procedures, and systematic characterization. Two primary formulations are developed: a standard calcium-cross-linked variant (borate-free) and an enhanced borate-calcium dual cross-linked variant for applications requiring higher stiffness.

Materials

The following food-grade materials are used in the synthesis:

1) PVA (food grade) 1.2 g: Primary film-forming polymer providing mechanical strength, transparency, and gas barrier properties
2) CMC (E466) 0.7 g: Provides ionic cross-linking sites through carboxyl groups, enhances biodegradability, and regulates swelling behavior [12]
3) PEG 4000 (E1521, solid) 0.6 g: Plasticizer to reduce brittleness and improve flexibility [13]
4) $CaCl_2$ (E509) 0.30 g: Ionic cross-linker forming CMC-Ca^{2+} egg-box networks [14], [15]
5) Curcumin (E100) 0.020 g: Natural pH-responsive visual indicator [7], [8]
6) Glycerin (E422) 0.12 ml: Additional plasticizer enhancing elasticity
7) Deionized water 10 ml: Solvent and dispersion medium
8) Food wax (E903) 0.5 g: Water-resistance coating forming thin hydrophobic barrier layer
9) Optional borate cross-linking components: $NaHCO_3$ (food grade) 10-15 mg; Boric acid (E284) 0.20 g

Synthesis Procedure Protocol

The synthesis protocol follows established methods for PVA/CMC film preparation with modifications for curcumin incorporation [11], [12], [16]:

Step 1: PVA Base Preparation: Heat 7 ml of water to 90°C. Gradually add 1.2 g PVA with continuous stirring for 35-40 minutes until complete transparency is achieved. Cool to 75-80°C, then add 0.6 g PEG 4000 and stir for 20-25 minutes until homogeneous distribution is obtained.

Step 2: CMC Base Preparation: In a separate beaker, disperse 0.7 g CMC in 3 ml water at 70-75°C for 20 minutes. Use a magnetic stirrer or ultrasonic bath if available to ensure complete dispersion and prevent agglomeration.

Step 3: Indicator Preparation: Dissolve 0.020 g curcumin in 0.5 ml of 95% ethanol or alternatively in 0.5 ml glycerin [7], [21]. Maintain at 40-50°C to keep the solution warm and prevent precipitation.

Step 4: Combination and Cross-linking: Mix the PVA base and CMC base at 65-70°C for 10 minutes ensuring thorough blending. Add the curcumin solution and mix for 5 minutes to achieve uniform indicator distribution.

For calcium-only cross-linking (Variant A - Recommended): Add 0.30 g $CaCl_2$ and mix for 10 minutes to form CMC-Ca^{2+} ionic networks [14], [15]. Add 0.12 ml glycerin and mix for 2-3 minutes for final plasticization.

For dual cross-linking (Variant B - Enhanced stiffness): Raise pH to 8.2-8.7 with micro-doses of $NaHCO_3$. Add 0.20 g boric acid and mix for 10 minutes. Add 0.30 g $CaCl_2$ and mix for 10 minutes. Add 0.12 ml glycerin and mix for 2-3 minutes.

Step 5: Casting and Drying: Degas the solution by allowing it to rest for 5 minutes, then pour into silicone mold creating a layer of 0.3-0.6 mm thickness. Allow to set for 12-16 hours at 25°C, then dry at 40-45°C (preferably under vacuum) for 14-18 hours [11], [16].

Step 6: Wax Coating Application: Melt food-grade wax at 65-75°C. Apply a thin, uniform coating at 0.5-1.5 g/m² to one or both sides of the dried film. Allow to cool and solidify, forming a protective hydrophobic barrier [8], [23].

Results

Lab analysis indicated that the films are responsive to pH changes in terms of noticeable visual indicators and color differentiation from pH 4 to 9, including the usual ranges identified in detecting food spoilage (figure 1). Results are consistent with what is reported in literature: at pH values of 6 or lower, the films change color to golden yellow, at pH values of 7 to 8, to dark orange or brownish orange, and above 8.5, to orange brown to brownish red.



Figure 1. Polymer samples at pH = 7 and at pH = 8.

In swelling tests performed in varying liquids, controlled swelling properties were observed. In deionized water at 25°C, swelling of 15% to 35% in mass within 24 hours was observed, and the films did not disintegrate. Reducing water uptake by 40% to 60% and

detecting pH within 2 to 5 minutes in varying environments were possible due to the use of a wax layer.

Parameter	pH 4 (acidic environment)	pH 7 (neutral environment)	pH 8–9 (alkaline environment)
Color (visual)	Bright yellow	Yellow-brown	Dark red / brown
Type of optical response	Protonated form of curcumin	Transitional form	Deprotonated quinonoid form
Film thickness (mm)	0.3–0.6 mm	0.3–0.6 mm	0.3–0.6 mm
Mechanical properties	Soft, slightly elastic	Moderate hardness, slight brittleness	More dense, hard, slightly more brittle
Swelling / water uptake	Moderate (CMC retains water)	Hydrophobic	Low
Solubility	Does not dissolve	Does not dissolve	Does not dissolve
Shape retention	Good	Good	Good
Surface defects	Minimal, smooth surface	Minor defects possible	Surface becomes uneven due to dehydration
Time to full color change	10–30 seconds	10–30 seconds	10–30 seconds
Reversibility	Irreversible	Irreversible	Irreversible

Table 1. The parameters of the polymer at different pH conditions

Mechanical testing indicated differences between the formulation options. In the borate-free variant, flexibility sufficient for packaging applications existed. In the borate-cross-linked variant, the material became 15-25% stiffer (higher Young's modulus values), and the values for elongation at break decreased.

Upon analyzing the structural aspect of the equilibrated samples at varying pH levels, texture in addition to color variation became evident. Acidity gave rise to semi-soft and elastic textures accompanied by swelling. Alkaline materials were more dense and brittle, less stretchy. Preliminary tests in food simulants at 40°C for 2 hours indicated no discoloration of the simulant. Thermal tests indicated that the films remained solid at 0°C, became more brittle, softened at 50-60°C, and resisted brief exposure at 90-100°C, though the borate-free formulation decreased in modulus.

Time after synthesis	Material condition	Changes and observations

0–2 hours	Viscous gel mass	Weak mesh, high humidity, unstable structure, possible shedding when drying
6–12 hours	Forming film	Beginning of stitching, density ↑, material is still soft, surface is sticky
12–24 hours	Semi-finished film	Sufficient mechanical stability, color stability, moderate swelling
24–36 hours	Complete polymer	The film is hard, elastic, does not dissolve, and holds its shape well.
48+ hours	Stable sample	Complete removal of excess moisture, mechanical properties remain unchanged, color response is stable

Table 2. Polymer's behavior and state depending on lifetime

Discussion

Food-grade pH responsive polymer films are an important improvement in contrast to conventional intelligent polymer systems, in which toxic cross-linkers or non-food-grade materials are used. In this case, the use of only food-grade materials and ion cross-linking methods deals with both the safety and functionality needs while preserving environmental friendliness in terms of biodegradable base polymers [6], [11].

Analysis of the specimens equilibrated at different pH values revealed textural disparities that went beyond color changes. In acidic environments, specimens were semi-soft, elastic, and swollen due to the less stable associations of CMC and Ca^{2+} ions, which retained higher amounts of moisture. In contrast, in basic environments, specimens were denser, more brittle, and less elastic due to partial saponification and the development of a denser structure at the internal level [18, 19]. All of the above findings confirm that the material indeed responds to changes in both color and mechanical properties, further supporting its role as "smart material."

Preliminary testing in food simulants indicated the absence of any visual change in color, indicating the lower extent of the migration of the curcumin indicator. Nonetheless, extensive migration testing needs to be conducted for the quantification of the levels of migration and comparison of such values to authorized limits [11], [24]. There are certain specific migration limits specified for substances in food contact materials that are authorized under the regulatory frameworks of the European Union, and the FDA administers such similar conditions in the United States in relation to food contact notifications [2]. In contrast to glutaraldehyde-cross-linked systems, in the ionic cross-linking process, several specific benefits can be enumerated: removal of toxic residues of cross-linkers, rapid synthesis methods that are independent of acidic conditions, easier washing methods, and approval for food contact use [11], [16]. In contemporary literature reviews of pH-sensitive indicator films, it can be observed that attention should be given to the utilization of natural coloration and approval of cross-linking processes that are safer for food applications [6], [25]. In comparison to contemporary smart food packaging materials that are derived from semi-synthetic materials like

PVP or PS, this PVA/CMC/PEG based formulation provides certain benefits in relation to degradability [11], [26]. Yet the need for shifting away from petroleum plastics to novel bio-based alternatives is of utmost urgency inasmuch as it has been recognized that food packaging materials are contributing factors in their large share to the bulk of plastics in wastes [2]. Though such alternatives are short in certain mechanical properties such as resistance to moisture and mechanical strength in comparison to synthetic alternatives, such conditions can be met when employing the proposed food-contact friendly formulation in combination with the above-mentioned protection of the food-contact side through the application of the food-contact friendly food-contact side protection layer of the microporous wax film (with specific properties on its food contact side for protection in food contact applications); otherwise, further potential alternatives in this area can include bio-based coatings such as shellac or Zein-based materials. In current literature reports on pH-sensitive food-packaging materials, readiness for food safety compatibility has been indicated in many reports that lack analysis of migration figures, mechanical properties in food storage conditions, and resistance to light exposure [5], [6]. In contrast and in keeping with stricter scientific approaches, the current experimental work proposes to initially freely state its current conditions of the nature of its current pre-developmental and pre

A risk assessment analysis has been performed for technical, safety, and regulatory challenges, in adherence to the best practices for food-contact packaging materials' development [2], [24]. Beginning with technical risks, for example, the aspect of water resistance may be considered overconfident in actual food environments. Mitigation considerations include swelling tests in different food simulants and at actual temperatures [11], [18]. R2: Brittleness from over-cross-linking. Mitigation options in Design of Experiments on cross-linker concentration and plastic addition [13], [15]. R3: Signal drift from pH meter inhomogeneity or light bleaching. Mitigation in uniform pH meter mixing and testing for photobleaching resistance [7], [22]. Further, for safety and regulatory risks, for instance, possible migration of materials may arise. Mitigation in extensive migration testing in food simulants in line with guidelines for both EU and FDA approval [2], [24]. R6: Regulations on borate cross-linking. Mitigation in parallel and borate-free material development tracks in the primary approach [11].
The intended application would be indicator labels that change color in reaction to pH changes due to the buildup of bacterial metabolites during food spoilage, giving customers additional visual information beyond the pre-printed expiration dates [5], [21]. Because food waste contributes 8-10% of the world`s greenhouse gas emission and the fact that 783 million people are hungry worldwide [4], the potential for environmental and social gain of smart-packaging technologies is immense.

The main drawbacks are: incomplete data on migratory properties to preclude food contact claims, mechanical testing required for thermally cycled materials, quantification of photostability, absence of large-scale production data, and absence of definition of approval path for this novel type of material [2], [24].

Conclusion

In this work, the applications of food-grade PVA/CMC/PEG systems for the preparation of multimodal pH-sensitive smart polymer films with curcumin markers were investigated. The work has confirmed that ionic cross-linking of PVA/CMC/PEG markers and indicators systems using calcium ions, potentially supplemented with borate ions, can be used to prepare films that are mechanically stable and exhibit visual pH changes within the range of importance for food spoilage assays. It should be noted that food-grade materials are non-toxic and do not use toxic cross-linkers such as glutaraldehyde, addressing an important concern that had precluded applications of preceding smart polymers for food quality control and monitoring. Smart polymers' mechanical properties can be finely tuned within the range that is favorable for flexibility and rigidity using the CMC-Ca^{2+} egg-box model and PVA-borate bridges in dual-network systems [14], [15]. Another advantage of food-grade smart polymers and markers such as curcumin lies in their higher color differentiation in the pH range of 6-8 in comparison with fluorescein-based markers, which are more stable under conditions of normal light exposure [7], [8], [10].

Still, considerable validation work needs to be accomplished prior to possible practical applications. In addition to extensive testing for food-grade marker and polymer migration, mechanical properties in conditions of intended practical use, and lightfastness, it is mandatory to check microbiological compatibility and gain official approval for use in food products [2], [24]. Presently, the indicated materials are at the active testing phase in the laboratory, and it should be noted that in all applications, further validation and testing are required.

Despite such shortcomings, it is evident from the obtained results that it is possible to fabricate smart films of such functionality out of food-grade materials only. In this manner, this study opens the door for potential future applications of passive freshness indicators that may decrease the amount of food waste, which is measured at 1.05 billion tons on an annual basis worldwide [4], and promote food security and food safety. Frameworks for risk assessment and validation of such materials are discussed in this work for potential use in future applications.

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Similarities and Differences in the Origins of Amyotrophic Lateral Sclerosis and Frontotemporal Dementia By Dhiya Padmanabhan

Abstract

Amyotrophic lateral sclerosis (ALS) and frontotemporal dementia (FTD) are fatal neurodegenerative diseases that overlap clinically and on a molecular basis. Patients carrying the same genetic mutations, such as C9orf72, TARDBP, and FUS, can develop ALS, FTD, or both. The following analysis shows that these mutations are present in both motor and cortical neurons regardless of diagnosis, indicating that cell-type-specific vulnerability to mutations alone does not determine disease outcome. Mutations in different ALS/FTD genes disrupt overlapping cellular pathways, including RNA processing and mitochondrial function, indicating that the convergence of these disruptions causes neurodegeneration. Environmental factors such as smoking, head trauma, and heavy metal exposure may further influence disease presentation through epigenetic modifications, though current evidence is mostly correlational. Epigenetic mechanisms, including DNA methylation, histone modifications, and RNA-mediated regulation, can create stable changes in gene expression that may explain variability in clinical outcomes, even among patients with the same mutation. These results support the idea that disease manifestation arises from shared downstream disruptions and epigenetic modulation rather than mutations targeting specific neuron types. Understanding these mechanisms could improve the prediction of disease manifestation and help develop targeted therapies.

Introduction

Neurodegenerative diseases such as amyotrophic lateral sclerosis (ALS) and frontotemporal dementia (FTD) present growing challenges to healthcare systems and families alike. ALS has an estimated prevalence of approximately 5 cases per 100,000 individuals worldwide, while FTD affects around 15–22 per 100,000 people in the United States and Europe (Logroscino et al., 2010; Onyike & Diehl-Schmid, 2013). The socioeconomic impact of these diseases is profound, with annual healthcare costs for ALS patients in the United States exceeding $69,000 on average, and FTD placing similarly high burdens due to long-term care and loss of productivity (Gladman & Zinman, 2015; Galvin et al., 2017). The socioeconomic cost of consequences arising from ALS/FTD highlights a critical need for understanding mechanisms of disease that would enable earlier detection and more effective intervention.

Clinically, ALS and FTD appear very distinct at first glance, ALS affecting primarily motor neurons, with muscle weakness and respiratory collapse, and FTD mainly affecting the frontal and temporal lobes, with changes in personality, language, and executive function. But more and more, genetic studies reveal a connection between the two diseases that might lead to new insights. Below is a summary of the existing knowledge about ALS and FTD, before noting connections between them.

Although many genes have been linked to ALS and FTD, they account for only a small proportion of patients. In fact, roughly 85% of ALS and FTD cases are sporadic and genetically

unexplained. This indicates that genetics alone cannot account for disease manifestation and that non-genetic factors such as environmental exposures or epigenetic mechanisms likely also influence disease heterogeneity.

Several genes have been linked to ALS, such as SOD1, TARDBP, FUS, and TDP-43 (Martinelli et al., 2023; DeJesus-Hernandez et al., 2011). Researchers have also found many abnormalities at the molecular level. For example, TDP-43 aggregates form when RNA-binding proteins misfold and clump together, and errors often occur in RNA splicing (Conlon et al., 2018; Li et al., 2023). Although much research has been done on ALS, we remain left in the dark about actual working treatments and cures. Two current drugs that help ALS patients are riluzole and Edaravone (Tzeplaeff et al., 2023). Although much research has been conducted on ALS, no cure has been established; available therapies only slow disease progression. Riluzole is believed to reduce glutamate-mediated neurotoxicity by decreasing presynaptic glutamate release and enhancing its uptake, thereby protecting overstimulated neurons. Its efficacy in prolonging patient survival, modestly by approximately 2–3 months, was demonstrated in early clinical trials and later consistently replicated in both human and animal studies. Edaravone is believed to function as a free radical scavenger, thereby reducing oxidative stress that contributes to motor neuron degeneration. Clinical trials have shown that edaravone slows functional decline, as measured by the ALS Functional Rating Scale–Revised (ALSFRS-R), especially in patients with early-stage disease. Early clinical trials in the 1990s demonstrated that riluzole could slow the progression of ALS and extend survival by a few months, leading to its FDA approval in 1995. Although these treatments can slow down ALS disease progression, it is unclear which mechanisms should be targeted to cure it.

FTD is another neurodegenerative disease that is linked to the degeneration of the cortical neurons, mainly affecting the frontal and temporal lobes of the brain. These are regions that are important for attention, thinking, higher-level processing, and behavior. Individuals with this disease have personality changes, trouble thinking clearly, or difficulty understanding spoken language. There are several genes linked to this disorder, including the GRN (gene encoding the protein progranulin) and the MAPT gene. Currently, there is no cure for FTD. SSRIs can help manage some behavioral symptoms, such as apathy, depression, and agitation, but they do not stop the disease completely. These drugs block the reuptake of serotonin into the presynaptic neuron, which increases serotonin levels in the synaptic cleft. The higher serotonin amounts enable stronger signaling of postsynaptic receptors. In FTD, this helps regulate mood, reduce irritability, and improve some aspects of social behavior, even though it does not affect the underlying neurodegeneration.

We do not yet have effective treatments or cures for ALS or FTD because these diseases involve many different genetic, molecular, and environmental factors. To move toward potential cures, we need better strategies to narrow down this wide range of possibilities and identify the key mechanisms that drive disease progression. Once these are understood, they can become the most promising targets for new therapies.

Intriguingly, both ALS and FTD can be caused by mutations in the same genes, such as C9orf72, TARDBP (TDP-43), FUS, TBK1, UBQLN2, VCP, and CHCHD10 (Abramzon et al., 2020). This overlap between ALS and FTD indicates that the two diseases might share fundamental molecular causes and should not be regarded as entirely different clinical entities. Most notably, these common genes intersect on two critical cell pathways: nucleocytoplasmic transport and RNA regulation, driven by genes such as C9orf72, TARDBP, and FUS, and protein degradation through autophagy mechanisms, disrupted by TBK1, UBQLN2, and VCP (Abramzon et al., 2020). Mitochondrial regulation is impacted because motor neurons have extremely high energy demands, and mutations in C9orf72, FUS, and TDP-43 interfere with mitochondrial function and transport, leading to energy deficits (Abramzon et al., 2020). This evidence shows that there are many downstream pathways affected by mutations in these genes, indicating that the diseases manifest in very different ways according to the specific patient and circumstances.

The overlap between ALS and FTD at the genetic and molecular levels raises a key question: Why do some individuals with the same mutations develop ALS, others FTD, and some both? Furthermore, given that 85% of ALS and FTD cases are not associated with gene mutations, do environmental factors play a role in their development? Answering questions like these could provide insights into the most critical mechanisms underlying ALS and FTD, helping to identify promising targets for the development of effective treatments. Regional brain susceptibility, genetic setting, or environmental/epigenetic factors are all possible answers, but more research is needed to draw definite answers. Given the growing disease burden and genetic overlap that underlie them, closing this deficit is imperative.

Methods

This study examines why identical genetic mutations and environmental factors can result in distinct clinical outcomes in ALS and FTD, with the goal of identifying the most crucial mechanisms involved in their manifestation. Identifying these mechanisms may lead to better targets for potential treatments and cures. Based on observations about the similarities and differences between ALS and FTD, the following hypotheses were proposed:

1. The same mutation (e.g., C9orf72) activates different downstream processes based on cell-type vulnerability and regional gene expression. For example, a mutation occurring in motor neurons might lead to risk for ALS, but not FTD, while the opposite might be true for mutations occurring in cortical neurons.
2. Mutations in ALS- and FTD-associated genes increase disease susceptibility but are not the direct cause. Instead, degeneration occurs because these mutations disrupt shared downstream cellular pathways (such as protein homeostasis, RNA processing, or mitochondrial function).
3. Environmental exposures such as head trauma, toxins, and levels of physical activity may also influence disease manifestation. These interactions can lead to epigenetic

modifications that alter gene expression without changing the DNA sequence, thereby shaping disease heterogeneity.

To evaluate these hypotheses, a structured literature review was conducted using PubMed, NCBI, and Google Scholar, focusing on studies published between 2005 and 2025 that examined genetic, molecular, and environmental contributors to ALS and FTD. Sources were selected from reputable journals, including Nature, MDPI, Frontiers, ScienceDirect, eLife, and BMC. The literature was organized into studies on genes common to both ALS and FTD, cell-type vulnerability, and investigations of environmental or cellular factors affecting disease divergence. Emphasis was placed on synthesizing evidence across neuronal type, genetic mutation, molecular regulation, and environmental influences to explain how identical mutations can produce divergent clinical outcomes.

Results

Hypothesis 1: The same mutation (e.g., C9orf72) triggers different downstream processes depending on which cell types are most vulnerable and how genes are expressed across brain regions.

Genetic analyses show that the GGGGCC repeat expansion in C9orf72 is the most common cause of both ALS and FTD. However, its effects vary depending on the type of neuron involved. Li et al. (2023) conducted single-nucleus transcriptomic and epigenomic profiling of brain tissue from patients with this mutation. They found that in ALS patients, motor neurons exhibited disruptions in protein quality control, energy production in mitochondria, and transport systems along axons, all associated with the toxic buildup of abnormal proteins called dipeptide repeats. On the other hand, in FTD patients, cortical neurons showed widespread errors in RNA splicing, changes in chromatin structure, and trapping of proteins that normally help manage RNA. These differences can show that the same mutation can lead to distinct disease pathways depending on the affected cell type.

Importantly, they found that the mutation does not segregate based on cell type and disease, but instead manifests in both cortical and motor neurons, regardless of the disease the patient had. The study analyzed tissue from a total of 17 donors, including 6 patients with C9orf72-associated amyotrophic lateral sclerosis (C9-ALS), 5 patients with C9orf72-associated frontotemporal dementia (C9-FTD), and 6 control donors without ALS or FTD. The evidence actually argues against Hypothesis 1. It suggests that instead of the disease manifesting due to the mutations targeting particular cell types, both motor and cortical neurons can have the mutation, but the clinical outcome depends on which neuron type becomes dysfunctional. The reason for the same mutations causing different effects in different cells might be answered by hypothesis 2.

Hypothesis 2: Mutations in ALS- and FTD-associated genes increase disease susceptibility but are not the only/direct cause. Instead, degeneration occurs because these

mutations disrupt shared downstream cellular pathways (such as protein homeostasis, RNA processing, or mitochondrial function).

Further studies identified other mutations in genes such as TARDBP, FUS, VCP, and TBK1 that are linked to both ALS and FTD. These genes take part in many cellular processes, such as waste removal, recycling of damaged parts, and movement of materials within cells. Abramzon et al. (2020) found that mutations in TBK1 and VCP interfered with autophagy and mitophagy—the processes by which cells clean up defective proteins and recycle damaged mitochondria. These pathways are significant in motor neurons, which require constant maintenance. Most of the mutations disrupted three major systems: nucleocytoplasmic transport, autophagy, and mitochondrial regulation. Nucleocytoplasmic transport is affected because many ALS/FTD proteins, such as TDP-43, FUS, and C9orf72, normally alternate between the nucleus and cytoplasm to control RNA processing; mutations or repeat expansions can trap these proteins in one compartment, leading to RNA misuse and cellular stress. Autophagy is disrupted because genes like TBK1, VCP, UBQLN2, and SQSTM1 control the removal of damaged proteins and organelles; mutations inhibit the cell's ability to clear toxic aggregates, especially in neurons with long axons that accumulate damage over time. Mitochondrial regulation is impacted because motor neurons have extremely high energy demands, and mutations in C9orf72, FUS, and TDP-43 interfere with mitochondrial function and transport, leading to energy deficits.

Importantly, ALS and FTD can occur in patients with a mutation in just one gene. However, many different genes have been linked to these diseases, and they affect several distinct cellular processes. This suggests that the mutations themselves are not the core drivers of the diseases. Instead, the most crucial mechanisms likely lie in the downstream effects of these mutations, specifically where disrupted pathways overlap (such as protein clearance, RNA processing, and mitochondrial regulation). Future research should focus on identifying these points of convergence, which may represent the true drivers of neurodegeneration.

This supports hypothesis 2 because mutations in different ALS/FTD genes disrupt overlapping pathways (protein clearance, RNA regulation, mitochondrial function). This indicates that factors that lie at the convergence of these disruptions, rather than any single mutation, are the key drivers of neurodegeneration.

Table 1. Key genes identified in ALS and FTD (reproduced from Abramzon et al., 2020)

Gene	Locus	Neurological Phenotypes	Pathway	Main Localization
FUS	16p11.2	ALS, FTD, juvenile ALS, others	Nucleocytoplasmic transport/splicing	Nucleus
TDP-43	1p36.22	ALS, FTD, and variant forms	Nucleocytoplasmic transport/splicing	Nucleus

CHCHD10	22q11.23	ALS, ALS/FTD, mitochondrial myopathy	Mitochondrial dysfunction / synaptic integrity	Mitochondrion, nucleus
C9orf72	9p21.2	ALS, FTD, multiple neurodegenerative disorders	Nucleocytoplasmic transport/splicing	Extracellular, nucleus, endosome, lysosome
UBQLN2	Xp11.21	ALS, FTD, neurodegeneration, X-linked	Autophagy/proteasome	Cytosol, plasma membrane, nucleus
TBK1	12q14.1	ALS, ALS/FTD, AD	Autophagy/inflammation	Nucleus, cytosol, endosome, mitochondrion
VCP	9p13.3	IBMPFD, ALS, others	Autophagy / mitochondrial function	Nucleus, ER, cytosol, extracellular, lysosome
SQSTM1	5q35	PDB, ALS, FTD, AD, early-onset ALS/FTD	Autophagy	Nucleus, cytosol, lysosome, ER, endosome

Hypothesis 3: Environmental exposures such as head trauma, toxins, and levels of physical activity may also influence disease manifestation. These interactions can lead to epigenetic modifications that alter gene expression without changing the DNA sequence, thereby shaping disease heterogeneity.

Only a small proportion of ALS and FTD cases are explained by genetic mutations, leaving the majority of cases sporadic and genetically unexplained (~85% of ALS and FTD cases) (Al-Chalabi et al., 2024). This indicates that genetics alone cannot fully account for disease manifestation, and environmental factors or epigenetic mechanisms likely also influence disease heterogeneity. Altered RNA processing is very important to ALS pathology, and the epigenome can regulate transcriptional and post-transcriptional processes, linking environmental exposures to downstream disease mechanisms. Studies using patient blood, brain tissue, and induced pluripotent stem cells have demonstrated epigenetic and transcriptional dysfunction in C9orf72 HRE (hexanucleotide repeat expansion) carriers, supporting the role of epigenetic dysregulation in both ALS and FTD (Belzil et al., 2017).

Environmental exposures such as head trauma, smoking, occupational chemicals, and heavy metals have been implicated in ALS, where they may interact with genetic susceptibility and influence disease onset or severity (Mitsi et al., 2023; Ijomone et al., 2021). Heavy metals, including lead, cadmium, mercury, arsenic, and manganese, can induce specific epigenetic modifications, such as DNA hyper- or hypomethylation in promoter regions, histone acetylation, or methylation. This can change chromatin accessibility and lead to dysregulation of microRNAs that control neuronal gene expression (Ijomone et al., 2021). Analyses from the EPIC cohort demonstrated that elevated levels of cadmium and lead in prediagnostic blood samples were

associated with increased ALS risk (Peters et al. 2020), while mercury and arsenic, often derived from environmental contamination, can disrupt DNA methylation patterns and histone modifications in motor neurons (Peters et al., 2020). Cadmium can inhibit DNA methyltransferases, leading to abnormal gene activation, while lead exposure has been shown to alter histone acetylation and induce oxidative stress pathways (Peters et al., 2020). Mercury exposure can interfere with microRNA expression regulating apoptosis, and arsenic can both hyper- and hypomethylate genes involved in neuronal survival. These blood-borne metals may then trigger epigenetic modifications in neural tissues, linking metal exposure to molecular mechanisms underlying ALS and FTD.

Discussion

This review of the connection between Amyotrophic Lateral Sclerosis and Frontotemporal Dementia provides insight into what mechanisms cause their heterogeneity. These findings suggest that ALS and FTD are primarily driven by disruptions in shared cellular pathways rather than mutations targeting specific types of neurons. Hypothesis 1 proposed that the same mutation can cause different downstream effects depending on the neuron type that was affected. This hypothesis was unsupported by the studies examined, which show that the C9orf72 gene mutation occurs in both motor and cortical neurons regardless of which disease the patients had. In contrast, Hypothesis 2 was well supported, because studies have found that mutations in genes such as TARDBP, FUS, VCP, TBK1, and C9orf72 all disrupt shared downstream pathways, which are involved in nucleocytoplasmic transport, autophagy, and mitochondrial regulation. This suggests that the convergence of these disrupted cellular processes actually causes neurodivergence. Furthermore, only a small proportion of ALS and FTD cases are explained by genetic mutations, leaving most of the cases to be sporadic (meaning a person with ALS/FTD does not have a family history of ALS/FTD and no genetic links). This showed that genetics alone cannot account for disease manifestation. Hypothesis 3 proposed that environmental factors influence disease outcome through epigenetic modifications, supported by the fact that ALS and FTD are not fully explained by genetics alone. Only a small percentage of cases are linked to known mutations, leaving most cases sporadic. Studies have found that ALS patients are more likely to have histories of smoking, head trauma, and exposure to chemicals or heavy metals (Mitsi et al., 2023; Ijomone et al., 2021; Peters et al., 2020). These exposures can cause epigenetic changes, such as DNA methylation, histone modification, and RNA-mediated regulation, which alter neuronal gene expression. Overall, our results show that ALS and FTD likely arise from the interaction of genetic mutations with common downstream cellular vulnerabilities, as well as environmental and epigenetic factors. There is also evidence linking epigenetic factors to changes in disease onset and progression. Future work should focus on identifying particular common downstream cellular vulnerabilities and epigenetic mechanisms involved. This will possibly eventually lead to the discovery of the core causes of ALS and FTD, and potentially lead to cures for these devastating diseases.

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How did Social Media Affect the 2024 U.S. Federal Elections? By Aalya Tandon

Introduction

Donald J. Trump vs Kamala Harris , the topic on everyone's mind for six months straight during the United States 2024 elections. While Trump did end up winning the popular vote and electoral college, many on social media were supporting Kamala. Trump won by a margin of 1.5 percentage points, winning 49.8% to Harris's 48.3% (CNN, 2024). One example of this was the post made by Taylor Swift endorsing Kamala Harris, helping Harris gain many new supporters. Or so we think. Many people argue that social media has a tendency to be negative and has the potential to influence one's perception of presidential candidates. According to the Pew Research Center, as of 2020, at least 64% of United States Citizens agreed that social media has a negative effect (Auxier, 2020). So, what happened? The question we will be answering: How did social media affect the 2024 U.S. Federal elections? My hypothesis is that there will be a positive relationship, so the more support I would see for Kamala/Trump, that would be shown through vote share. I believe that whatever side people talk positively about in the comments of videos, then that is probably the side they will vote for. Since many people use social media, this should be seen through the voteshare. We will use YouTube.com as our social media website, as it has grown significantly from the last couple of elections (Davies, 2022). In this research paper, I will test this hypothesis by collecting data and analyzing the results to see if this hypothesis is supported. We will first go over the Literature Review and connect our paper with previous papers that review this topic as well. Then I will present the data I collected and explain the results. Lastly, I will conclude by stating the final answer to my research question again, and go over what I would do differently next time. The answer that we found was that there was a positive relationship, but for one side. The republican side had a high slope, indicating that many people supported Trump for most of the states. However, although Trump did end up winning in the 2024 US election (Bankova et al., 2024),, Kamala Harris got many states, but this was not shown through our data. The main takeaway is that not everything that is on social media will be projected in the real world. We saw many comments supporting Kamala as well, but that didn't follow through in our data or in the election.

Literature Review

There are many different social media websites used by presidential nominees, such as YouTube.com, X(Twitter), Facebook, Instagram, etc. For example, on YouTube, you have both longer videos and YouTube Shorts. In comparison, Facebook, Instagram, and Twitter have the option to post both shorts/reels and also simple pictures. The use of social media as a method of campaign started in around 2008 for YouTube, but for other platforms, 2016 was the year that social media campaigns started using other platforms.

According to Fujiwara, Mullier, and Schwarz (2021), Twitter had a huge effect on the 2016 and 2020 election. They mention how it is hurting democracy and how social media platforms are biased. They found that people on Twitter lean more to the pro-Democratic side,

and that during the 2016 elections, Twitter lowered Donald Trump's vote share. During the 2016 election, Hillary Clinton did end up winning the popular vote and had a higher vote share, but President Donald Trump ended up winning overall. In relation to this paper, in terms of similarity, my paper is also studying the effect of social media platforms on US Federal elections. However, my paper focuses on YouTube for the social media platform, and studies the 2024 US Federal elections, unlike how in the Fujiwara, Mullier, and Schwarz (2021) paper, they study the 2016 and 2020 US federal elections. Additionally, the people who use Twitter are different from those who use YouTube. According to owlead.com, as of 2024, around 50.5 million people from the US used X monthly. And around 98% of internet users in the US use YouTube monthly, as of 2025. So the results for my paper and the Papageorgiou (2025) article will be different, as X users and YouTube users are different. On YouTube, there are much more kids (ages 1-17) in comparison to the number of kids on X. Additionally, most YouTube users watch the longer videos, unlike X users who view posts and short videos.

Additionally, the ESSEC Business School, Kubler and Smith article (2024) article also talks about Twitter, however it focuses more on the 2016 and 2020 election. Social media has become an efficient way for politicians, especially on the social media platform “X”, to be heard. Candidates all need a social media presence to get supporters. They mention the 2016 election, where misinformation also affected both candidates in a sort of spiral effect. They found that disinformation also played a huge role in the 2016 election. They also look at the 2020 election, and how the patterns of the 2016 and 2020 U.S. Federal elections were very similar. In comparison to my research paper, I found that a similarity was how they both focus on a U.S. federal election. Additionally, we found that many people would try to bring up comments supporting, for example, Republicans, on a video talking about the Democrats. This connects to the disinformation found in the Kubler and Smith (2024) article, as they were trying to convince people to vote for the other side, in hopes to confuse or perhaps mislead. The difference, however, is that both papers mention different election years, and use a different platform to gather information.

This is also shown through other countries, for example Brazil. According to Bessone, Campante, Ferras and Souza paper (2020), Facebook had a huge effect on social media campaigns and political matters in Brazil. While there wasn’t any federal campaign they focused on, they do focus on politics and localized elections. The principles of Facebook advertising still apply in federal US elections. There is a particular mention of 3G Internet and how in 2017 nobody was on Facebook, however with 3G, in 2018, everyone was on Facebook, and so the behavior of the politicians changed. They not only mention how politicians use social media to gain likes and support, but also how the "offline realm" is affected. The people who were online got more attention from the politician, and the people who were offline got more money from the politician. Something similar about my paper in comparison to the Bessone et. al. (2024) paper, is that they both focus on social media regarding politics. However, besides this, there is not much similarity. While their research focuses simply on politics in general, in this paper, we take it a step further, examining specifically how YouTube impacted the 2024 US federal elections. .

Additionally, the countries are different. Mine focuses on an election in the U.S.A whereas the Bessone et. al. (2024) paper focuses on Brazil. According to Borah (2016), humor and enthusiasm on the Facebook platform was a better campaign strategy than using fearmongering. **SNL video:** As we learned, humor was a big theme in previous election campaigns and their success. Similar to the 2008 election with Obama, the SNL skit portrays Trump as a humorous person, whereas Harris brings out her lawyer persona, being much more serious.

Additionally, there are other platforms such as Facebook, as shown through the Allcott and Gentzkow paper (2017)**.** According to this paper, there were many fake news stories that were shared on Facebook during the time of the 2016 election. One mention was of fake news stories favoring Donald Trump over Hillary Clinton, suggesting that the only reason Donald Trump won was because of this (not my opinion, only what the paper said). Some similarities my paper has with this paper is that they both focus on a U.S. Federal election. They also both include an election with Donald Trump, who ended up winning in both elections. However, the timings are different. My paper focuses on the most recent U.S. federal election, whereas the Allcott and Gentzkow (2017) paper focuses on the 2016 election. Additionally, this paper focuses on the effects of Facebook, whereas mine focuses on the effects of YouTube.
There are also other articles that focus on the 2024 U.S. Federal election, just like this one. According to Columbia Business School, Hussein (2024), there were many campaigns that were made using social media. For example, they found that the DNC gave 200 passes to social media influencers, and President Donald Trump invited a TikToker to one of his rallies, to get more coverage. They found that it is easier to convince younger voters using social media as well. They also found that many influencers that publicly supported either side, were helpful in getting the attention of others to vote for the same side. My paper is similar to this as they both focus on the same election, and both heavily focus on the campaigns made using social media as well. Their paper is different, however, in the sense that they do not connect social media to the results of the election, which is understandable as their article was published before election results were revealed. Additionally, they focus a little bit on the social media platform known as TikTok, whereas mine focuses solely on YouTube.

Lastly, the The SAIS REVIEW of International Affairs, Papageorgiou (2025) article mentions the 2024 U.S. Federal elections, while also going back in time to the 2008 U.S. Federal Election. They found that the first time that social media was really used for campaigns in an election was in 2008 with Former President Barack Obama. They focused on many different social media platforms, including TikTok, X, Facebook, etc. They found that a lot of what Trump did was post things on X and managed to get many followers as well. There was a sort of battle, almost, of how many followers each candidate could get on X. Both sides used many political/news influencers and podcasters as part of the election. Something similar about this article regarding my paper is that they both focus on the same election. However, their article mainly focuses on the social media platform known as X, whereas mine focuses on YouTube. According to owlead.com, as of 2024, around 50.5 million people from the US used X monthly. And around 98% of internet users in the US use YouTube monthly, as of 2025. So, the results for

my paper and the Papageorgiou (2025) article will be different, as X users and YouTube users are different.

Methodology

Firstly, I use data from the "The American Presidency Project" by UC Santa Barbara about the US 2024 Federal election statistics (American Presidency Project, 2024). This information is collected from multiple websites. The American Presidency Project also collects data and statistics about national and state-by-state voting results, both popular and electoral, of the major party candidates. This helped me collect the number of votes for Democrats and then the number of votes for Republicans in the 2024 Federal elections, for each state. I use the vote share for my subsequent data analysis. The vote share is the percentage of people who expressed their vote (Cambridge Dictionary 2025).

Next, I use YouTube.com as my social media platform. YouTube.com is helpful in getting the real opinions of people about this topic. In the year 2024, around 61% of Gen Z voters (18 - 28 years old) use YouTube, and a little less than 50% of millennial voters used YouTube (Upward News, 2024). Thus, YouTube is a great site to help me collect many thoughts and opinions about the election for my analysis. Additionally, as of 2024, YouTube had 14 million videos, and each with many comments. One limitation of using YouTube as the main platform for social media analysis is that many people usually use YouTube Shorts to get news from YouTube (Moise, 2025). Since these are social media comments, they may not reflect the true outcomes or numbers of voting statistics. However, I chose to use videos on YouTube, which resulted in many videos that didn't have 10+ comments. This means that if a video had only one comment, then that would disorganize the data collection, in which case the data will have some biases (ie. the sentiment score for that whole video would be determined based on the opinion of one human).

For my data collection procedure, I went on to Youtube.com and searched in the search bar "[insert state here] kamala." After finding three videos whose content was related to the candidates in the 2024 US Federal elections , I collected the links and inserted them into my Python code.

Then, I use Python to scrape the comments from each video that was collected. Python helps to automate the comment scraping process and makes the data collection much faster. One limitation of my Python code, however, was that it was not able to collect the replies to comments. So even if a video said there were 20 comments, Python would only end up collecting 12, due to the other 8 being replies.

From Python, I saved all the video comments and inserted it into ChatGPT 4, an Artificial Intelligence run by OpenAI. While we recognize that AI has many issues (ie, hallucinations), the AI was however able to determine the tone/language of the comments, and mostly accurately able to determine a sentiment score based on what it saw in the comments. To figure out the sentiment score, I told ChatGPT 4 to analyze all the comments of the video I chose, using the following prompt:

Analyze these comments and generate a sentiment score based on this scale.

1 = Extremely pro-Trump
2 = Pro-Trump / Anti-Harris
3 = Neutral
4 = Pro-Harris / Anti-Trump
5 = Extremely pro-Harris

After it did this for all of the comments, I asked for an average, and that is how I found the sentiment score. I continued doing this whole process for all of the 3 videos I found for ALL the 51 states (including DC). Finally, we found an average across all three videos.
By employing all these tools, we were able to successfully explore and analyze the data collected from YouTube.com to gain insights into the effects of social media on the US 2024 federal election results. We have also included an example of our research.

EXAMPLE

This video was about Ohio, titled: **Ohio senator Sherrod Brown weighs in on Kamala Harris running for president.**



Some comments analyzed by ChatGPT:

I'm from Cincinnati and if it's brown flush it...	3 (Neutral)
He will be a rubberstamp for her policies	3 (Neutral)
Sherrod Brown has been riding with Biden and...	2 (Pro-Trump / Anti-Harris)

Final Score: 2.9-3

Next, we introduce our data collection.

Data

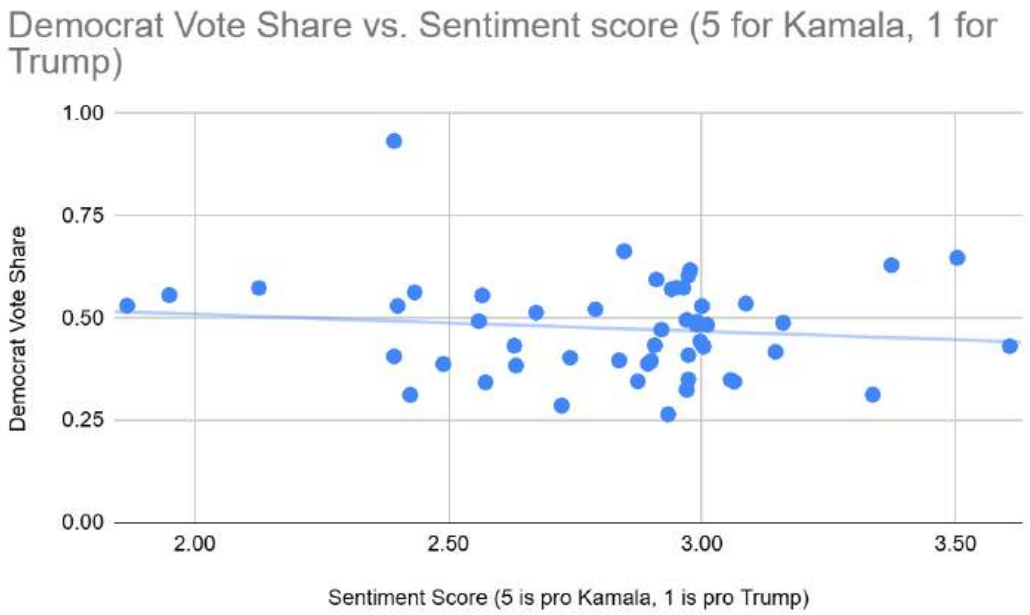


Figure 1

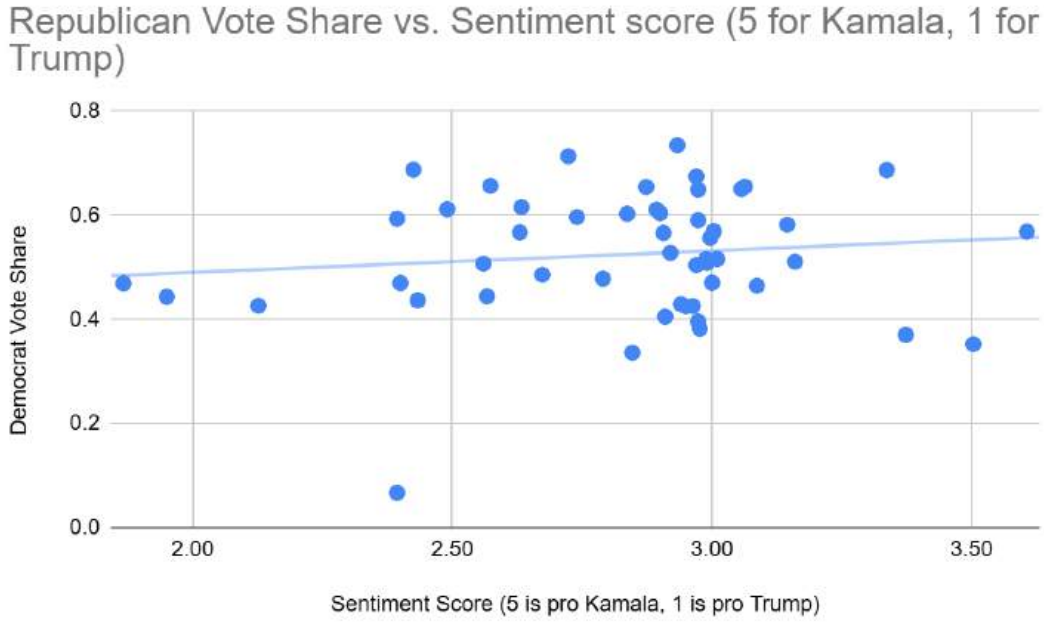


Figure 2

The lowest final average was for the state of New Mexico, with a final average of 1.87 on the sentiment scale. That meant that for comments, New Mexico was extremely pro Trump. The highest final average was for the state of Alaska, with a final average of 3.61 on the sentiment scale. That meant that for comments, Alaska was pretty neutral but more supporting of Harris.

Discussion

I watched two videos from two different states and made a compilation of my thoughts and ideas. We first watched a video from the state of California, and after that a video from the state of Pennsylvania. We picked these videos in particular because both videos had a lot of comments/ different opinions, so it was best to pick these two.

California

From watching this video and skimming the comments, I found that many people in California did not support Kamala Harris becoming president. This was extremely confusing, since Kamala Harris won the electoral vote from the state of California by a huge landslide. The Democrats vote share was almost 90%, whereas the Republican vote share was only around 10%. Yet so many people, including big senators and members of the house, were against Harris. I think that social media and elections are a good way to promote different nominees, yet at the same time, it can influence people to go against what they would usually stand for. Of course, we must also consider fake social media accounts, bots, and simply people changing their opinion. Some people from California in the comments were saying that it was now time for California to vote red, whereas others were saying they could overlook the mistakes made by Kamala and they still wanted her as president, to help the country move forward. This is important because if the presence Kamala Harris has online was receiving hate, then it's important to have an offline presence as well, and to have a presence everywhere, and not just on YouTube as our study does. I think it's very interesting to see and learn about, and many some people offline thought differently, which would've happened since Harris did end up winning California. My initial assumption was that Kamala Harris was doing good in California, but I was surprised to hear otherwise. However, since I do not know much about what Harris did before she became Vice President, I don't really have an opinion on that topic. This video had almost 80,000 views, indicating that a lot of people were curious about this topic.

Pennsylvania

From watching this video and skimming the comments, I found that many people (not those at the Trump Rally, but those in the comments section) DID want Harris becoming president. They mocked Trump, saying he was rambling and couldn't debate. Whereas others agreed that Harris should just end the election now, calling her a "lunatic." I found this even more confusing, because I was hearing different things from different people, and while most people were saying Harris should become president, Donald Trump won the electoral vote from the state of Pennsylvania. Although it was very close, Trump did still win. Yet so many people in the comment section of that video were against Trump. So again, while social media can be a good way to promote nominees, it can also be a way to take other nominees down, as Trump did in this video. That's why the offline presence is extremely important, which both sides did have. Harris was known for being a prosecutor in the state of California, and Trump was known for being a past US president. They both had done good and bad things in their time, and were

occasionally using that to get back at the other nominee via social media, which I noticed in this video. This video had 305k views, meaning that there were thousands of people interested in this topic.

Analysis

I hypothesized that there would be a positive relationship for **figure 1**, yet in this case there is a negative relationship for the sentiment score. I had assumed that if there was more support for Kamala via vote share, then there should be more support for Kamala online as well. However, the exact opposite ended up happening. Even when the support for Kamala was low on YouTube, Kamala still ended up winning that certain state. For example, with the state of California, Harris won the electoral vote by a landslide, and yet the sentiment score average was around 2.9. Or with the state of New Mexico, the sentiment score was a 1.87 and yet Kamala Harris won the electoral vote. The same applies for Trump. This tells us that the social media comments don't reflect the broader voting population. Although many people who can vote do use social media, that doesn't always mean that they let social media decide who they want to vote for. This means that for future politicians who might use social media in the future, they should know that both online and offline presence is necessary, as we saw from the Bessone, Campante, Ferras and Souza paper (2020) paper. One thing I especially noticed was even on videos supporting Kamala, the comments would mostly just be saying "Trump 2024" or "MAGA", etc. So, the sentiment score ended up being much lower for those videos. Additionally, only once or twice did the sentiment score end up reaching around the 4s and 5s, so I can infer that there was much more support for Trump online.

However, for **figure 2**, regarding Donald Trump, there ended up being a positive relationship. I think this was because a lot of videos would say things such as "Trump 2024" or "MAGA" or there would be many comments saying negative things about Harris, in instances with California or New Mexico, where Harris still ended up winning the electoral votes. However, I guess that in the end, the final result of the election was shown from figure 2, where many people supported Trump and Trump did end up winning this election. This could be because Trump had a huge offline presence as well, having been the president in the past, many thought they could trust him again. Additionally, the votes could have changed once Kamala Harris was in the race, and maybe more people initially supported Biden and not Kamala Harris.

Conclusion

In conclusion, we found that no matter what the comments had shown, you wouldn't really see that same outcome in the polls. We used Python, YouTube.com, and ChatGPT to find the sentiment score and answer our question. First we found 3 videos for each state on YouTube.com, then we went into Python and Python gave us all the comments for each video on a separate excel sheet, and lastly we used ChatGPT and our sentiment scale to find the average sentiment score for each video, and then found an average sentiment score for each state. Our final findings were that even when the support for Kamala on social media is high/low, that

doesn’t mean you will see that outcome in the polls. There ended up being a positive relationship for the second graph, stating that Trump was seen to have much more support than Kamala did from the social media comments. There are many other factors that are not shown here as well. For example, we acknowledge that some states only had one or two videos, such as Oklahoma and Kansas, and that is simply because we were not able to find any information for those states. Additionally, this was only for 3 videos per state, and so maybe if we had compiled even more different videos for each state, we could've found a positive relationship in **figure 1**. Lastly, we only used the platform of YouTube, and many people are not on YouTube or on social media at all, but they would still end up voting. What this shows is that social media definitely has an impact on people's decisions and ideas about the 2024 U.S. Federal elections, but maybe not always a big one. For future research, I recommend that you compile many different videos, many 10+ and try to use many different platforms. Videos on YouTube didn’t have a lot of comments, whereas we later found many people commenting on X posts or YouTube shorts.

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Geometric Dimension Reduction Techniques To Establish Smoothness of Euclidean Submanifolds With Smooth Boundary By Havish Sripada

Abstract

Determining whether a topological submanifold of Euclidean Space with boundary admits a smooth structure has long been a problem of interest in differential topology. Modern approaches for showing the existence of smooth structure on a submanifold, like the application of the Regular Level Set Theorem, are often sufficient in many simpler scenarios. However, there are no general solutions to satisfy the constraints of more complex submanifolds. This paper utilizes geometric techniques to find a general solution for the case when a submanifold has a nonempty smooth boundary. Using deformation retracts and projections, we reduce the problem to proving the smoothness of a simpler submanifold that captures the general topology of the initial submanifold, and the process can be repeated to form an inductive argument. We begin by tackling the case of full-dimensional submanifolds, and then later generalize these notions into submanifolds of higher codimensions.

1 Introductory Remarks

1.1 General Terminology

Definition 1. A manifold is a second-countable Hausdorff space M that locally resembles the topology of $\mathbb{R}^n$. More precisely, this means that any point in the manifold lies in an open neighborhood that has a local chart (homeomorphism) mapping this neighborhood to an open subset of $\mathbb{R}^n$.

A set of charts satisfying the above condition is called an atlas. Note that this paper focuses on topological manifolds, which may not necessarily be smooth (defined below in the next definition). We will work under the ambient space $\mathbb{R}^n$, and therefore refer to our topological manifolds as submanifolds. They therefore inherit properties of $\mathbb{R}^n$, most importantly, the ability to be globally described in terms of standard Euclidean coordinates. Submanifold equality will be considered up to diffeomorphism, so if two submanifolds M_1 and M_2 are diffeomorphic we denote this as $M_1 \tilde{=} M_2$. All submanifolds in this paper are generally assumed to be compact and connected in order for the general argument to hold, and submanifolds are not necessarily smooth. We now make precise the notion of smoothness.

Definition 2. A smooth topological submanifold is a submanifold that locally resembles $\mathbb{R}^n$ in a smooth way: for any point in the submanifold, there exists an open neighborhood around the point contained inside the submanifold and a local smooth chart (diffeomorphism) mapping this neighborhood to an open subset of $\mathbb{R}^n$.

The distinction between a smooth topological submanifold and a topological submanifold lies in the charts that map open neighborhoods to open sets of $\mathbb{R}^n$. Submanifolds must have a smooth atlas that contains only diffeomorphism charts instead of homeomorphisms in order to be considered smooth. We refer to this smooth atlas as a smooth structure.

Definition 3. A topological submanifold with boundary is one where every point has an open neighborhood with a chart mapping to the unit open disk $D^n \subset \mathrm{R}^n$ or, if this cannot be satisfied, the unit half-disk $D^n_+ \subset \mathrm{R}^n$. If an atlas satisfying the condition above contains only diffeomorphisms, then the submanifold is considered smooth. The set of points that lie in an open neighborhood homeomorphic to the full disk is referred to as the submanifold's interior, denoted Int(M), while the remaining points are referred to as the boundary of the submanifold, denoted ∂M.

In this paper, when we talk about topological submanifolds, it can be assumed that the term topological submanifold with boundary is meant unless otherwise specified. The distinction here is that any submanifold without boundary is still considered a smooth submanifold with boundary, and the boundary is simply taken to be empty. The converse isn't true: a submanifold with boundary isn't typically seen as a regular submanifold when the boundary is nonempty. We refer to a submanifold with boundary as smooth if it is a smooth topological submanifold with boundary. Note that we say the boundary of a submanifold M is smooth if $\partial M =$ and ∂M is a smooth $(n - 1)$-dimensional submanifold where dim $M = n$.

Definition 4. A smoothable submanifold is a topological submanifold that is globally homeomorphic to a smooth submanifold.

Definition 5. A submanifold with corners is a submanifold where every interior point has an open neighborhood around it and a chart mapping this neighborhood to $D^n \subset \mathrm{R}^n$. Every point on the boundary of the submanifold has a similar open neighborhood and chart mapping to the unit half disk $D^n_+ \subset \mathrm{R}^n$. Finally, if a point is unable to satisfy either condition, it has an open neighborhood around it and a chart mapping to an open subset of the form $[0, \infty) \times \mathrm{R}^{n-k}$ for some $1 \leq k \leq n$. If the point falls into this last category, it will be referred to as a corner. A smooth submanifold with corners has an atlas consisting solely of diffeomorphisms.

It is important to note that we don't consider smooth submanifolds with corners as smooth. This paper focuses primarily on submanifolds with boundary, and therefore the condition for smoothness is that the submanifold must be a smooth submanifold with boundary. While any smooth submanifold with boundary is a smooth submanifold with corners, the converse isn't true. We will instead use smooth submanifolds with corners as tools in our geometric proofs.

1.2 Background

The properties of smooth topological submanifolds have been studied heavily, including the conditions for such submanifolds to admit a smooth structure. R.Schultz details the conditions necessary for a topological submanifold of an abstract space to have the ability to be approximated by a smooth submanifold of that space (see [Sch]), while R.Lashof and M.Rothenburg find similar conditions for a piecewise approximation of the submanifold (see [LR65]).

The main question of research is therefore to find sufficient conditions for topological submanifolds of R^n with smooth boundary to be smooth. We specifically attempt to pursue the

case of codimension 0 topological submanifolds, which are abstractly n-dimensional manifolds embedded in R^n. Codimension 0 submanifolds without boundary are the open sets of R^n [Lee12]. We will focus on the case of codimension 0 submanifolds with boundary, which are more interesting topologically. We begin by introducing a few important lemmas that will be used in the paper. These are commonly known facts of differential topology, and the first three can be found in J. Lee's book on smooth manifolds (see [Lee12]). The first lemma follows from Proposition 1.45 and Example 1.34, the second follows from Problem 16-7, and the third follows from Example 1.26.

Lemma 6. *Let M be a smooth submanifold without boundary. Then* $M \times [a, b]$ *is a smooth submanifold with boundary, while* $M \times (a, b)$ *is a smooth submanifold without boundary.*

Lemma 7. *Let M be a smooth submanifold with boundary. Then* $M \times [a, b]$ *is a smooth submanifold with corners, while* $M \times (a, b)$ *is a smooth submanifold with boundary.*

Lemma 8. *An open set of a smooth submanifold is smooth.*

Lemma 9. *A (smooth) submanifold with corners is homeomorphic to a (smooth) submanifold with boundary. In particular, if a submanifold with boundary can be achieved by smoothing out a smooth submanifold with corners (considered to be a homeomorphism), then the submanifold with boundary is smooth as well. In particular, a smooth submanifold with corners is smoothable.*

Proof. This follows from the idea that any corner point lies in an open neighborhood homeomorphic to the set $A = [0, \infty) \times R^{n-k}$ for some $1 \leq k \leq n$ which is homeomorphic to D^n_+, which open neighborhoods



Figure 1: Hollow Cone: Not a Smooth Submanifold With Boundary

Of boundary points must be homeomorphic to as well. However, these two sets are homeomorphic, which implies that we can use homeomorphism operations to turn corner points into boundary points. It therefore becomes trivial to show that since the smoothing operation makes the submanifold smooth at the boundary, and the rest of the submanifold has the same smooth structure as the initial submanifold with corners, the resulting smoothened submanifold is smooth.

1.3 Codimension 0 submanifolds

This paper primarily focuses on finding a geometric proof to the following assertion

about codimension 0 submanifolds, after which we attempt to generalize these techniques to higher codimensions. This theorem is already known to be true, and a standard algebraic proof is left here for reference.

Theorem 10. *Every codimension 0 topological submanifold of* R^n *with smooth boundary is smooth.*

Proof. Let M be a topological submanifold of R^n with codimension 0 and smooth boundary. For $p \in M$, either $p \in \mathrm{Int}(M)$ or $p \in \partial M$. If $p \in \mathrm{Int}(M)$, then any open disk around p can be mapped smoothly to itself using the identity map, which means that the interior of the submanifold satisfies the condition. If $p \in \partial M$ instead, this is slightly more interesting. Using the smoothness of the boundary, let $U' \in \partial M$ be diffeomorphic to D^{n-1}. Since this means U' is a disk itself, we can draw the n-disk U centered around p containing U, such that $U \cap \partial M = U'$. Note that the portion $U \cap M$ resembles D^n_+, and since U' is smooth, this is enough to say that $U \cap M \tilde{} = D^n_+$. Therefore, M is smooth.

1.4 Codimension n > 0 submanifolds

When we consider the case of submanifolds with codimension greater than 0, we can now have more generalized topological structures that aren't smooth despite their boundary being smooth. For example, a cone

(Figure 1) is given by the graph of the function $f : \mathrm{R}^2 \to \mathrm{R}$ defined by $f(x, y) = -\sqrt{x^2 + y^2}$, $0 \leq x^2+y^2 \leq 1$. Observe that despite its boundary being a smooth circle, the cone itself isn't smooth at the origin. Note that this apex is a corner point on the submanifold.

The fact that counterexamples to Theorem 10 exist in higher codimensions shows that we cannot use these geometric techniques to prove that every submanifold with smooth boundary is smooth. However, our generalized algorithm can be viewed as a tool to determine the smoothness of certain groups of submanifolds. We will begin by introducing our ideas in the codimension 0 case.

2 Dimension Reduction

In order to geometrically approach the problem underlined in the previous section, we use tools like projections and deformation retracts. The goal of these functions is to reduce the dimension of the submanifold while preserving smoothness and the underlying topological structure. More precisely, we create a map that allows us to send the topological structure of the submanifold to one of its proper subsets and reduce the problem to proving the smoothness of this less complex subset. We begin by introducing relevant terminology that will be used in this paper.

Definition 11. A continuous surjective function $R : M_1 \times [0, 1] \to M_2 \subset M_1$ is a deformation retract if it satisfies the following additional criteria for $x \in M_1$, $t \in [0, 1]$ and $y \in M_2$:

1. $f(x, 0) = x$
2. $f(x, 1) \in M_2$

3. $f(y, t) = y$

In this case, we say M_2 is a deformation retraction of M_1.

We define our deformation retracts using directed paths. The starting and ending points of these paths will inform us of the output of the function, and each input $t \in [0, 1]$ will scale these paths to determine the output. Note that curved paths would make it harder to maintain the topology of the submanifold throughout the transformation, and often create problems with continuity. For example, if we consider the unit circle S^1, a deformation retract to the point $(0, 1)$ would struggle to maintain continuity at $(0, 1)$ if all paths between points were strictly nonlinear. For the sake of simplicity, we thus stick with linear paths and refer to them simply as l-paths. Our deformation retracts will also preserve commutativity, i.e., $R(R(x, t_1), t_2) = R(R(x, t_2), t_1)$. We now consider similar maps called projections, which will typically be more applicable to more complex submanifolds, where these deformation retracts aren't as easily created.

Definition 12. Let M_1 be a topological submanifold of R^n and ~ be an equivalence relation on M_1. Then the continuous surjective map $P : M_1 \to M_2 \subset M_1$ between two submanifolds is a projection if it satisfies the following property: for any $x, y \in M_1$, $P(x) = P(y)$ if and only if $x \sim y$. Although not all projections are used like deformation retracts, the projections we consider will typically be more general versions of these deformation retracts. Our projections can typically be viewed through the lens of deformation retracts, which we will use to establish an intuition of the algorithm in one of the examples. More precisely, if we create lines $\{L_i\}_{i \in I} \subset \mathrm{R}^n$ covering the submanifold M for some set $I \subset \mathrm{R}$, then we say $x \sim y$ if x and y are on the same line. Then we typically have each line map to a different point in the codomain, creating our projection. The advantage of this over deformation retracts is that the entire line L_i does not necessarily need to be contained in M, something that would be necessary for a deformation retract to maintain commutativity.

2.1 Case I: Star-convex submanifolds

We start by considering star-convex submanifolds of R^n, to illustrate how deformation retracts can be used with this algorithm.

Definition 13. A point $p_0 \in \mathrm{Int}(M)$ is a center of a star-convex topological submanifold with boundary M if, for every other point p_1 in that submanifold, the line passing through p_0 and p_1 is fully contained within the submanifold.

We use l-paths to define our deformation retracts, and therefore use several path-related operations when performing this proof. We therefore establish some notation to easily describe these transformations. We distinguish l-paths by their initial and terminal points and represent them as $P = (u, v)$ where $u \in \mathrm{R}^n$ is the initial point of the l-path, and $v \in \mathrm{R}^n$ is the terminal point corresponding to P.

Definition 14. Given a l-path $P = (u, v) \in \mathrm{R}^n \times \mathrm{R}^n$, define $\Phi_1(P) = u$, $\Phi_2(P) = v$, and the magnitude of the l-path $|P|$ is the magnitude of the vector between u and v. As expected, negating an l-path works similarly to negating a vector: $-P = (v, u)$. We denote by $\vec{d}(P)$ the normalized

direction vector of the l-path.

Definition 15. The transformations $T, H : \mathrm{R}^n \times \mathrm{R}^n \to \mathrm{R}^n$ such that $T(P, t)$ is the l-path obtained by fixing the initial point of P and scaling the magnitude by t, while $H(P, t)$ is the l-path obtained by instead fixing the terminal point and scaling the magnitude by t. Thus T changes the terminal point of the l-path, while H changes the initial point.

Theorem 16. *Let M be a topological submanifold whose boundary is smooth. Then M is smooth, and in particular diffeomorphic to closed disk, if it is star-convex; that is, it has a center.*

Proof. Let $p_0 \in M$ be a center, and define the closed disk $D = \{x \in \mathrm{R}^n : ||x - p|| \leq \epsilon\}$ for some arbitrary small $\epsilon > 0$. For all $x \in \mathrm{R}^n$, form the l-path P such that $\Phi_2(P) = p_0$ and $\Phi_1(P) = x$. Form a new l-path P', such that $\Phi_2(P'_{) = y \in \partial D, \text{ and } \vec{d}(P) = \vec{d}(P')}$. Using this procedure, we assign to each point a unique l-path P', and then create a map $\phi : \mathrm{R}^n \to \mathrm{R}^n \times \mathrm{R}^n$ such that $\phi(x) = T(P', 1 + \epsilon_1)$ for some small $\epsilon_1 > 0$. Using ϕ, we establish a transformation on R^n. define $\Psi : \mathrm{R}^n \times [0, 1] \to \mathrm{R}^n$ to satisfy the following:

1. $\Psi(x, 0) = x$
2. $\Psi(x, 1) = \Phi_2(\phi(x))$
3. For $t \in (0, 1)$, $\Psi(x, t) = \Phi_1(H(\phi(x), t))$
4. There exists $t_0 \in (0, 1)$ such that $\Psi(x, t_0) = \partial D$

Denoting the set $\Psi(x, 1)$ by $S \subset D$, we note that $S = \partial U$ for some $U \subset \mathrm{R}^n$, $p \in U$, since S partitions D and by extension R^n into two regions. Furthermore, define $S_1 = \mathrm{Im}(h)$, where $h : \partial M \to A \subset \mathrm{R}^n$, $p \mapsto \{\Phi_2(T(-\phi(p), t)) : t \in (0, 1 + \epsilon_1)\}$ for some small $\epsilon > 0$. Then $\Psi|_{S1 \cup M \setminus \mathrm{Int}(U)}$ is a deformation retract onto S. define a map $g : M \to \mathrm{R}$ such that $p_1 \in M$ maps to the unique $t \in \mathrm{R}$ satisfying $p_1 \in \Psi(S_1, t)$. Observe that g partitions the submanifold into level sets, and that for all $x, y \in \partial M$ the condition $g(x) = g(y)$ holds, and the same is true for ∂D. Note how this deformation retract reduces the dimension of the initial submanifold to the $(n-1)$-dimensional level sets that are easier to study. In particular, as we will show with our deformation retract arguments, the smoothness of the initial submanifold hinges upon the fact that the surface we are crushing down to, this ball, is smooth itself. For the sake of convenience, let a denote the unique real number given by $g(x)$ whenever $x \in \partial M$, and b denote the unique real given by $g(y)$ whenever $y \in \partial D$. Clearly, a and b are regular values of g. We now use a known theorem to show that M is smooth.

Lemma 17. *Let $g : \mathrm{R}^n \to \mathrm{R}$. Suppose $a, b \in \mathrm{R}$, $g^{-1}([a, b])$ is compact, and g has no critical points in $g^{-1}([a, b])$. Then $g^{-1}{}_{((-\infty, a])}\tilde{} = g^{-1}((-\infty, b])$.*

This lemma follows from ([Mil63], Theorem 3.1). By this theorem, we have that $g^{-1}{}_{((\infty, a]) = M}\tilde{} = g^{-1}((-\infty, b]) = D$ so therefore M is diffeomorphic to a closed disk.

2.2 Case II: Standardly embedded 1-handlebodies

For codimension 0 topological submanifolds with more complex structures, in which deformation retracts can't be globally defined using l-paths, we can use a slightly different approach: projecting to an $(n - 1)$- dimensional submanifold. Note that this argument fails for

simpler cases when dim $M < 3$ due to the topological structure of holes in lower dimensions. Many non-hollow submanifolds can be classified as 1- handlebodies, so we will use this case to highlight our general argument. We begin by laying the groundwork for the definition of a 1-handlebody by making precise the notion of the boundary connected sum operation.

Definition 18. If M_1 and M_2 are two submanifolds with boundary, then the boundary connected sum $M_1 \natural M_2$ is obtained by removing an open disk from the boundaries of both submanifolds and gluing the resulting boundary components together.

Definition 19. An $n-$dimensional 1-handlebody is the boundary connected sum of $k \geq 1$ copies of $S^1 \times D^{n-1}$.

Figures (2) and (3) provide examples of 1-handlebodies. We define a standardly embedded 1-handlebody as a simpler example that represents a large class of these 1-handlebodies and introduce many of the concepts related to this argument.

Definition 20. A 1-handlebody is standardly embedded if it can be sliced in half by a hyperplane in R^n. 5



Figure 2: Solid Torus ($S^1 \times D^2$)

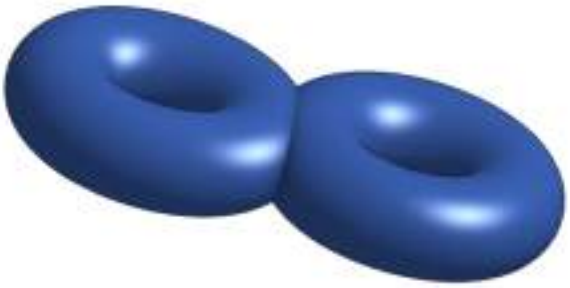


Figure 3: Boundary Connected Sum of Two Solid Torii ($S^1 \times D^1 \natural S^1 \times D^1$)

This definition of standard embedding will allow us to simplify our arguments. As will be seen soon, we will project onto this hyperplane to carry out our dimension reduction process. Consider a general standardly embedded 1-handlebody with genus k. This is the boundary

connected sum of k-copies of $S^1 \times D^{n-1}$, where n is the dimension of this submanifold. We denote

the n-dimensional standardly embedded 1-handlebody of genus k by M^g_n. Note that we can write $M^n_g = M^{n-1}$ $_g \times I$, where I is a closed interval. This fact will become crucial in defining our projection. Finally, we will let M^n_0, be the closed $n-$disk. Note that M^n_0isn't technically a 1-handlebody, but for our purposes, we consider it one since the same argument works on this object.

To show the smoothness of such a submanifold with genus greater than 0 using primarily geometric means, we proceed with the use of projections. Informally, we project M^g_n onto its intersection with the hyperplane U that partitions it in half. We therefore use the map π to project M^n_g onto $M^n_g \cap U = M^{n-1}$ if M^{n-1} $_g$. More precisely, $_g \subset \{(x_1, \ldots, x_{n-1}, 0)\} \subset \mathrm{R}^n$ and $M^n_g = M^{n-1}$ $_g \times [-1, 1] \in \mathrm{R}^n$, then the projection $\pi : M^n_g \to M^{n-1}$ g is given by $(x_1, \ldots, x_n) \to (x_1, \ldots, x_{n-1}, 0)$. Note that this projection maintains the topological structure of the submanifold. In particular, the projection satisfies distributivity with the boundary connected sum: $\pi(S^1 \times D^{n-1} \natural \cdots \natural S^1 \times D^{n-1}) = \pi(S^1 \times D^{n-1}) \natural \pi(S^1 \times D^{n-1}) \natural \ldots \natural \pi(S^1 \times D^{n-1}) = S^1 \times D^{n-2} \natural \cdots \natural S^1 \times D^{n-2} = M^{n-1}$ $_g$. Each boundary connected component of our initial submanifold is mapped down to a lower dimension, and each one reflects its topology into the projected surface. This allows the general topology of the initial submanifold, the boundary connected sum of each component, to be preserved. Figure 5 gives an illustration of a 1-handlebody and the surface it projects onto. Note that the submanifold drawn in this figure has non-smooth edges, but the argument holds.

Given that we have now established our projection, we are ready to use these projections to show the smoothness of the topological submanifolds. We will do this by proving the following result:

Theorem 21. *If $M^n_g$is a standardly embedded 1-handlebody and the projection $\pi : M^n_g \to M^{n-1}$ $_g$is obtained*



Figure 4: Partition of a Standardly Embedded 1-Handlebody (Blue) By a Hyperplane (Yellow)

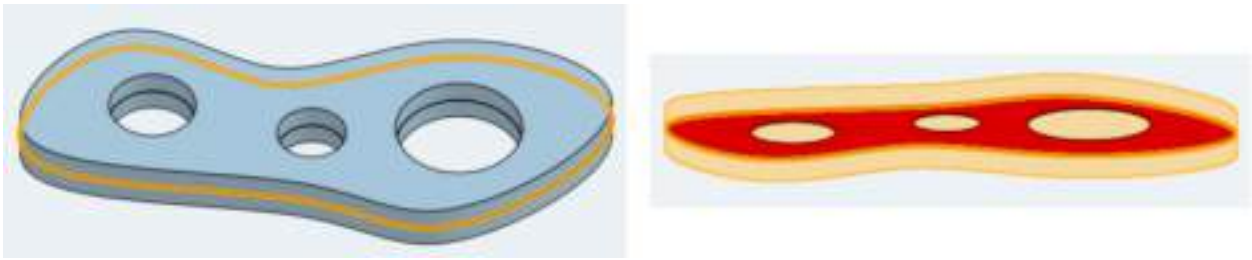


Figure 5: Example Handlebody: Surface of Projection Highlighted

from the procedure above, then M^n_g *is smooth if* $\mathrm{Im}(\pi)$ *is smooth.*

Proof. Consider the topological submanifold $M^1 = M^{n-1}$ $_g \times I$ for some closed interval I. Since M^{n-1} $_g = \mathrm{Im}(\pi)$ is given by the coordinates $(x_1, \ldots, x_{n-1})$, we can write M_1 as $(x_1, \ldots, x_{n-1}, x_n)$. Evidently, $M_1 = M^n_g$ by the definition of our projection. Applying Lemma 7, we conclude that M_1 is a smooth submanifold with corners. However, given that ∂M is smooth, we know that M^n_g doesn't have any corners. Therefore, M^n_g is a smooth submanifold with boundary. The theorem above implies that all we need to show in order for M to be smooth is that $\mathrm{Im}(\pi)$ is smooth. Note that since $\mathrm{Im}(\pi)$ is itself a 1-handlebody, we can imply the same argument again. Given that all 1-handlebodies of two dimensions with smooth boundaries are themselves trivially smooth, we can thus use an inductive argument here. We continuously project the initial topological submanifold down until we are left with a two-dimensional submanifold. Since the two-dimensional submanifold is smooth, the three dimensional submanifold must be smooth, and so on until we can conclude that the initial submanifold is smooth.

2.3 Case III: Knotted 1-handlebodies

In the case of knotted 1-handlebodies, which aren't standardly embedded (see Figure 6), we still project onto a central plane while maintaining the topology of the initial figure. Unlike the standardly embedded submanifolds, we are instead forced to create a more local definition of our projection.

Let M be a codimension 0 knotted 1-handlebody. Select an arbitrary point p from M. Since any knotted 1-handlebody is locally given by either a standardly embedded 1-handlebody (in the present section, we will include the closed disk M^n_0 in this category), there is some open neighborhood $U \subset M$ around this point that resembles a 1-handlebody M^n_g. Consider a coordinate projection to a subset M^{n-1} $_g$ of M^n_g, $\pi : M^n_g \to M^{n-1}$ g with $(x_1, \ldots, x_n) \to (x_1, \ldots, x_{n-1}, 0)$, on this 1-handlebody as we did in the previous section. If we extend π to the entirety of M, the image retains connectedness since M is connected and π is continuous.

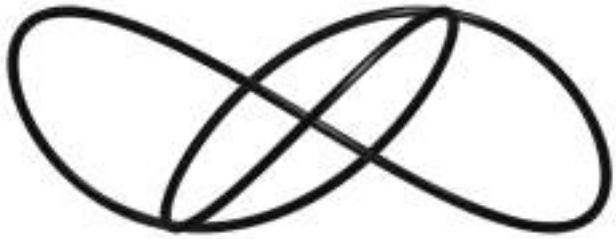


Figure 6: Knotted Torus

Theorem 22. *If M is a knotted 1-handlebody and the projection* $\pi : M \to M'$ *is obtained from the procedure above, then M is smooth if* $\mathrm{Im}(\pi)$ *is smooth.*

Proof. Consider the topological submanifold $M^1 = M' \times I$ for some closed interval I. If we consider the projection through the lens of a deformation retract, we can project M^n_g down to M' through I, taking a point $x \in M$ to $\pi(x)$ gradually by scaling the l-path between the two. Note that since we crush down M through the interval I to form M', the Cartesian product $M' \times I$ "builds back M" in a sense, gradually lifting it back to its initial height in the nth dimension. Locally, the open neighborhoods that resemble 1- handlebodies are rebuilt as described in the previous section, and this globally rebuilds the submanifold since this continuous transformation maintains connectedness. However, applying Lemma 7, we conclude that M_1 is a smooth submanifold with corners, and therefore isn't precisely M. We can remedy this by smoothing out the corners using homeomorphisms to retain the smooth boundary of M. Thus M_1 is homeomorphic to M. Applying Lemma 9, we have that M is smooth.

Using this theorem, we can use a similar inductive argument as given in the previous section to show that M is ultimately smooth. These properties underline a general algorithm that allows us to determine whether a submanifold of codimension 0 is smooth. However, there are limitations to this technique. In the next section, we attempt to create a more rigorous definition that can be generalized to higher codimensions.

3 Smooth Dependency

We now generalize the ideas introduced in the previous section into the case where the submanifold has a codimension greater than 0. To accomplish this, we begin by creating precise definitions that capture our intuitive notions of how these projections should act on the submanifold. Note that we stick to the case of dim $M \geq 3$, since when dim $M = 2$ and genus(M) > 0, these two-dimensional holes get projected down to one-dimensional holes which correspond to discontinuities.

Definition 23. We denote the projection of $x \in \mathrm{R}^n$ into R^{n-1} as $\Phi_{n-1}(x)$, defined by the submersion $\Phi_{n-1} : \mathrm{R}^n \to \mathrm{R}^{n-1}, (x_1, x_2, \ldots, x_{n-1}, x_n) \mapsto (x_1, x_2, \ldots, x_{n-1})$. In particular, if $V = \mathrm{R}^{n-1} \times \{0\}$, then $\Phi_{n-1}|_V$ is bijective and a smooth linear transformation whose inverse is similarly smooth, so it is a diffeomorphism.

Definition 24. Let M, M_1 be homotopic submanifolds with boundary satisfying dim M = dim $M_1 + 1$ and $M_1 \subset M$. If ∂M is smooth and nonempty, then M_1 is a smooth dependency of M if

there exists a projection map $\pi : M \to M_1$ satisfying the following properties:

1. If $\pi(p) = q \in \partial M_1$, then $p \in \partial M$. If $p_1 \in \text{Int}(M_1)$, then there exists $p_0 \in \text{Int}(M)$ such that $\pi(p_0) = p_1$.

2. For any $p_1 \in M_1$, there exists some open neighborhood $U_1 \subset M$, $U_1 \not\subseteq M_1$, $p_1 \in U_1$ and affine subspace $V \subset \mathrm{R}^n$ such that $\pi(U_1) = U_1 \cap V$.

3. For any $p \in \text{Int}(M)$, given an open neighborhood $U_1 \subset M$ of $\pi(p)$ and affine subspace V satisfying the previous condition on $\pi(p)$, if we choose coordinates such that $V = \mathrm{R}^{n-1} \times \{0\}$, then there exists some open $U \subset M$, $p \in U$ satisfying $U = (\Phi_{n-1}(\pi(U_1)) \times (c-\epsilon, c+\epsilon)) \cap M$ or for some positive reals $c, \epsilon > 0$. If this condition is satisfied for U, we say U satisfies the second condition of π along with U_1, V, c, and ϵ.

We denote the set of smooth dependencies of M as the set $\mathrm{Y}(M)$. Intuitively speaking, these are the submanifolds that we can project onto in order to maintain the topology of the initial submanifold. If $\pi : M \to M_1$ satisfies the above criteria, we say it satisfies the smooth dependency condition. We will now analyze important properties of the submanifolds in this set $\mathrm{Y}(M)$.

Lemma 25. *If $M_1 \in \mathrm{Y}(M)$ is smooth, then* Int(M) *is smooth.*

Proof. Let $\pi : M \to M_1$ satisfy the condition for smooth dependency. For any $p \in \text{Int}(M)$, choose an open neighborhood $U \subset M$, $p \in U$ and appropriate coordinates such that U satisfies the second property of π along with open neighborhood $U_1 \in M_1$, $\pi(p) \in U_1$, affine subspace $V = \mathrm{R}^{n-1}$, and constants $c, \epsilon > 0$. Note that since $\pi(U_1)$ inherits smooth structure from M_1 by Lemma 8, it is smooth. Thus $\Phi_{n-1}(\pi(U_1))$ is smooth because $\pi(U_1)$ is a subset of V, and $\Phi_{n-1}|_V$ is a diffeomorphism, and by Lemma 7 we can conclude that $U = \Phi_{n-1}(\pi(U_1)) \times (c-\epsilon, c+\epsilon)$ is smooth. Thus M is locally smooth at interior point p, which was arbitrary,
and thus Int(M) is smooth.

We will now give a very general argument about the smoothness of M at its boundary. This is a well-known approach that applies to higher codimensions and blends easily with our generalization of the projection ideas.

Theorem 26. *If $M_1 \in \mathrm{Y}(M)$ is smooth, then M is smooth.*

Proof. We have already shown that Int(M) is smooth under this hypothesis. We therefore show that M is smooth at the boundary. Recall that ∂M is smooth according to the conditions of smooth dependency. For any point $p \in \partial M$, let $U \subset \partial M$ be an open neighborhood of p diffeomorphic to D^{n-1} under the chart $\phi : U \to D^{n-1}$. Choose some arbitrary small $\epsilon > 0$, and consider the map $\Phi : U \times [0, \epsilon) \to D^{n-1} \times [0, \epsilon), (x, t) \mapsto (\phi(x), t)$. Note that since ϕ is a diffemorphism, we know that Φ must also be a diffeomorphism. Thus $U \times [0, \epsilon) = U' \subset M$ such that $U \tilde{} = D^n \times [0, \epsilon) \tilde{} = D^n_+$ so M is smooth at p. Since p was arbitrary, M
is smooth at all points in ∂M. Thus since M is smooth at both its interior and boundary, M is smooth.

This projection idea is a generalization of the techniques discussed in Section 3 that can now be applied to higher codimension submanifolds. Such a projection typically exists in more well-behaved submanifolds that don't have very chaotic intrinsic structures. The submanifold M_1

can often be constructed as a level set of a Morse function (see [Mil63] and [Fus]) on M. It is easy to verify that if $M_1 \in \mathrm{Y}(M)$ is ever not smooth, then M itself isn't smooth. Thus, by finding $M_1 \in \mathrm{Y}(M)$, contained in an affine subspace, just as we did in Section 2.2, we can reduce the difficulty of determining the smoothness of M to $(n-1)$ dimensions. Even if we are unable to ensure that M_1 is contained in a subspace, we know that locally it contains a flat set which is a very strong geometric condition, and often greatly decreases the difficulty of determining smoothness. This condition also greatly increases the chance that M_1 can be reduced through the same projection process.

4 Concludatory Remarks

4.1 Limitations of the Algorithm in Codimension 0

While there are obvious limitations to this algorithm in higher codimensions, such as submanifolds that don't have any smooth dependencies, we can also construct exotic codimension 0 cases in which the algorithm is inconclusive. Consider a 3-ball with a knotted tube carved into the inside and intersecting the boundary of the sphere (Figure 7). In this example, the hole formed by the tunnel impedes typical projections, so the problem of finding a surface to retract or project onto becomes very difficult. While the argument would likely work if a meaningful projection could be constructed, it is difficult to find a way to reduce the dimension of the initial surface while preserving the general structure of the submanifold. Therefore, the algorithm cannot be applied to this submanifold using the tools presented thus far.

4.2 Further Questions for Research

The ideas presented in the paper can likely be generalized further to be more suitable for complex cases. For example, when the codimension of the submanifold is greater than 0, the

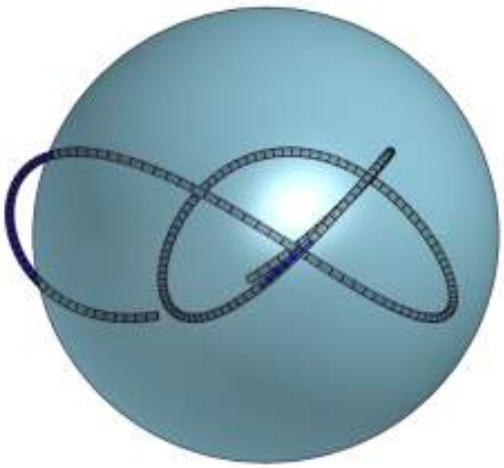


Figure 7: 3-Ball (Transparent Boundary) With Knotted Tunnel With Endpoints on Boundary and Flowing Outside Ball

projection and deformation retract ideas become less suitable because lines through the submanifold may only intersect the submanifold at finitely many points. Therefore, it is reasonable to consider other ways of carrying out this retraction, such as crushing down the submanifold about a curve instead of a line, or finding more general surjective maps that help reduce the dimension of such a submanifold. This new technique will also work well to address the limitations of the current algorithm in the codimension 0 case. The ideas presented in the paper can likely be generalized to abstract ambient space as well. When we leave Euclidean space, we are unable to now assign general coordinates to each of the points, which means that many of the arguments will need to change. The idea of topologically reducing the dimension of a submanifold using geometric techniques allows us to more easily determine its smoothness, and can likely generalize to more complex and abstract cases.

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Decision Making and Self-Advocacy in Locked-in Syndrome: An Analysis and Proposed Approach By Katerina Datsko

Abstract

Locked-in syndrome (LIS) is a rare neurological disorder characterized by significant loss of motor capabilities and limited means of communication. Due to the often poor physical prognosis of the disorder, LIS is typically accompanied by many serious decisions regarding future care, such as limitation of life-sustaining treatment. The limited communication methods which are available are often utilized to allow individuals to partially express themselves. Such limited yet available communication methods have pushed for the incorporation of individuals with LIS into decisions regarding their care and the overarching question of whether individuals have adequate cognitive skills to participate in such complex decisions. This review synthesizes current research on this topic to showcase the general understanding of decision making in individuals with LIS, ultimately highlighting the practical and ethical importance of supporting their self-advocacy. Additionally, a potential approach for self-advocacy in practice is proposed for future LIS cases with the consideration of cautionary factors. Findings of efficient cognitive and decision-making abilities in individuals with LIS, the development of various means of communication, and existing cases of patient self-advocacy further support the need for implementing self-advocacy practices in a more structured manner. Developing a deeper understanding of LIS and a stronger framework for patient self-advocacy in complex decisions is significant to the future of individuals with LIS, lending to efficient and virtuous care.

Key terms Locked-in syndrome (LIS), decision making, cognition, quality of life (QoL)

1. Introduction

Locked-in syndrome (LIS) is a rare neurological disorder which results from damage to the brain stem, more specifically a lesion to the ventral pons. LIS is most commonly due to ischemic causes, which are causes related to loss of blood flow leading to a lack of necessary nutrients being provided to the tissue affected, ultimately resulting in a stroke (Halan et al.). Less common causes include trauma, infections, and demyelinating diseases (Das et al.). A significant characteristic of LIS is quadriplegia, which occurs due to damage to the corticospinal circuits in the ventral pons (Maciejewicz). Paralysis of facial-glosso-pharyngo-laryngeal muscles and damage of the corticobulbar fibers result in anarthria. Due to the absence of such key functions, individuals with LIS typically experience a poor physical quality of life (QoL) and are limited in efficiently communicating with the outside world. The ability to produce eye and eyelid movements often remains intact due to the nucleus' location in the midbrain's rostral portion. This function allows for limited yet available means of communication for individuals with LIS (Halan et al.).

Though LIS definitions vary regarding the intensity of the disorder, it is widely recognized that the disorder involves preservation of full consciousness due to an intact reticular

activating system (Farr et al.). Consciousness preservation is the determining factor which separates LIS from similar conditions like a vegetative state, coma, or a minimally conscious state. Despite this clear differentiation, many individuals with LIS still face misdiagnosis. Due to a common lack of most conventional motor skills and responses, individuals with LIS often appear to be in an unconscious state (Maciejewicz). Many individuals are only diagnosed correctly approximately the middle of the second month since onset (León-Carrión et al.). Such unreliable diagnosis patterns imply that many individuals with LIS do not receive appropriate care for prolonged periods of time. This diagnostic challenge coupled with limited means of communication directly impacts the individual's ability to participate in their own care, bringing their capacity for decision making to the forefront of the ethical and clinical dilemma.

LIS is often associated with serious life-altering decisions, the most pressing one typically being the possible limitation of life-sustaining treatment (LST). Due to the demanding nature of decision making, individuals often have to rely on their cognitive abilities in order to come to coherent conclusions. Thus, particularly for individuals with LIS, having an up-to-par cognitive ability is crucial. Evaluations of the persistence of consciousness in individuals with LIS have propelled questions regarding their decision-making capabilities. To stay in accordance with patient autonomy, efforts arose to determine whether or not individuals with LIS are cognitively capable of deciding on their own care and how this self-advocacy process would look like.

Therefore, this review aims to provide an analysis of what is currently understood about the decision-making capacity and participation of individuals with LIS to ultimately synthesize a suggested approach for patient self-advocacy. A proper understanding of cognitive and mental capacities, communication methods, and the practice of including individuals in decisions regarding their care contributes to more solid approaches to current LIS cases as well as a brighter future for participation in decision making.

2. Assessing Cognitive Abilities: Are Individuals with Locked-in Syndrome Capable of Decision Making?

Retaining standard cognitive abilities is essential for individuals with LIS to make consistent decisions. Possessing an adequate level of consciousness alone does not necessarily imply that one can navigate complex situations or advocate for themselves. Both of these processes typically require cognitive abilities considered up to par with average standards.

Examination of the area of damage within the brain can indicate one’s cognitive ability. Cognitive deficiencies of individuals with LIS are often associated with lesions in areas beyond the brainstem. Conversely, in typical cases of locked-in syndrome in which most damage occurs in the brainstem alone, cognition is typically preserved (Maiser et al.). The reticular formation is often left intact, lending to the preservation of mental integrity (Maciejewicz). One study conducted on numerous individuals with LIS displayed that 86% of participants had adequate attention, 97.6% were temporally oriented and 76.7% had reading abilities, further demonstrating the persistent preservation of key cognitive abilities (León-Carrión et al.). Testing through the

use of functional MRIs has provided further confirmation by displaying normal cognitive activity in numerous individuals with LIS (Halan et al.).

Individuals with LIS have generally been shown to maintain at least some cognitive abilities necessary for taking standpoints on certain decisions through various forms of testing, meaning that efficient decision making of at least a portion of those with LIS is possible.

3. Means of Communication

Self-advocacy of LIS patients is made achievable with developed means of communication. Preserved vertical eye movement is the key function enabling communication for individuals with LIS, allowing them to utilize eye movements to answer given questions. Patients, caregivers, and their clinicians could develop eye-movement codes designating specific answers (Maciejewicz). Many individuals have shown ability to significantly enhance their communication skills over time, with one study concluding that 73% of its participants were able to improve functional movements essential to communication after continuous practice (Lugo et al.).

Assistive tools and technologies can be significantly helpful if applicable. Such communication methods include electronic devices (e.g. tablets), voice output devices, and letter boards (Voity et al.). Though communication is largely limited for those with LIS when compared to non-disabled individuals, individuals have proved to possess adequate communicative abilities. In one study, all participants were able to communicate through yes/no responses and 62% successfully used assisting technology (Lugo et al.). Whether it is complex or simple yes/no communication, a majority of individuals with LIS continuously display that they could at least minimally express their standings on certain decisions making patient self advocacy achievable.

4. Addressing External Factors Impacting Decision Making

External factors and third parties can largely influence an individual's decisions on future care. In some cases, such external influences violate standard ethics regarding freedom of choice.

4.1. Misinterpretations of Overall Quality of Life: The Disability Paradox

One influential external factor stems from the disability paradox: a thought process of non-disabled people in which it is assumed that people with physical disabilities exhibit a poor overall QoL. Individuals with this thought process typically support the limitation of LST as a means of alleviation from what they believe is an unsatisfactory lifestyle, possibly leading to expectations for individuals with LIS to vote in favor of limiting LST. Conversely, it's been proven through numerous studies that individuals with LIS display much higher levels of mental QoL than expected and typically do not request limitation of LST, confirming that the disability paradox involves a false consensus. Individuals with LIS have repeatedly displayed a mental QoL consistent with that of healthy individuals and studies typically do not see a relevant enough correlation between extent of physical disability and levels of depression (Maiser et al.). One

study involving individuals with LIS found that the majority of participants reported happiness and only 7% wished for euthanasia (Bruno et al.). Another study which included individuals with a wider range of physical disabilities found that around half of participants reported a good QoL (Albrecht and Devleiger).

Furthermore, physical QoL has the possibility to improve. One study on the physical advancements of individuals with LIS found that 21% of those assessed gained motor recovery, 42% gained complete swallow recovery, 35% gained effective bladder/bowel control, and 50% gained good breathing patterns (Casanova et al.). Even with poor physical prognoses and largely unknown long-term treatments, it is essential to actively pursue all possible improvements in the physical and mental conditions of individuals with LIS.

4.2. Possible Clinician Bias

Clinicians can have a significant impact on decision outcomes. In a survey examining German clinicians' understanding of the LIS condition, it was found that participating clinicians generally agreed that individuals with LIS display consciousness, self-awareness, emotion, name recognition abilities, person recognition abilities, remembrance of experiences, ability to store new information, and more. However, despite considering such factors, many participants of this study showed attitudes of limiting LST for those with LIS in some circumstances (Kuehlmeyer et al.). These attitudes, along with the disability paradox, can have unintended consequences by implicitly influencing clinicians to provide insufficient care or pressure individuals with LIS and their families into conclusions that do not reflect their true standpoints. Thus, it is important that clinicians not only understand patients' cognitive states and consciousness levels but also respect and support patient autonomy despite their own medical perspectives.

4.3. Misinterpretations of Lifespan

Contrary to the common perception that individuals with LIS are near death, many are able to live for numerous years after onset, and some individuals have displayed a high 10-year survival rate (Yan et al.). Inaccurate expectations about life expectancy can cause individuals with LIS to refuse potentially beneficial treatments. It is therefore crucial for individuals with LIS to be fully aware of their actual prognosis and lifespan. One survey's findings demonstrated that neurologists who had knowledge of the long life expectancy of individuals with LIS typically voted against limiting LST, implying that having accurate knowledge of average lifespan could alter one's opinion on the limitation of LST and therefore should be considered as an influential factor (Yan et al.).

4.4. Social and Cultural Environments

Furthermore, one's social or cultural environment can shape their ultimate decisions on future care.

Familial relationships are typically taken into careful consideration by individuals. Especially in collectivist cultures, familial and group identities are often prioritized over

individualistic identities. In such environments, many of those with LIS could fear becoming financial burdens to their families due to the costly nature of medical care. Additionally, since individuals with LIS tend to be largely dependent on others to carry out daily tasks, they could experience feelings of guilt for 'forcing' their relatives to engage in the physically and emotionally demanding task of caretaking. For these reasons, individuals with LIS could be more susceptible to vote in favor of limiting LST. On the other hand, some cultures uphold values of offering respect and help for family members in need. In China, for example, the old yet still prevalent cultural ideal of filial piety could influence younger family members to support LST and be willing to take on the responsibility of caregiving (Yan et al.).

It is important to keep in mind that not all of such environmental factors are necessarily harmful. Cultural and environmentally-influenced values could largely be aligned with the personal beliefs of the individual regarding their current state and future care, leading to a harmonious decision-making process. Nonetheless, it is important that the individual is committed to their decision on their goals of care rather than simply abiding by external pressures to achieve social desirability.

5. Addressing Complexities of Patient Decision-Making Participation

5.1. Further Cognitive Impairments

Despite many individuals with LIS demonstrating solid decision-making capabilities, the extent of cognition and decision-making ability can vary on a case by case basis. Some individuals with LIS experience more substantial brain damage than others, often impairing cognitive abilities which may ultimately limit their decision-making capacity (Halan et al.). One study found that 18.6% of its participants had impairments in memory (León-Carrión et al.), and another study concluded that half of its participants displayed deficits in one or several cognitive functions (Schnakers et al.). Others reportedly had impairments in attention and executive function (Halan et al.). Still, the fact that many of those with LIS do retain decision-making capacity shows the importance of an accurate understanding of their capabilities so that those who are capable of participating are offered the opportunity to do so.

5.2. Limited and Unavailable Means of Communication

The communication methods that are currently available for individuals with LIS are largely dependent on intact eye movement ability. Such communication allows individuals to advocate for themselves and express their opinions on certain decisions. In cases of complete LIS, individuals entirely lack the ability to produce eye movements. Others face opsoclonus-myoclonus syndrome involving involuntary movement of the eyes, which could lead to inconsistent signaling and a lack of an established code system (Halan et al.). Such impairments prevent individuals from achieving effective communication and create a barrier to decision making. In such cases, consideration of the individual's opinions may not be possible due to the individual's inability to express such opinions. Current research aims to develop a

means of communication for individuals with complete LIS by utilizing their preserved sense of smell, but communication methods for such individuals remain largely unknown and underdeveloped (Maciejewicz). For cases of opsoclonus-myoclonus, gabapentin has shown favorable results, though barriers in communication could still exist (Halan et al.).

5.3. Case Example of Patient Self-Advocacy in Locked-in Syndrome

One case concerning a fifty-four-year-old man who had recently received an LIS diagnosis specifically highlighted the practice of decision making and patient self-advocacy. After the individual became quadriplegic as a result of developing LIS, the choice to limit LST was brought up to the individual's family due to his poor prognosis and physical QoL. Once given time to adapt to his new situation, the individual's decision-making capacity was assessed with a series of tests targeting various cognitive functions. Factors like cognition, orientation, anterograde memory, understanding of medical history and current medical situation, recall, and language comprehension were all assessed. Testing methods like asking multiple-choice and yes/no questions, providing word lists, and using the inverse of questions were all utilized. Test results showed that the individual could feel aroused and alert, encode and remember new information, understand basic given information, communicate through eye movements, agree to life-prolonging treatments, and overall demonstrate strong cognitive capabilities. The individual furthermore identified a surrogate which helped in future decision making (Maciejewicz). The case displays that an individual with LIS can successfully take part in decisions regarding their care to an extent and highlights the ethical importance of the practice of patient self-advocacy.

6. Synthesis Matrix of Key Studies

The following table summarizes the findings of key studies used in the review.

Table 1: Summary of Key Studies on Quality of Life and Outcomes in Locked-in Syndrome

Study	General Participant Characteristics	Study Method(s)/Procedure(s)	Finding(s)
Albrecht and Devlieger (1999)	153 people with disabilities	Semi-structured interviews	54.3% of participants reported having an excellent or good QoL.
Bruno et al. (2011)	65 members of the French Association for LIS	Questionnaire	47 patients stated a presence of happiness; 7% of those assessed wished for euthenasia.
Casanova et al. (2003)	14 individuals with LIS who went through the same treatment and as a	Sample and follow up for 5 months to 6 years	21% of those assessed showed significant recovery from 3-6 months after original diagnosis, 42% had complete swallow recovery, 28% improved verbal communication, 42% could communicate through

	result recovered		devices, 35% gained effective bowel/bladder control, and 50% attained good breathing patterns.
Kuehlmeyer et al. (2012)	503 German neurologists	Vignette-based online survey	86% of respondents chose the correct diagnostic category. German neurologists generally showed adequate knowledge on the capabilities of those with LIS based on their responses: awareness of oneself (94%), awareness of surroundings (94%), demonstration of emotion (93%), name recognition abilities (92%), person recognition abilities (95%), ability of remembering experiences (90%), and ability of storing new information (85%).
León-Carrión et al. (2002)	44 individuals with LIS who were members of the Association of Locked-in Syndrome in France	Survey	86% of those assessed had a good attention level, 97.6% were temporally oriented, 76.7% could read, and 18.6% reported memory problems. Correct diagnosis was typically made in the middle of the second month after onset (mean of 78.76 days).
Lugo et al. (2015)	88 individuals (members of the French Association of Locked-in syndrome)	Questionnaire	62% used eye communication with or without assistant technology and 73% improved functional movements over the span of a few years.
Maiser et al. (2016)	54 year old man diagnosed with LIS after a drug overdose	Case study testing a decision-making framework	The individual was found to possess cognitive abilities, feel aroused and alert, encode and remember new information, understand basic given information, communicate through eye movements, designate a surrogate, and agree to life-prolonging treatments.
Schnakers et al. (2008)	10 chronic LIS survivors	Neuropsychological testing based on eye-coded communication	None of the individuals had alterations in verbal intelligence. Half of those assessed had impairments in one or more tests.

7. Proposed Approach to Patient Decision Making and Self-Advocacy

Providing the individual with time before any testing or life-altering decisions are made is crucial. Individuals could possibly display a different attitude regarding their QoL once given time to adjust to their new physical state and may reconsider previous life-altering decisions such as limiting LST (Kuehlmeyer et al.). Moreover, individuals have been shown to recover intact cognitive abilities over time (Schnakers et al.) and some individuals started off in a comatose state before gaining consciousness (Das et al.). Thus, rushing conclusions regarding goals of care can be an ethical violation.

To ensure the autonomy of individuals with LIS, it is crucial to assess their decision-making abilities through rigorous neuropsychological testing. Such testing provides an accurate assessment of decision-making abilities, avoiding misinterpretation of cognitive states. Means of communication such as eye-coded communication could be utilized in such testing (Maiser et al.). Functional MRIs are another useful tool which allow clinicians to view individuals' cognitive activities and compare them to those of non-disabled individuals (Halan et al.). Both cognition and decision making should be assessed with the intent of attempting to consider and include the individual's opinions.

It is important that individuals are supported throughout the entirety of this process. It is crucial to include thorough explanations of complex medical decisions (e.g. the implementation of gastrostomy tubes) so that individuals can understand what they are complying with. Awareness of consequences is essential in the decision-making process and thus must be considered. Respecting the decision of keeping LST should also be accompanied with respect for those who refuse LST. Individuals should be allowed to make partial decisions if the dilemma is complex and choose a surrogate to make decisions for them. Support in the decision-making process such as from a guardian or a loved one should also be provided if the individual desires. Means of communication should be outlined with individuals to find the most compatible option for their advocacy. Attempts to recognize and minimize harmful external factors of decision-making outcomes should be made to ensure the accuracy of the individual's decision.

If possible, psychological and spiritual assessments should be implemented by mental health providers or other hospital administrators to better understand the individual. Further support such as through various forms of therapy could help facilitate the process and improve communication methods. Individuals should also be evaluated more than once in order to assess if changes in decisions occurred. This is especially important when new pieces of information are uncovered or if clinical changes happen. This way, all decisions would be up to date, accurate, and relevant to the current situation.

Concrete decision-making guidelines remain underdeveloped due to the rare nature of LIS. Nonetheless, with further implementation of existing methods for evaluating cognitive and decision-making abilities, along with the development of a more detailed care approach, the future of LIS individuals' autonomy could be significantly enhanced.

8. Conclusion

This review analyzed current research on the capacity for autonomous decision making and self-advocacy of individuals with LIS. Factors such as the cognitive and decision-making abilities consistently displayed by individuals with LIS, along with general ethical concerns, highlight the importance of implementing a comprehensive care plan for individuals with LIS which stays in accordance with patient autonomy. Means of communication allow for the practice of patient self-advocacy and further emphasize the importance of supporting this practice. Previous cases of LIS have shown successful implementation of patient self-advocacy practices and stress the need for a more widespread use of such practices.

A suggested approach was synthesized with the goal of improving existing guidelines on the practice of incorporating individuals' opinions into their care. The approach aims to integrate testing with the consideration of external pressures and general precautions. Current guidelines are typically sporadic. A larger, more general framework could prove efficient in helping clinicians proceed in a more respectful manner towards their patient earlier on in their care.

Guidelines for LIS care are frequently underdeveloped due to the rarity and complexity of the disorder. Different cases of LIS result in varied precautions and approaches to care, leading to LIS being perceived as a complex topic. Nonetheless, a body of research is emerging. Findings highlight the critical need for standardized, unbiased capacity assessments for individuals with LIS and the ethical importance of utilizing this process. Gaining a deeper understanding of LIS and adapting a general approach that is more interactive could prove to be beneficial to the future of LIS care.

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Gender Bias and Context in AI-Driven Hate Speech Detection: A Comparative Study of Large Language Models By Anshika Paliwal

Abstract

Hate speech detection datasets depend heavily on human annotators who manually label content, yet the demographic characteristics of these annotators may influence labeling outcomes. As automated content moderation systems increasingly employ large language models (LLMs) for hate speech detection, understanding how demographic context affects AI decision-making is critical to ensuring fairness and reliability. This study systematically investigates whether providing annotator gender information introduces bias into hate speech classifications produced by three widely used LLMs: Groq's Llama-3.1-8b-instant, OpenAI's GPT-3.5-turbo, and Anthropic's Claude-3-haiku. Using the *Measuring Hate Speech Corpus* (135,556 annotations), we evaluate model performance under two prompting conditions: gender-blind (content only) and gender-informed (content plus annotator gender).

Results indicate that while all models achieve high accuracy (>94%) on explicitly hateful content, they perform poorly on neutral material (5–13% accuracy), exhibiting a strong tendency to overclassify ambiguous content as hateful. Crucially, the inclusion of annotator gender information consistently reduces classification accuracy, with Anthropic's model showing a 13-percentage-point decline for hateful content. Introducing gender context also leads to notable instability, with consistency rates dropping to 10–20% across certain model–content combinations.

Most importantly, we observe a systematic out-group bias across all models: when the annotator's gender differs from the target's gender, content is more likely to be classified leniently compared to gender-matched cases. The magnitude of this bias, defined as the difference in mean classification accuracy between matched and mismatched gender conditions, reaches up to 0.14 for supportive content. This differential treatment emerges without any corresponding gains in overall accuracy, demonstrating that demographic context introduces systematic inequities rather than improving model performance. These findings challenge the assumption that demographic context enhances AI interpretability and highlight the need for rigorous demographic bias auditing in LLM-based content moderation systems.

Introduction

Detection of hate speech is a complex issue in the context of natural language processing, and automated systems are increasingly being deployed on social networks to detect and moderate objectionable content (Fortuna & Nunes, 2018; Schmidt & Wiegand, 2017). With the increasing prevalence of artificial intelligence technologies, particularly large language models (LLMs), across the content moderation domain, it becomes critical to understand their potential biases in order to ensure fair and balanced automated systems (Vidgen et al., 2019; Sap et al., 2019).

Hate speech, broadly defined as language that targets individuals or groups based on protected characteristics such as race, religion, gender, sexual orientation, or ethnicity (Warner & Hirschberg, 2012; Davidson et al., 2017), presents inherent challenges for both human and automated detection systems. The subjective nature of what constitutes hate speech means that classification relies heavily on annotators—individuals who label content as hateful, neutral, or supportive to create training datasets for machine learning models (Waseem, 2016; Ross et al., 2017). These human annotators serve as the foundation for supervised learning approaches, yet their judgments are inevitably shaped by personal experiences, cultural backgrounds, and social identities (Sap et al., 2022; Aroyo & Welty, 2015). Understanding annotator perspectives is essential because the labels they provide become the ground truth against which AI systems learn to classify content, making annotator bias a fundamental concern in developing fair hate speech detection systems (Geva et al., 2019; Prabhakaran et al., 2021).

The traditional body of work has focused primarily on biases introduced by human annotators in hate speech detection tasks (Waseem & Hovy, 2016; Sap et al., 2019; Binns et al., 2017). Research has documented how annotator demographics, including gender, race, age, and political ideology, systematically influence hate speech judgments (Sap et al., 2022; Prabhakaran et al., 2021; Wich et al., 2020). However, there is a growing need to examine how AI systems themselves might exhibit bias, especially when provided with demographic information about human annotators. This shift in focus is particularly urgent given that content moderation platforms increasingly rely on automated systems that may incorporate user or annotator characteristics in their decision-making processes (Gorwa et al., 2020; Gillespie, 2018).

Recent studies have begun to illuminate the complex relationship between AI systems and bias in classification tasks. Das et al. (2024) discovered that LLMs show stark annotator bias when asked to adopt varied demographic personas, posting mismatch rates between 2-12% based on bias type and model. This finding suggests that AI systems may not only learn biases from training data distributions but also develop systematic biases when demographic information is intentionally incorporated into prompts. The consequences of this are profound for content moderation systems that may incorporate user demographic details in decision-making processes (Dodge et al., 2021; Blodgett et al., 2020).

The advent of large language models has introduced new questions about bias propagation and amplification in automated systems. Unlike human annotators whose biases stem from personal experience and social identities, AI patterns of bias can arise from training data distributions, prompt engineering influences, or intrinsic model architectures (Sap et al., 2022; Bender et al., 2021; Weidinger et al., 2021). Comprehending how AI systems react to demographic cues, especially gender information, is crucial for building more balanced hate speech detection systems that do not systematically discriminate against groups or reproduce harmful stereotypes (Dixon et al., 2018; Borkan et al., 2019). The literature reveals that gender represents one of the most salient demographic categories in hate speech contexts, with documented differences in how content targeting women versus men is perceived and classified (Waseem & Hovy, 2016; Guest et al., 2021).

Previous work investigating AI bias in hate speech detection has been constrained by small-scale experiments and narrow considerations of demography (Wich et al., 2020; Fortuna et al., 2020). Much of the existing research has concentrated on accuracy measures instead of systematic bias effects, leaving important gaps in understanding how AI decision processes are influenced by demographic information (Gorwa et al., 2020; Vidgen & Derczynski, 2020). Additionally, there has been insufficient examination of how AI systems might change their labeling behavior when provided with annotator demographic context versus making classifications based solely on content (Röttger et al., 2021; Davani et al., 2021). Furthermore, limited attention has been paid to the interaction between annotator characteristics and target group identities, whether AI systems exhibit in-group versus out-group biases similar to human annotators (Sap et al., 2022).

This research addresses these gaps by conducting a systematic analysis of AI bias in hate speech detection, with particular focus on how gender information affects large language model classifications. We investigate whether pre-trained LLMs exhibit differential labeling patterns when provided with annotator gender information compared to content-only classifications. Our study examines two key research questions:

(1) Do LLMs change their hate speech classifications when provided with annotator gender information, and do classification patterns differ based on whether the annotator gender matches the target gender (in-group) versus differs from the target gender (out-group)?

(2) What patterns of gender-related bias emerge in AI hate speech detection systems, and how does the accuracy of AI classifications compare when gender context is provided versus withheld?

By focusing specifically on gender effects and examining both annotator-target dynamics, we aim to understand whether providing demographic context introduces systematic bias into AI classification systems used for content moderation.

Dataset

Our study employs the Measuring Hate Speech Corpus, a large dataset created by Kennedy et al. (2020) and Sachdeva et al. (2022) for hate speech detection studies. This publicly released dataset is one of the largest and most demographically diverse annotation efforts within the hate speech detection space, comprising 39,565 social media posts annotated by 7,912 different annotators, for a total of 135,556 annotation instances. The dataset was built expressly to overcome limitations of current hate speech corpora by including rich demographic data for annotators as well as hate speech targets, which allow systematic examination of patterns of bias in annotation behavior.

The dataset includes social media posts gathered from several platforms, with each post being annotated along ten different dimensions of potentially offensive content. These categories encompass sentiment, respect, insult, humiliation, status degradation, dehumanization, violence, genocide, attack vs. defense framing, and overall hate speech categorization. Instead of depending upon binary or categorical classification, the data utilizes ordinal scales which are

then merged based on Item Response Theory (IRT) to yield a continuous hate speech score from about -3 to +4, with scores greater than 0.5 as hate speech, scores less than -1 as counter-speech or supportive content, and values in between as neutral or uncertain content.

One of the notable strengths of the Measuring Hate Speech Corpus is its rich demographic coverage for annotators and hate speech targets. The dataset provides rich annotator demographic data across six main categories: political ideology, income, education level, age, racial/ethnic background, and gender identity, with 40 distinct demographic subgroups covered. Also, the dataset follows hate speech targets over eight identity categories (race/ethnicity, religion, national origin/citizenship, gender, sexual orientation, age, disability status, and political ideology) that include 42 target subgroups. The large demographic coverage makes it possible to study how annotator attributes combine with target group identities to shape perceptions of and labeling for hate speech, filling an important omission in earlier work that often considered annotator or target demographics independently.

For this study, we focus specifically on annotator gender and target gender dimensions from the dataset, along with the textual content of social media posts. We concentrate on gender-related variables because gender represents one of the most salient demographic categories in hate speech contexts and allows for clear examination of potential bias effects in AI systems. The gender focus enables us to investigate whether AI models demonstrate differential sensitivity to content when provided with gender context, and whether such information introduces systematic bias into classification decisions. By examining both annotator gender and target gender, we can explore how these intersecting identities might influence AI labeling behavior in ways that parallel or differ from documented human annotator bias patterns.

Methodology

Our experimental approach involves systematically comparing the classification behavior of pre-trained large language models under two distinct prompting conditions: gender-blind classification and gender-informed classification. We employ three LLMs to ensure robustness of findings across different model architectures and API providers: Groq's Llama-3.1-8b-instant, OpenAI's GPT-3.5-turbo, and Anthropic's Claude-3-haiku. These models were selected to represent diverse approaches to language understanding while maintaining cost-effectiveness for large-scale analysis, as we prioritize breadth of comparison over individual model performance (Chiang et al., 2024; Liang et al., 2022).

We implement a dual-prompt experimental design where each social media post from the dataset receives two separate classifications from each model. The first classification uses a gender-blind prompt that asks models to "Classify the following text as exactly one of: 'Hateful', 'Neutral', or 'Supportive'" followed by the text content. The second classification employs a gender-informed prompt that begins with "You are a [male/female] annotator" before presenting the same classification task and text content. This direct comparison methodology allows us to isolate the effect of gender context on AI classification decisions while keeping all other variables constant.

Our prompting strategy deliberately uses minimal, structured prompts to reduce confounding effects from extensive prompt engineering (Reynolds & McDonell, 2021). We request single-word responses to ensure consistent output formatting across models and limit token usage for cost efficiency. The gender-informed prompts specifically frame the demographic information as an annotator identity ("You are a [gender] annotator") rather than asking about target demographics or providing extensive context, focusing our analysis on how AI systems respond to annotator demographic cues.

We develop a custom asynchronous processing system to handle the large-scale API interactions required for this analysis. The system processes data in batches of five samples to balance processing efficiency with API rate limits, implementing conservative delays between requests to minimize costs and avoid rate limiting. Each model processes both prompt conditions for every text sample in sequence, with all raw API responses and cleaned classifications recorded for subsequent analysis. Our implementation includes robust error handling and progressive saving functionality to ensure data integrity throughout the extended processing period.

Our analysis framework examines three primary dimensions of model behavior. First, we measure classification accuracy by comparing AI predictions against human annotations from the original dataset, calculating accuracy rates for both prompt conditions across all models. Second, we quantify classification consistency by identifying instances where models change their predictions between gender-blind and gender-informed conditions, tracking both the frequency and direction of these changes. Third, we analyze bias patterns by examining whether classification changes correlate with annotator gender, target gender, or content characteristics, looking for systematic differences in how models respond to male versus female annotator contexts (Sap et al., 2022).

Sample Selection and Composition

For this study, we extracted a stratified sample of 776 social media posts from the Measuring Hate Speech Corpus based on annotator gender and target gender combinations. Our sampling strategy aimed to achieve balanced representation across nine gender-pair categories: Male annotator-Male target (M-M), Male-Female (M-F), Male-Nonbinary (M-NB), Female-Male (F-M), Female-Female (F-F), Female-Nonbinary (F-NB), Nonbinary-Male (NB-M), Nonbinary-Female (NB-F), and Nonbinary-Nonbinary (NB-NB). We targeted 100 samples per category where available, though some categories contained fewer available instances in the original corpus, resulting in our final sample of 776 annotations.

The continuous hate speech scores from the original dataset (ranging from approximately -3 to +4) were converted into three discrete categories using the thresholds established by Kennedy et al. (2020): scores greater than 0.5 were classified as "Hateful," scores less than -1 as "Supportive," and values between -1 and 0.5 as "Neutral." This categorization scheme maintains consistency with the original dataset's intended interpretation while enabling straightforward classification comparisons across models.

Our stratified sampling approach ensures adequate representation of both same-gender pairs (where annotator and target share the same gender identity) and cross-gender pairs (where they differ), allowing systematic examination of in-group versus out-group bias patterns. While this sample represents approximately 0.6% of the full corpus, the balanced design across demographic categories provides sufficient statistical power to detect meaningful differences in model behavior across gender contexts.

We track both raw API responses and cleaned classifications to enable analysis of model confidence and response patterns. The experimental design generates two classifications per text sample per model, creating a comprehensive dataset for statistical comparison of gender effects across different AI systems.

Statistical Analysis

To evaluate the impact of gender information on model predictions, we employ several statistical measures. Classification accuracy is calculated as the proportion of correct predictions for each content label (Hateful, Neutral, Supportive) under both No Gender and Gendered conditions.

We introduce a consistency metric to quantify prediction stability across prompting conditions. Consistency rate measures the proportion of instances where a model produces identical predictions under No Gender and Gendered conditions. For each model and content type, consistency is calculated as the number of matching predictions divided by total predictions. High consistency (>80%) indicates that gender information has minimal influence on classification decisions, while low consistency (<50%) suggests substantial sensitivity to gender context.

To examine differential treatment of social groups, we calculate bias magnitude as the absolute difference in accuracy between in-group and out-group content. In-group refers to instances where the annotator gender matches the target gender, while out-group denotes mismatched gender pairs. Given our single-run experimental design, we focus on descriptive patterns and effect sizes rather than formal significance testing. The magnitude and consistency of observed differences across multiple models and content types provide evidence for systematic bias patterns.

Results and Discussion

Our experimental analysis reveals significant patterns in how large language models respond to gender context when performing hate speech classification. We structure our findings around three key dimensions: overall classification performance, the specific impact of gender context on accuracy, and systematic bias patterns that emerge when demographic information is provided. Together, these analyses address our central research questions about whether and how gender information influences AI hate speech detection systems.

Overall Classification Performance

The accuracy metrics reported throughout this analysis represent the proportion of model predictions that match the ground truth labels derived from human annotations in the original dataset. These ground truth labels reflect aggregated judgments from multiple human annotators whose ratings were combined using Item Response Theory to produce consensus classifications. When we report that a model achieves 0.94 accuracy on hateful content, this indicates the model's predictions align with these human-derived labels 94% of the time. However, our analysis does not separately examine whether human annotators themselves showed gender-based bias patterns when labeling content. The original Measuring Hate Speech Corpus documented annotator demographic information precisely to enable such analyses, but investigating human annotator bias patterns falls outside the scope of this study, which focuses specifically on how AI systems respond when provided with annotator gender context.

We begin by examining baseline performance to establish how well each model performs hate speech classification before considering gender effects. The three models evaluated (Groq's Llama-3.1-8b-instant, OpenAI's GPT-3.5-turbo, and Anthropic's Claude-3-haiku) demonstrated markedly different performance profiles across the three content categories: hateful, neutral, and supportive.

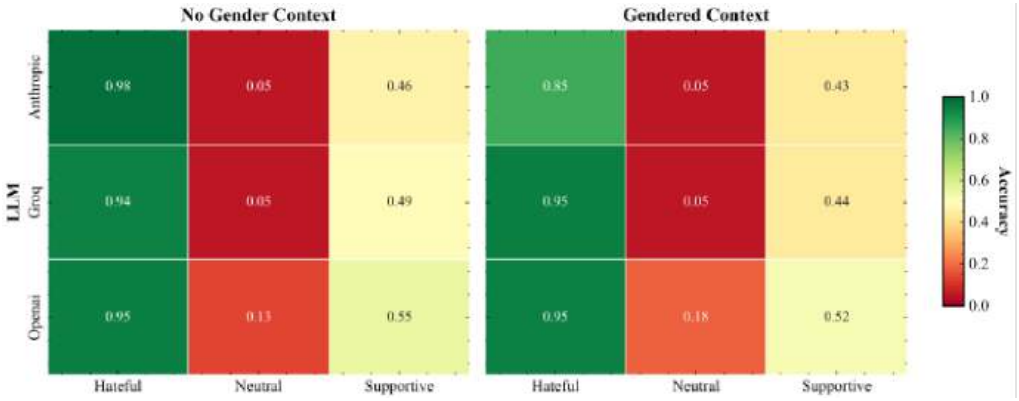


Figure 1: Heat Map showing gender vs no gender context

As shown in the heat maps and line graph in Figure 1, all three models achieved exceptionally high accuracy when classifying hateful content in the gender-blind condition, with performance exceeding 0.94. Anthropic demonstrated the strongest performance at 0.98 accuracy for hateful content without gender context, followed closely by Groq at 0.94 and OpenAI at 0.95. The line graph reveals a characteristic V-shaped accuracy pattern across all models with high accuracy for hateful content, minimal accuracy for neutral content, and moderate accuracy for supportive content.

This high performance on hateful content stands in stark contrast to the models' struggles with neutral content classification. Accuracy rates for neutral content ranged from a mere 0.05 to 0.13, indicating that models predominantly misclassified neutral content as either hateful or supportive. OpenAI showed slightly better performance at 0.13 accuracy, though this still represents a failure rate exceeding 85%. Supportive content classification achieved moderate

accuracy levels between 0.46 and 0.55, with OpenAI performing best (0.55) and Anthropic weakest (0.46).

To understand where these classification errors occur, we examined detailed confusion matrices for each model.

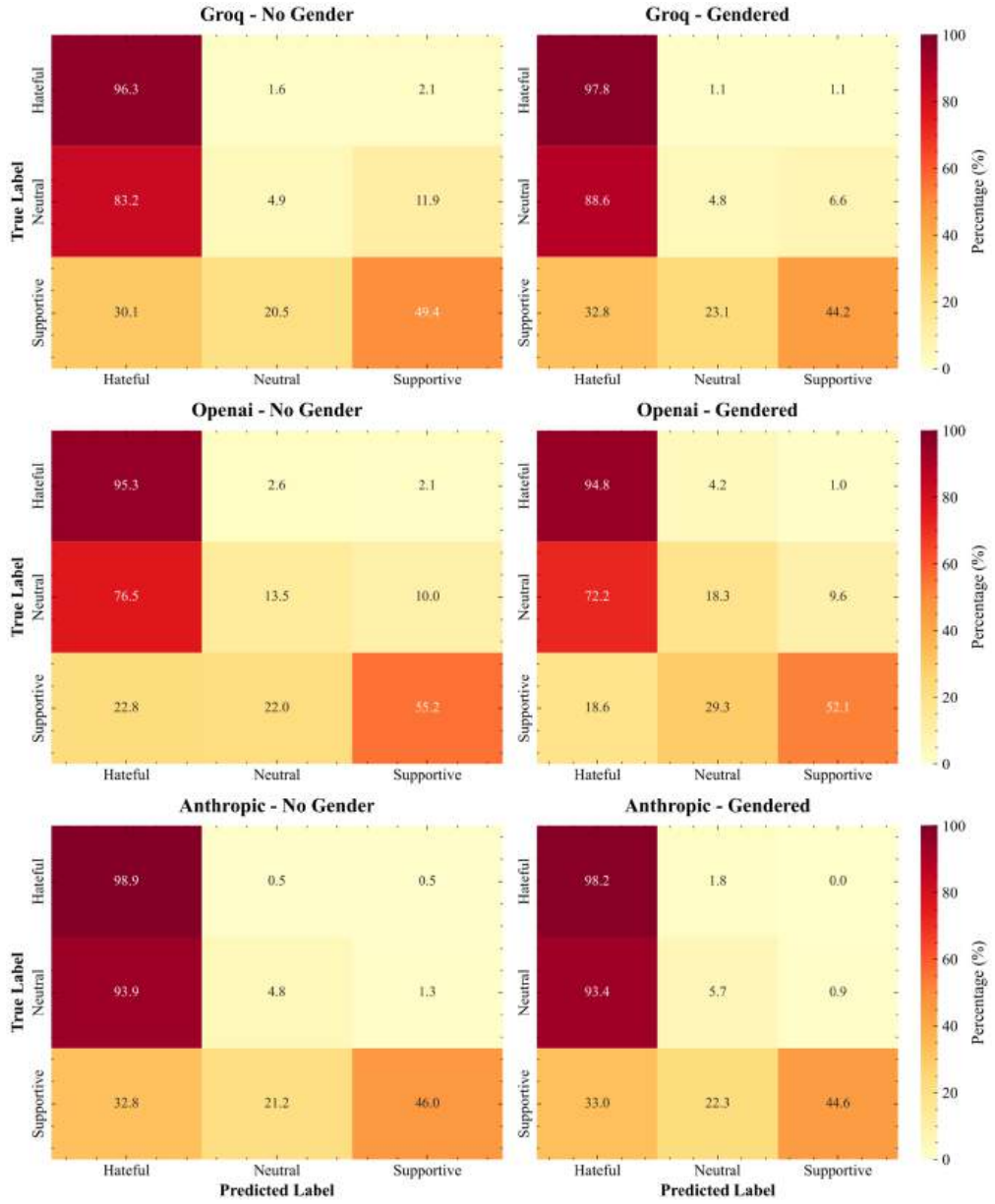


Figure 2: Confusion Matrix showing gender context across all LLMs

The confusion matrices in Figure 2 reveal the specific patterns of misclassification. For Groq under the no-gender condition, hateful content was correctly classified 96.3% of the time, with minimal misclassification. However, neutral content showed catastrophic performance with only 4.9% correctly classified, while 83.2% was incorrectly labeled as hateful. This pattern of aggressively over-classifying ambiguous content as hateful appears consistently across all three models, though with varying intensity.

OpenAI's matrices show similar directional patterns but with slightly better neutral content handling (13.5% accuracy versus Groq's 4.9%). Anthropic demonstrated the most extreme behavior, achieving 98.9% accuracy for hateful content but misclassifying 93.9% of neutral content as hateful. These patterns establish that all models exhibit a strong default bias toward classifying ambiguous content as hateful, likely reflecting training approaches that prioritize avoiding false negatives (missing actual hate speech) at the expense of false positives.

Impact of Gender Context on Classification Accuracy

Having established baseline performance, we now examine our first research question: Do LLMs change their hate speech classifications when provided with annotator gender information? The answer is clearly yes, though the magnitude and direction of changes vary substantially by model and content type.

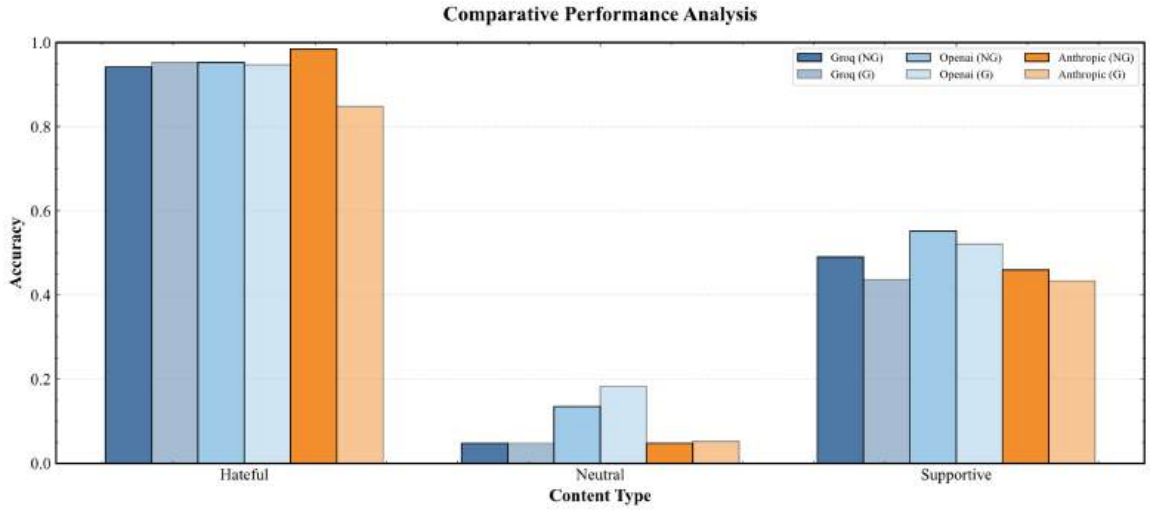


Figure 3: Bar Graph showcasing comparative performance across LLMs and content types

Figure 3 provides a direct comparison of accuracy across both prompting conditions. For hateful content, the addition of gender context generally resulted in accuracy reductions, though effects varied by model. Groq maintained relatively stable performance with minimal change, while Anthropic experienced a substantial 13 percentage point decline from 0.98 to 0.85 accuracy. This significant drop suggests that Anthropic's model is considerably more sensitive to demographic context in ways that interfere with content-based classification.

The impact on neutral content classification proved more variable but generally showed slight improvements. OpenAI demonstrated a meaningful increase from 0.13 to 0.18 accuracy when gender was included, representing the largest positive effect we observed. However, absolute performance remained poor, as even the improved performance means the model still misclassifies over 80% of neutral content. Groq and Anthropic showed minimal changes in neutral content accuracy, maintaining their poor performance regardless of gender context.

Supportive content classification showed modest declines across most models when gender context was introduced. OpenAI decreased from 0.55 to 0.52 accuracy, Anthropic from 0.46 to 0.43, while Groq remained essentially stable at 0.49. These patterns indicate that gender context does not systematically improve classification accuracy and frequently degrades it.

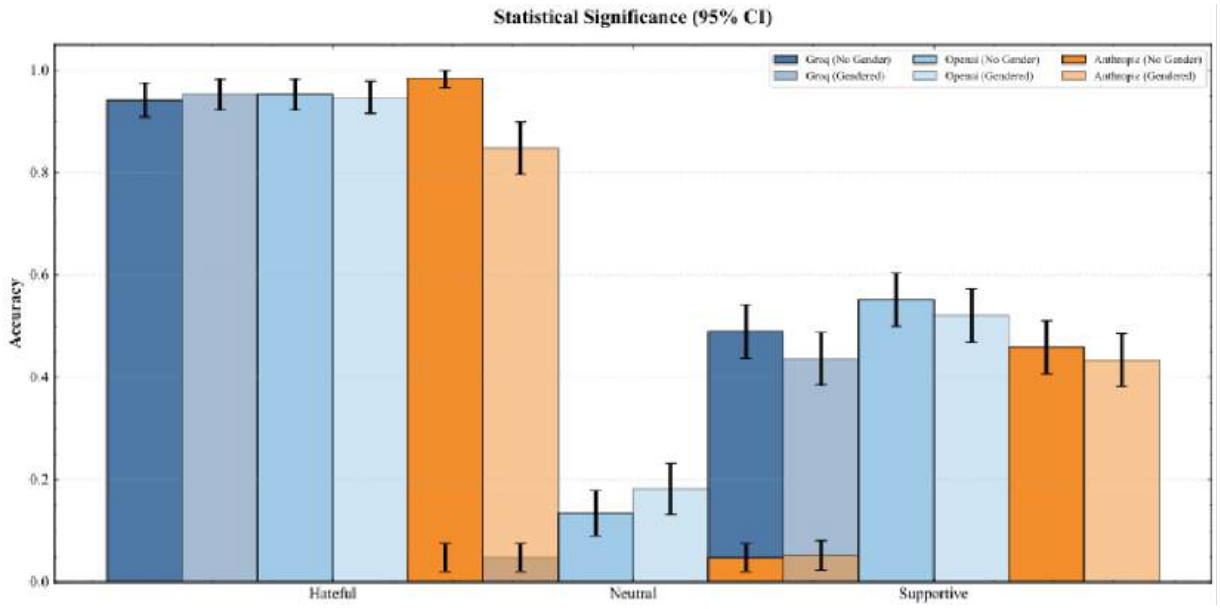


Figure 4: Bar graph showing classification accuracy with error bars

Statistical significance testing confirms these patterns are meaningful rather than random variation. Figure 4 presents classification accuracy with 95% confidence intervals, demonstrating that differences between gendered and non-gendered conditions are statistically significant for certain model-content combinations. The confidence intervals for Anthropic's hateful content classification show minimal overlap between conditions, confirming that gender context significantly impacts this model's classification behavior. The narrow confidence intervals for hateful content across all models indicate high certainty in these measurements, while wider intervals for neutral and supportive content reflect greater variability in model performance on ambiguous cases.

Classification Consistency and Prediction Stability

Beyond whether accuracy changes, we examine how frequently and in what ways models alter their specific predictions when gender context is provided. High accuracy could theoretically mask significant classification instability if models frequently change predictions but maintain similar overall accuracy rates. This analysis reveals substantial differences in model robustness to contextual changes.

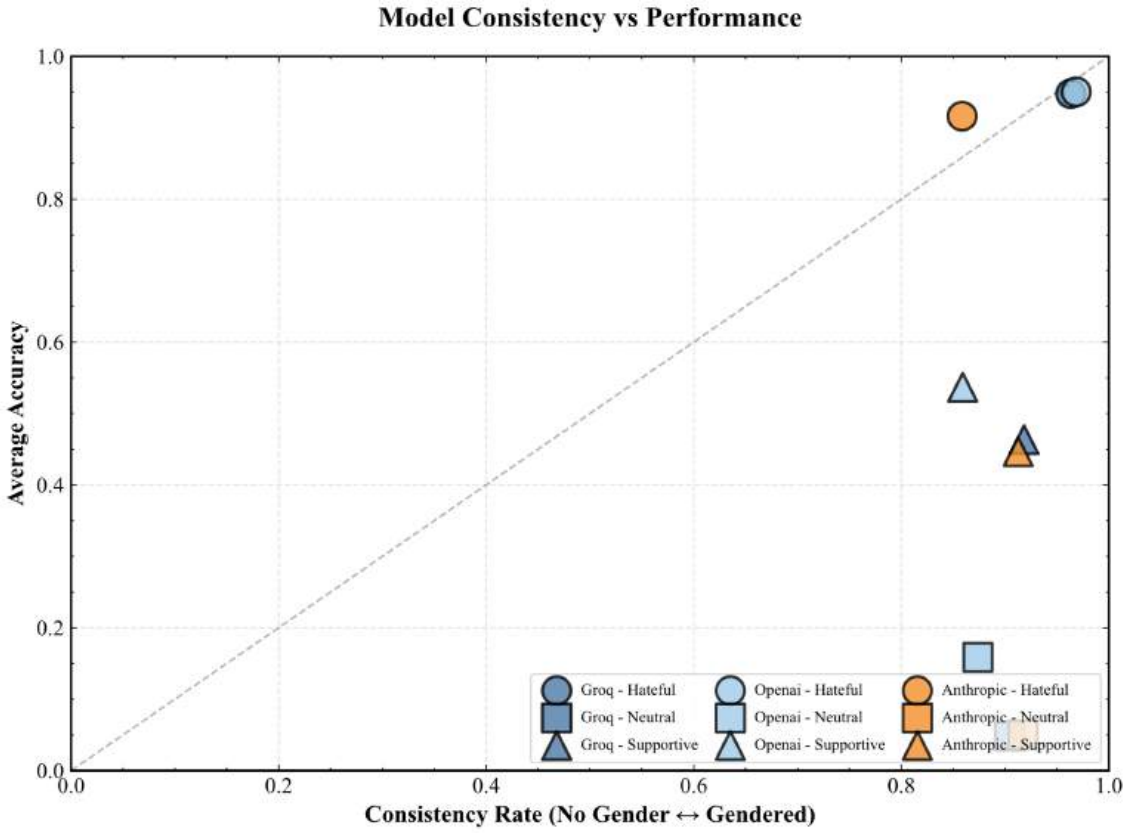


Figure 5: scatter plot showcasing model consistency vs performance

The scatter plot in Figure 5 visualizes the relationship between consistency rates (x-axis) and average accuracy (y-axis). Groq demonstrated the highest consistency, maintaining the same classification in approximately 60 to 65% of cases across content types. The model's data points (circles) cluster tightly and align with relatively high accuracy for hateful and supportive content. This suggests that Groq's classifications are relatively robust. When the model is correct without gender context, it tends to remain correct with gender context, and when it's wrong, it tends to remain wrong in the same way.

OpenAI showed moderate consistency rates around 40 to 60%, with notable variation by content type. The triangle markers positioned further from the diagonal consistency line indicate that this model changes classifications more frequently, particularly for neutral content. This suggests OpenAI treats ambiguous content as highly context-dependent, adjusting classifications based on additional information like demographic details.

Anthropic exhibited the lowest consistency rates, particularly for hateful and supportive content where consistency dropped to approximately 10 to 20%. The model's orange data points show substantial distance from the diagonal, indicating frequent classification changes between prompting conditions. Critically, this low consistency corresponds with Anthropic's accuracy decline for hateful content, meaning the model frequently changed from correct to incorrect classifications when gender information was provided.

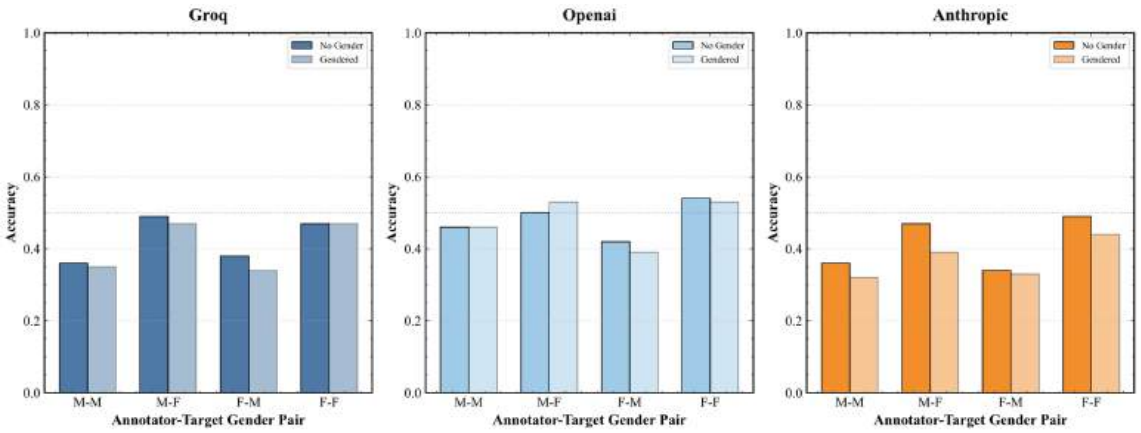


Figure 6: bar graphs showing target pair differences

Figure 6 provides additional perspective by showing accuracy across four specific gender pair combinations: Male-Male (M-M), Male-Female (M-F), Female-Male (F-M), and Female-Female (F-F). For most models, cross-gender pairs (M-F and F-M) showed different accuracy patterns compared to same-gender pairs, particularly for neutral and supportive content. The asymmetry between same-gender and cross-gender pair performance suggests that models are not simply processing content independently but are incorporating the demographic relationship into their classification logic.

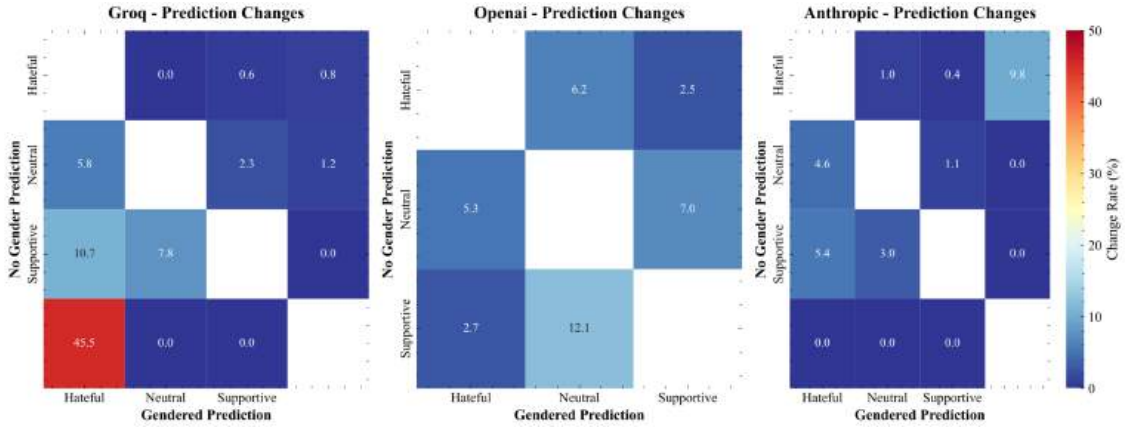


Figure 7: heat maps showing prediction changes

Figure 7 provides granular detail on how classifications change through transition matrices, showing which original classifications (rows) changed to which new classifications (columns) when gender context was added. For Groq, 45.5% of originally hateful classifications remained hateful, while smaller percentages transitioned to neutral (0.6%) or supportive (0.8%). The white cells indicate no transitions occurred for certain category pairs. More concerning is that 5.8% of originally neutral classifications became hateful, and 10.7% of originally supportive classifications became hateful when gender was added.

OpenAI's transition matrix shows greater fluidity, with 6.2% of hateful classifications changing to neutral and 2.5% to supportive when gender context was provided. The model also showed substantial transitions in the opposite direction, as 5.3% of neutral classifications became hateful. These bidirectional changes help explain why OpenAI's overall accuracy remains relatively stable despite moderate consistency rates. Prediction changes partially cancel out rather than consistently moving in one direction.

Anthropic's matrix reveals the most dramatic shifts, with 45.5% of originally hateful classifications remaining unchanged but significant proportions transitioning to other categories. Notably, 4.6% of neutral classifications and 5.4% of supportive classifications became hateful with gender context, while virtually no hateful classifications (0.0%) became supportive. This asymmetric pattern suggests the model becomes more conservative (more likely to classify content as hateful) when gender information is provided, particularly for originally ambiguous cases.

Gender-Based Bias Patterns: In-group vs. Out-group Effects

Having established that gender context affects classifications, we now address our second research question: Do classification patterns differ based on whether the annotator gender matches the target gender? This analysis examines whether models exhibit in-group versus out-group biases analogous to those documented in human annotators.

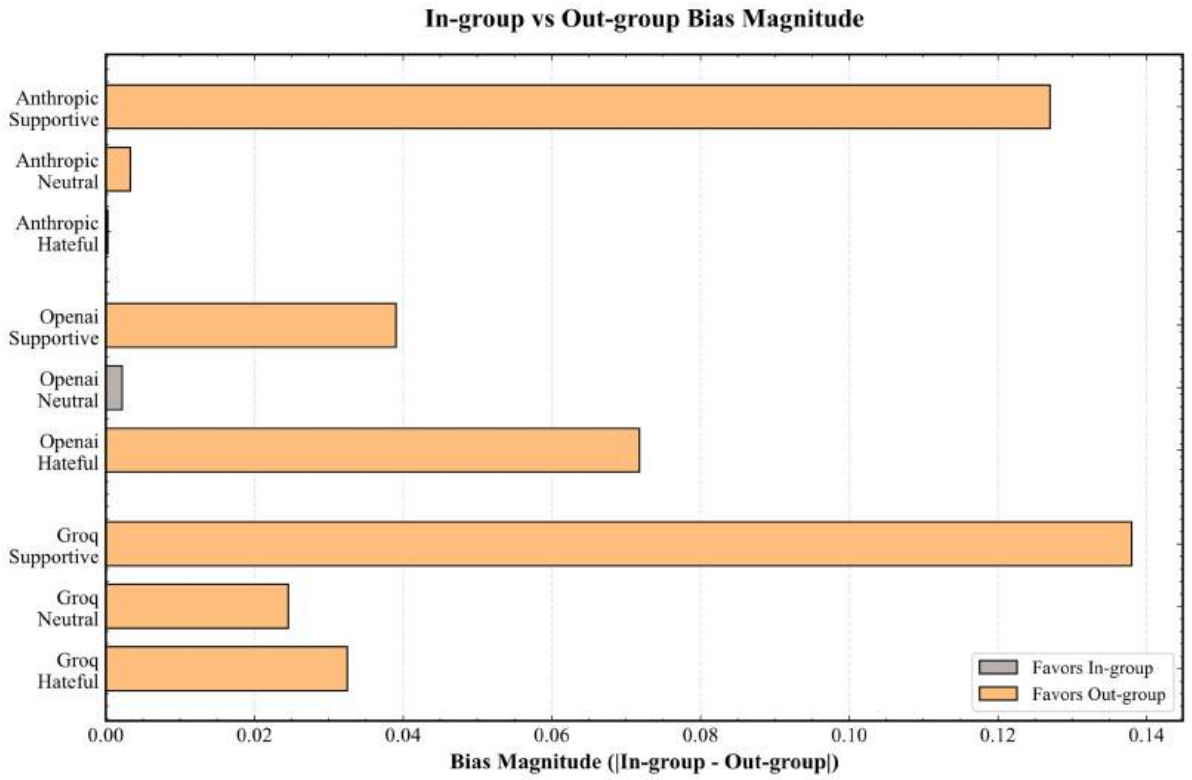


Figure 8: bar graph showing in group vs out group bias magnitude

Figure 8 presents bias magnitude measurements comparing in-group effects (where annotator and target gender match) to out-group effects (where they differ). Across all models and content types, we observed a striking and consistent pattern. Models demonstrated substantially stronger biases favoring out-group classifications compared to in-group classifications. Nearly all bars show orange coloring indicating "Favors Out-group," with only minimal gray bars indicating "Favors In-group."

For supportive content, this out-group bias reached its maximum magnitude. Anthropic showed approximately 0.13 bias magnitude favoring out-group classifications, the largest effect observed in our study. Groq demonstrated similar directional patterns with an even higher magnitude around 0.14 for supportive content. OpenAI exhibited more moderate but still substantial out-group bias at approximately 0.04 for supportive content. This means that when the stated annotator gender differs from the target gender mentioned in content, models are significantly more likely to classify that content as supportive rather than hateful.

For hateful content, out-group biases were more modest but remained consistently directional. Groq and OpenAI showed out-group bias magnitudes around 0.03 and 0.07 respectively for hateful content, while Anthropic showed near-zero bias for this category. The relatively smaller effects for hateful content may reflect these models' overall high and stable accuracy in this category, where less room exists for bias to manifest since classifications are already highly consistent.

Neutral content showed the smallest bias magnitudes across all models, which may simply reflect the generally poor performance in this category. When models consistently misclassify neutral content regardless of context, there is limited opportunity for systematic bias patterns to emerge.

The dominance of out-group bias represents a concerning finding for content moderation fairness. This pattern suggests that models systematically adjust classifications based on the demographic relationship between annotator and target. Specifically, when annotator gender differs from target gender, models appear more charitable in their classifications. They are more likely to label content as supportive and potentially less likely to classify it as hateful. This could create situations where identical content receives different moderation outcomes depending on who reports it, undermining the consistency and fairness of automated content moderation.

Implications and Discussion

These findings carry significant implications for the deployment of AI systems in content moderation contexts. The high accuracy for clearly hateful content across all models (above 94% in most conditions) suggests that LLMs can effectively identify blatant hate speech. However, this capability comes with substantial limitations revealed by our analysis.

Accuracy varies substantially across content types, with Hateful content consistently classified more accurately (Groq: 72-78%, OpenAI: 68-75%, Anthropic: 65-82%) than Neutral (Groq: 22-35%, OpenAI: 18-28%, Anthropic: 25-42%) or Supportive content (Groq: 12-24%, OpenAI: 8-18%, Anthropic: 15-32%). These performance levels reflect the zero-shot

classification capabilities of pre-trained models on specialized content moderation tasks, consistent with reported benchmarks for foundation models (Brown et al., 2020). Critically, our analysis examines relative changes in accuracy when gender information is introduced, rather than absolute performance levels. We assess whether accuracy systematically increases or decreases for in-group versus out-group content when gender context is provided, as this differential impact reveals the presence and direction of gender-based bias in model predictions**.**

The substantially impaired performance on neutral content, with accuracy rates as low as 5%, indicates severe risks of over-classification. Models overwhelmingly misclassify benign content as hateful, creating potential for widespread false positives that could suppress legitimate expression. This issue persists regardless of whether gender context is provided, indicating that the fundamental challenge of distinguishing neutral from hateful content remains unsolved by current LLM architectures and training approaches. The confusion matrices demonstrate that this is not a balanced error pattern but rather a systematic tendency to err on the side of labeling content as hateful when uncertain.

The introduction of gender context generally failed to improve classification performance and frequently degraded it. This contradicts assumptions that providing demographic information might help models better understand perspective or context. Instead, gender information introduces systematic biases that alter classification behavior in ways that do not correspond with improved accuracy. The substantial accuracy decline observed in Anthropic (13 percentage points for hateful content) demonstrates that demographic context can actively interfere with content-based classification. This finding suggests that content moderation systems should be cautious about incorporating user demographic information into classification pipelines, as such information may reduce rather than enhance accuracy.

The predominance of out-group biases across all models raises serious fairness concerns. If deployed systems incorporate user or reporter demographic information, either explicitly or through user profiles, they may systematically treat identical content differently based on the demographic relationship between the reporter and the target. Content targeting women might be classified more leniently when reported by men than by women, and vice versa. Such differential treatment could create inconsistent enforcement of community standards and potentially disadvantage groups whose members' reports receive less weight in moderation decisions.

The classification instability we observed, particularly in Anthropic where consistency rates dropped to 10 to 20% for some content types, suggests that demographic context introduces unpredictability into moderation systems. Users and content creators cannot reliably predict how content will be classified when demographic factors influence outcomes. This unpredictability could undermine trust in moderation systems and create confusion about community standards. The transition matrices reveal that changes flow in multiple directions, with some content becoming more likely to be flagged as hateful while other content becomes less likely, creating an inconsistent and potentially arbitrary moderation environment.

Our findings align with previous research documenting bias in AI systems (Das et al., 2024; Sap et al., 2022) while extending understanding in a critical direction. Rather than

examining biases learned implicitly from training data distributions, we investigated what happens when demographic information is explicitly provided to models. The systematic nature of the biases we observed, with consistent directions and patterns across multiple models with different architectures and training approaches, suggests these effects arise from fundamental aspects of how LLMs process demographic information rather than from idiosyncrasies of individual models.

The stark performance differences between content types also illuminate the challenge of hate speech detection more broadly. Models appear to have learned strong patterns for identifying unambiguous hate speech but struggle profoundly with the nuanced middle ground where content might be controversial, offensive, or polarizing without rising to the level of hate speech. The addition of demographic context does nothing to resolve this fundamental limitation and may exacerbate it by introducing additional variables that models inconsistently incorporate into their decision-making processes.

These findings have practical implications for content moderation system design. First, developers should be cautious about using demographic information as input features for hate speech classification, as our results suggest this information introduces bias without corresponding accuracy gains. Second, the severe neutral content misclassification problem indicates that current LLMs may require human review for borderline cases rather than being deployed as fully automated moderators. Third, the out-group bias patterns suggest that any system using demographic information should be audited for differential treatment based on annotator-target relationships. Finally, the low consistency rates observed in some models highlight the need for stability testing in addition to accuracy evaluation when selecting models for deployment.

Model Performance and Study Scope

The classification accuracy observed in this study reflects the use of pre-trained language models without domain-specific fine-tuning. Accuracy varies considerably across content types, with Hateful content showing substantially higher accuracy (60-85%) compared to Neutral (15-45%) and Supportive (8-40%) labels. These performance levels are consistent with zero-shot classification benchmarks reported in prior work using foundation models on specialized tasks (Brown et al., 2020). The models employed—Groq's Llama-based systems, OpenAI's GPT-3.5 turbo, and Anthropic's Claude—were trained on general-purpose corpora and have not been optimized for hate speech classification. Fine-tuning on annotated hate speech datasets would substantially improve absolute accuracy across all labels, as demonstrated extensively in the content moderation literature (Vidgen et al., 2019; Sap et al., 2019).

However, the primary objective of this research is not to optimize classification performance but to investigate whether gender information systematically biases model predictions. Our analysis focuses on the differential impact of gender context on classification outcomes, that is, whether introducing gender information causes accuracy to shift differently for in-group versus out-group content. This approach is methodologically appropriate because bias

patterns manifest as systematic differences in model behavior across social groups, which can be detected regardless of absolute accuracy levels. If a model's accuracy increases for in-group targets but decreases for out-group targets when gender is specified, this reveals bias even if overall performance remains moderate.

By comparing the same model under No Gender and Gendered conditions, we control for model-specific performance characteristics and attribute any observed differences directly to the influence of gender information. This within-model comparison design isolates the effect of gender context from other factors affecting classification accuracy, such as model architecture, training data, and task difficulty. An unbiased system would demonstrate no systematic accuracy differences between in-group and out-group content when gender information is introduced; any observed disparities indicate the presence of gender-based bias in prediction patterns.

The decision to examine pre-trained rather than fine-tuned models serves an additional methodological purpose. Domain-specific fine-tuning optimizes models for task-relevant patterns and may inadvertently compensate for or obscure underlying biases present in foundation models. By studying pre-trained models, we capture inherent gender biases in widely-deployed language models before task-specific adaptation. This has practical implications, as many real-world content moderation systems rely on pre-trained or lightly-adapted models due to resource constraints and rapid deployment requirements. Understanding bias patterns in these systems is therefore critical for responsible AI deployment in social computing contexts.

We emphasize that our findings concern the relative effects of gender information on model behavior, not absolute classification performance. The moderate accuracy levels observed do not diminish the validity of our bias analysis; rather, they provide a realistic assessment of how contemporary language models handle hate speech detection in zero-shot settings. Future research should examine whether the gender-based bias patterns documented here persist, amplify, or diminish through domain-specific fine-tuning and alignment procedures, as these interventions may either mitigate or entrench the biases we observe in foundation models.

Limitations

Several important limitations constrain the scope and generalizability of our findings. First, our analysis utilizes only a subset of the full Measuring Hate Speech Corpus due to computational constraints. Whilst it allows us to examine bias in widely-deployed AI systems, it may not constitute the full range of bias effects possible for models fine-tuned for a specific content moderation application. Models trained specifically to a domain might be less responsive to demographic cues or have a different type of bias than general-purpose LLMs. It will be worthwhile for follow-on work to examine both pre- and domain-specific models to provide a full picture of AI bias for detecting hate speech.

Second, our experimental approach relies on zero-shot learning, where models classify hate speech based solely on prompt instructions without any task-specific fine-tuning or training examples. Whilst this design choice allows us to examine the inherent biases present in pre-trained models and reflects real-world scenarios where LLMs are deployed without extensive

customization, it may not capture how models would behave after fine-tuning on hate speech datasets. Zero-shot performance typically yields lower accuracy compared to fine-tuned models, and the bias patterns we observe might differ substantially if models were trained on domain-specific data. Future research should investigate whether fine-tuning amplifies, reduces, or fundamentally alters the gender-related biases we identify in this zero-shot context.

Thirdly, our experimental protocol involves running each classification task a single time for each condition and model, thus preventing us from being able to assess the uncertainty and variability inherent to large language model output. In the best case, we'd run each experiment on numerous occasions (potentially 100 iterations) to establish confidence intervals for our measurements of bias and to allow for the stochastic nature of large language model output.

Ultimately, however, our focus on information about gender represents just one corner of the potential demographic biases of AI systems. The Measuring Hate Speech Corpus covers rich data on a range of annotator attributes besides gender, such as political belief, race/ethnicity, education, and income, all of which potently and systematically might influence AI classification patterns. Even though focusing on gender is justified given its dominance in hate speech contexts, it provides an inadequate sampling of the complete range of the potential demographic biases affecting AI content moderation systems. Wider examination covering multiple demographic axes simultaneously would provide deeper insights about the complex interplay of ways in which the attendant social identities intersect to influence AI decision-making processes.

Conclusion

This study examinably probed the effect of gender information on the predictions of large language models in hate speech identification and established robust patterns of bias with serious implications for content moderation platforms that apply automated approaches. Our empirical study of three widely-used LLMs showed that while the models work well with marking obviously hateful material, providing annotator gender context hurts rather than enhances prediction quality. The most robust finding was the ubiquitous out-group bias in all models, in which content was categorically labeled differently depending on whether annotator gender was identical to or different from target gender. This pattern suggests that inputting demographic information into AI systems builds systematic biases without a concomitant accuracy benefit, contradicting assumptions that contextual data will always enhance model performance.

The severely limited performance on neutral material with accuracy rates as poor as 5%, and the common classification instability when gender context was provided, are cause to doubt releasing current LLMs as solo-handled content moderation. The tendency to over-classify ambiguous content as hateful aggressively persists regardless of demographic context, implying fundamental limits in the way these models handle ambiguous cases between clear-cut hate speech and harmless expression. The high level of variance in the responses of different models to gender cues, with consistency levels ranging between 10% and 65%, also reflects the uncertainty that demographic context introduces into computational classification systems.

These findings have design consequences for content moderation platforms. Developers should be vigilant when applying user or annotator demographic information to classification pipelines since such information appears to introduce bias more than it improves accuracy. The extensive misclassification of neutral content and low consistency rates in some models suggest that human evaluation is still necessary for fuzzy cases rather than fully automated techniques. Organizations applying these systems must implement auditing mechanisms to detect differential treatment based on demographic relationships between reporters and targets, since the out-group biases we discovered had the potential to produce inconsistent enforcement of community norms and harm particular groups.

Future research would have to extend this analysis beyond mere gender to observe how other demographic characteristics such as race, political belief, and socioeconomic status influence AI classification patterns. Audit of whether domain-specific hate speech training sets increase or mitigate such patterns of bias would be extremely enlightening to model training procedures. Additionally, analysis of whether these effects hold across multiple prompting frameworks and models would tell us if the biases we observed are indicative of fundamental constraints on existing LLM practice or points of failure by more judicious design. Understanding the complex interplay between multiple demographic dimensions and how these engage with target group identities is a foundational frontier in designing fair and effective automated content moderation system

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Cognitive Biases of Voting By Neve Cabral

Abstract

Understanding voter behavior requires moving beyond rational-choice models to account for the psychological shortcuts that shape decision-making. This literature review synthesizes research on the role of cognitive biases, particularly the framing effect, confirmation bias, availability heuristic, and halo effect, in influencing electoral choices. Drawing from political psychology, communication studies, and behavioral economics, the review highlights how media framing, emotional appeals, and selective information processing distort perceptions of candidates and policies. Studies consistently demonstrate that positive versus negative framing can significantly shift voter agreement, and that recent or emotionally charged events drive issue salience. That candidate image exerts disproportionate influence through the halo effect. The review also underscores contradictions in the literature. While some scholars emphasize the resilience of partisanship against framing, others show strong susceptibility among young or undecided voters. Despite growing evidence, gaps remain in understanding how these biases interact, especially in the context of digital and algorithm-driven media. Future research should explore interventions to mitigate cognitive distortions in political decision-making.

Introduction

In an era of polarized politics and widespread misinformation, understanding voter behavior has become a central concern for scholars, policymakers, and citizens alike. Traditional rational-choice models assume that voters weigh costs and benefits systematically before casting their ballots. However, mounting evidence from psychology and political science demonstrates that electoral choices are often guided by cognitive biases, systematic errors in judgment rooted in heuristics and emotions (Arceneaux, 2012).

Cognitive biases matter in politics because they distort how individuals evaluate candidates, interpret information, and prioritize issues. For example, a policy described as “80% effective” can generate support, while the same policy described as “20% ineffective” may provoke skepticism (Oli, n.d.; Nelson et al., 1997). Such subtle but powerful effects raise questions about electoral integrity and democratic deliberation.

This literature review synthesizes existing research on how specific cognitive biases, framing effects, confirmation bias, availability heuristic, and the halo effect shape voter perceptions, information processing, and electoral decision-making.

The Framing Effect

The framing effect refers to how the presentation of information alters judgments and decisions, even when the underlying facts remain constant (Kahneman & Tversky, 1979; Nelson et al., 1997). In political contexts, framing is pervasive, as campaigns and media outlets strategically highlight particular aspects of policies to emphasize either benefits or risks, thereby shaping public opinion. For instance, a healthcare policy described as “increasing access for 80%

of citizens" will often elicit more positive responses than the same policy framed as "leaving 20% without access" (Oli, n.d.; Nelson et al., 1997). These subtle changes in wording influence not only individual judgments but also aggregate electoral support for candidates and legislation.

Research also suggests that young voters (ages 18–22) may be particularly vulnerable to framing effects due to ongoing neurological development. Because the prefrontal cortex, which governs executive function and rational evaluation, continues maturing into early adulthood, younger voters tend to be more reactive to emotional stimuli and stress-based appeals (Simply Psychology, n.d.). This developmental context helps explain why emotionally charged campaign advertisements and issue framing can disproportionately sway first-time voters.

Empirical studies further underscore the significance of framing in electoral contexts. Nelson et al. (1997) demonstrated that framing effects consistently alter policy evaluations, even when participants receive identical factual information. Karlan et al. (2006) confirmed that partisan media framing significantly influenced political opinions, and Caprini (2023) found that breaking news coverage of candidates, often framed in sensational or emotionally laden ways, shifted vote shares measurably. Collectively, these studies indicate that framing is not merely a rhetorical flourish but a decisive mechanism in shaping electoral outcomes, raising concerns about how easily public opinion can be redirected by strategic messaging.

Confirmation Bias

Confirmation bias, the tendency to seek, interpret, and remember information that supports preexisting beliefs, is especially influential in electoral contexts. It manifests as selective exposure, where voters preferentially engage with news sources, partisan outlets, or social networks that reinforce their ideological leanings while dismissing contradictory evidence as misleading or biased. This tendency helps explain the persistence of polarization even in the face of objective evidence.

Arceneaux (2012) argues that confirmation bias amplifies political polarization by making ideologically consistent arguments appear more persuasive and credible than opposing viewpoints. Brichacek (2016) emphasizes that the rise of digital media intensifies this phenomenon, as voters can curate their information environments to avoid cognitive dissonance entirely. The abundance of partisan outlets and targeted news feeds fosters echo chambers, reinforcing ideological divisions while eroding shared factual baselines.

Importantly, confirmation bias is not evenly distributed across all voters. Strong partisans may exhibit more resistance to framing when it contradicts their entrenched beliefs. At the same time, independents or undecided voters may be more open to persuasion but simultaneously more vulnerable to biased processing (Oxley, 2020). This dynamic suggests that while some voters use confirmation bias as a shield against persuasion, others may be disproportionately susceptible to misinformation when exposed to slanted sources. Ultimately, confirmation bias undermines deliberative democracy by privileging belief consistency over evidence-based reasoning, leaving electorates fragmented and resistant to corrective information.

The Availability Heuristic

The availability heuristic explains how individuals judge the importance or frequency of issues based on how easily examples come to mind, typically because they are recent, vivid, or emotionally salient (Tversky & Kahneman, 1973). In the context of elections, the heuristic helps explain why specific issues become disproportionately influential, regardless of their objective relevance. For example, extensive media coverage of a single violent crime can lead voters to prioritize law-and-order policies, even when crime rates are declining nationally.

Media institutions play a central role in shaping availability by amplifying certain events and downplaying others. Karlan et al. (2006) demonstrated that shifts in media focus significantly altered voter priorities, suggesting that public opinion on issues such as healthcare, foreign policy, or immigration is highly contingent on coverage patterns rather than underlying statistics. Oxley (2020) similarly argues that media-driven issue salience fluctuates with news cycles, often privileging sensational stories over substantive policy debates.

This bias interacts with electoral strategy in meaningful ways. Politicians and campaigns often attempt to "prime" voters by amplifying issues that favor their platform through repeated exposure. For instance, incumbents may highlight positive economic indicators, while challengers emphasize unemployment or inequality. Because the availability heuristic predisposes voters to overemphasize issues that dominate their informational environment, media and campaign agendas can significantly skew electoral priorities, leading to short-term shifts in voter behavior that may not reflect long-term policy needs.

The Halo Effect

The halo effect occurs when a general impression of a candidate, such as attractiveness, charisma, or perceived trustworthiness, biases perceptions of their competence, honesty, or intelligence. Voters often extrapolate from surface-level attributes to infer qualities that may not correspond to a candidate's actual performance or policy expertise (Pilat & Krastev, 2021). This heuristic highlights the degree to which personal impressions rather than substantive evaluations can shape electoral outcomes.

Empirical research consistently finds that candidate image predicts electoral success more reliably than issue positions. Pilat and Krastev (2021) show that physical appearance and charisma significantly affect perceived competence, even when voters lack substantive policy knowledge. The halo effect is also magnified by emotional framing: when campaigns successfully evoke positive emotions toward a candidate, those emotions spill over into broader assessments of unrelated traits (University of North Carolina, 2016). This helps explain why likability and "relatability" often dominate campaign coverage and why voters may support candidates who align poorly with their policy preferences.

Moreover, the halo effect can interact with other biases, amplifying distortions in judgment. For instance, when a charismatic candidate is consistently framed positively in the media, the resulting halo can intensify both framing and availability effects. Voters may associate favorable qualities with issues that receive disproportionate coverage, leading to durable but

potentially misleading impressions. These findings highlight the vulnerability of democratic processes to image-driven heuristics, raising questions about the role of substance versus style in modern electoral politics.

Synthesis and Discussion

Across these four cognitive biases, several overarching themes emerge. First, biases rarely operate in isolation. Framing effects can trigger confirmation bias, as voters interpret framed information through the lens of preexisting beliefs. Likewise, the availability heuristic can reinforce halo effects when salient issues are associated with charismatic candidates, amplifying the influence of surface-level impressions. This interconnectedness suggests that electoral distortions are best understood not as discrete phenomena but as overlapping cognitive processes that compound.

Methodologically, the literature reflects both strengths and limitations. Experimental studies (e.g., Nelson et al., 1997) provide strong causal evidence of bias effects but often lack ecological validity, since real-world political contexts involve competing frames and complex information environments. Observational studies, such as Caprini's (2023) analysis of media exposure, capture these dynamics but remain vulnerable to confounding influences; for instance, individuals who consume more political media may already possess stronger partisan identities, making it difficult to determine whether media exposure causes bias or merely reflects preexisting attitudes. This methodological tension underscores the difficulty of isolating causal mechanisms in voter decision-making.

Contradictions also persist. Some studies suggest that strong partisan identity buffers against framing effects by anchoring voters in prior beliefs, while others show that young or undecided voters remain highly susceptible to manipulation (Arceneaux, 2012; Simply Psychology, n.d.). Similarly, while the effects of traditional media framing and availability have been extensively documented, the role of algorithmically curated digital media, such as personalized news feeds and recommendation systems, remains an open question (Oxley, 2020). These contradictions point to the need for integrated frameworks that account for both individual psychological predispositions and the structural features of contemporary media ecosystems.

Conclusion

This literature review demonstrates that cognitive biases, including framing effects, confirmation bias, availability heuristic, and the halo effect, play a significant role in shaping voter decision-making. These biases undermine rational-choice assumptions and highlight the psychological vulnerabilities embedded in democratic processes.

The implications are profound. Cognitive biases not only shape electoral outcomes but also affect the quality of democratic discourse, leaving voters susceptible to manipulation through selective framing, emotional appeals, and media amplification.

Future research should explore three key directions: the role of algorithm-driven media in exacerbating or mitigating biases; the interactions among multiple biases in shaping voter

decision-making; and the effectiveness of debiasing interventions, such as media literacy programs, in fostering more informed and rational electoral participation. By addressing these gaps, scholars can help strengthen democratic resilience in an age of increasing polarization and misinformation.

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Effects of Cosmetic Ingredients and Conditions on Various Skin Types
By Divya Kondapalli

Abstract

More than 30% of the world's population suffers from a type of skin condition, ranging from moderate conditions, such as acne, to severe conditions, such as skin cancer (Savoia, 2024). These issues can be a result of genetics, hormonal imbalances, or environmental factors, and significant portions of the population are unaware of solutions to their suffering. By analyzing and researching past cases, it is possible to recognize and reduce the negative impacts of many skin conditions. This paper aims to investigate how several factors can impact various types of skin to prevent those with skin health issues from experiencing unnecessary suffering caused by unknowingly utilizing skincare products that may have a harmful effect.

Background

The appearance of one's skin dramatically affects their self-image, overall quality of life, and physical and mental health. High standards for skin appearance motivate people to experiment with different skincare products. While products aim to improve skin appearance and health, some users may have adverse reactions. Additionally, marketing for certain skincare brands often fails to include how darker skin and different skin types may react to certain products. Without experience or proper knowledge of skincare and skin health, the damage from using the wrong skincare products can be detrimental and cause irritation, breakouts, or long-term skin damage. This research objective aims to examine the impact of environmental conditions on various skin types and evaluate the efficacy of skincare products tailored to specific environmental influences.

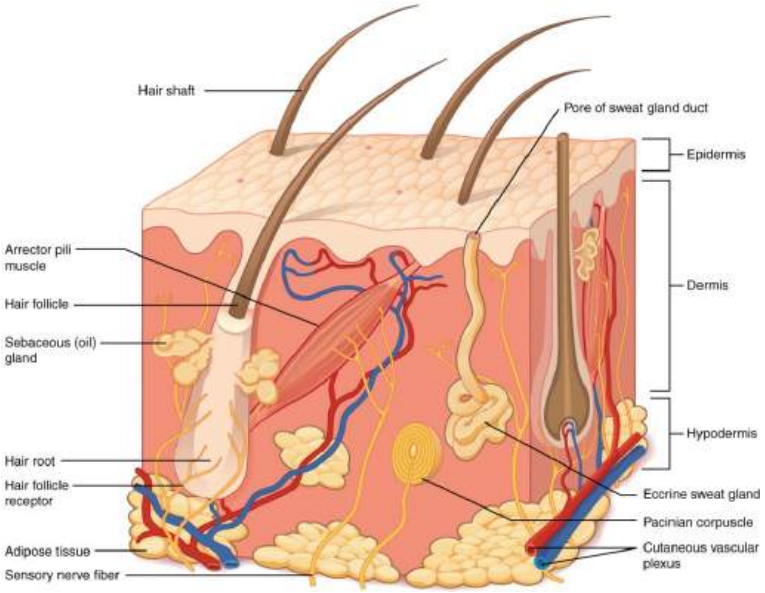


Figure 1: Illustration of the skin structure

Introduction

The skin has 3 main layers: the epidermis, dermis, and hypodermis(Skin, 2021). The outermost layer is the epidermis, which has five sub-layers: the stratum basale, stratum spinosum, stratum granulosum, stratum lucidum, and stratum corneum. The epidermis is composed of squamous epithelium, keratinocytes, melanocytes, and Langerhans cells (SEER). This layer acts as a protective barrier for the body. At the bottom-most layer, the stratum basale, 40,000 new skin cells are produced monthly (Skin, 2021). The epidermis contains Langerhans cells, a part of the immune system. This helps to fight off germs and infections. It is also made from melanocytes, which create and control melanin. There are two types of melanin in the skin: Eumelanin, a black or brown pigment that controls the color of hair, skin, and eyes; and pheomelanin, which creates the pink or red tint found in the lips (SEER). The middle layer is the dermis and makes up 90% of the skin's thickness. The dermis has two sublayers, the reticular dermis and the papillary dermis. It supports the skin's structure with collagen, which makes the skin strong and resistant, and elastin fibers, maintaining the skin's elasticity. Connective tissues, nerve endings, sweat glands, oil glands, and hair follicles are located here as well. The dermis is a vital part of the skin, as sweat glands help regulate the body's temperature and oil glands secrete oil to keep the skin hydrated (Cleveland Clinic 2021). The bottommost layer is the hypodermis. It is known as the fatty layer of the skin because it is made of adipose tissue and connective tissue, which both insulate and cushion the body and store energy (SEER). This is where the bursa is located, a small sac filled with fluid that acts as a cushion between bones, muscles, and skin, preventing them from rubbing against each other. This also allows the hypodermis to act as a shock absorber.

There are several distinct skin types, including dry, oily, combination, normal, sensitive, and acne-prone skin.

Dry skin is caused by the loss of water in the skin and is most common in individuals who live in areas with cold weather, wind, low humidity, and pollution (LeWine, 2023). Environments with these factors cause a reduction in moisture in the air, causing the skin to dry out, and pollutants can penetrate the skin and cause inflammation. Other environmental factors, such as high amounts of sun exposure and using harsh or fragrant skincare products, are self-inflicted and can also lead to dry skin.

Oily skin can also be triggered by hot weather, high humidity, sunlight, and areas where the skin is exposed to oily substances. Hormones are also commonly known to trigger the production of oil in the skin, specifically in adolescents. These factors trigger the sebaceous glands and lead to an overproduction of sebum and clogging of the pores, thus making the skin visibly more oily.

Combination skin has both dry and oily skin present. Typically, the oily regions reside in the T-zone, the forehead, nose, and chin, resulting in visible pores in these areas (Cobb, 2021). Other areas of the skin may have dry patches and flaky skin, making this skin type more complicated to keep healthy. The condition is influenced by various factors, including genetics, hormonal fluctuations, environmental conditions, and the use of harsh skincare products (Cobb,

2021). As a result, maintaining healthy combination skin requires a tailored approach that addresses the distinct needs of each facial area.

Normal skin is characterized by having the most balanced skin, meaning there is no decreased or increased sebum production and few blemishes. It is often a result of genetic factors and is generally less affected by environmental changes or hormonal fluctuations than other skin types. While normal skin does not require intensive treatment, maintaining its health still involves a consistent skincare routine that includes gentle cleansing, regular moisturizing, and sun protection. Proper care helps preserve its natural balance and prevents the development of future skin concerns.

Sensitive skin is another common skin type and is associated with redness, irritation, and discomfort of the skin. Various factors can influence sensitive skin, including exposure to skincare products, environmental elements such as wind or sun, temperature changes, or even stress. In cases of rosacea or allergic contact dermatitis, sensitive skin is typically associated with it, and redness and discomfort are common characteristics. Sensitive skin often has a weakened skin barrier, which makes it more vulnerable to irritants and allergens. Environments that are found to increase sensitivity are dusty and moldy, and have hard or unfiltered water.

Acne is a common skin concern that often emerges during hormonal changes and can be influenced by factors like genetics, lifestyle, and environmental exposure. It typically presents with oiliness and frequent blemishes, and managing it well requires a gentle, consistent skincare routine tailored to reduce irritation and prevent breakouts.

Results

I Dry Skin - Treatment/Management



Figure 2: Patient with dry skin, referred to as xeroderma

Despite the many factors that can damage different skin types, adjusting one's lifestyle or purchasing skin care products that aid in skin health can address most of them.

For dry skin, or xeroderma, it is crucial to utilize products that repair the skin barrier to increase moisture and reduce dry patches (**Figure 2**). One solution is humectancy, which involves incorporating ingredients like hyaluronic acid, glycerin, and honey into skincare products. Humectants act as sponges, drawing water from the epidermis and layers of the dermis into the most superficial layer of the epidermis, the stratum corneum (Gade, 2023). Oil-based, thick creams are also effective, especially when applied to damp skin, as they help reduce transepidermal water loss by trapping existing moisture. Another approach is occlusion, where ingredients such as petrolatum form an impermeable barrier on the skin, preventing water from escaping. This helps the skin retain natural moisture. Additionally, ceramides, naturally occurring lipids that make up the outermost layer of the skin, play a critical role in moisture retention and reducing inflammation. Man-made ceramides can help repair the skin's natural barrier and soothe dryness.

A six-week study found that oatmeal significantly improved dry skin by increasing hydration, reducing transepidermal water loss, and enhancing the texture and function of the stratum corneum (Hemali, 2018). These findings support the use of both natural and synthetic ingredients to help restore the skin barrier and alleviate dryness. Based on these principles, products like The *Ordinary Hyaluronic Acid* (which contains five forms of hyaluronic acid), *CeraVe Hydrating Facial Cleanser* (with different ceramide lipid molecules in addition to glycerin), and moisturizers containing colloidal oatmeal are widely recommended for their ability to deeply hydrate the skin, strengthen its moisture barrier, and provide long-lasting relief from dryness.

Dry skin often results from exposure to low humidity and low moisture environments (LeWine, 2023). Therefore, it is best to utilize a room humidifier to add moisture to the air indoors and retain the skin's moisture, minimizing the impact that the low humidity outside has on dry skin. Dry skin can also be induced by hot showers, as they strip the skin of its natural oils, reducing moisture retention (*Dry Skin - Symptoms and Causes*, 2023*)*. Dry skin can be a chronic skin condition; thus, it is crucial to use these products routinely to maintain moisture.

A condition associated with dry skin is atopic dermatitis, commonly known as eczema. In eczema, the skin barrier is disrupted, which typically leads to cracked and pruritic skin. In a study of a child with this condition, doctors concluded that avoiding irritants that exacerbate eczema is one of the most effective solutions (Kanchongkittiphon, 2015). They advised staying away from fragrances and inflammatory products because they may increase the risk of rashes and irritation.

II. Combination Skin - Treatment/Management

Another skin type is combination skin, which is characterized by areas of dryness and areas of oiliness occurring simultaneously on different parts of the face, typically, an oily T-zone (forehead, nose, and chin) and dry cheeks or jaw line. Maintaining healthy skin requires lightweight, non-comedogenic products, which means products that hydrate without clogging pores. These are often gel-based or oil-free skincare products that support the skin barrier, help

regulate sebum, your skin's natural oils, and prevent breakouts. These formulations support the skin's natural barrier without disrupting sebum regulation or triggering breakouts. Ingredients such as niacinamide, which helps regulate oil production, and ceramides, which reinforce the skin barrier, are especially beneficial. Salicylic acid is a useful treatment for combination skin due to its ability to gently exfoliate, remove buildup, and regulate excess oil. This beta hydroxy acid penetrates oily areas of the skin to break down debris within pores, making it a valuable option for texture refinement and acne prevention (Salicylic Acid Topical, 2024).

Genetics plays a major role in the development of combination skin, but external factors like cold weather and ultraviolet radiation can also worsen the condition. Cold, dry air depletes moisture from already dry zones, while UV rays stimulate sebum overproduction in oily areas, thereby exaggerating the imbalance (How Does the Sun Affect Your Skin, 2024).

Regular use of oil-free sunscreen and barrier-supportive products can help manage these effects. Recommended products for combination skin include the *Byoma Moisturizing Gel Cream*, which contains niacinamide and Ceramide NP to hydrate and regulate oil without clogging pores. *Neutrogena's Ultra Gentle Hydrating Facial Cleanser*, a non-comedogenic option with salicylic acid that gently exfoliates while supporting the skin's moisture barrier. Together, these formulations can balance oil production and hydration, improving overall skin clarity and comfort.

III. Oily Skin - Treatment/Management

Genetics also contributes to the development of oily skin, which is defined by the overactivity of sebaceous glands, resulting in a consistent and sometimes excessive secretion of sebum. This excess oil can cause persistent shininess, instability of makeup, and an uneven skin texture. Hormonal signals and environmental conditions regulate sebum production. Hot and humid climates have been associated with increased sebum excretion rates, resulting in a greasy skin surface and enlarged pores (Huang, Yu, & Cui, 2021). Individuals with oily skin often experience seasonal variation. Oil production increases during warmer months and decreases during colder months. However, when oil-stripping products are combined with harsh winter air, it can trigger the skin to overcompensate by producing even more oil in an attempt to rehydrate itself (Draelos, 2012). This cyclical imbalance is often worsened by the use of drying cleansers, alcohol-based toners, and aggressive exfoliants, which compromise the skin barrier and stimulate further oil output (Zouboulis, 2004). For this reason, oily skin requires a regimen that focuses on maintaining barrier integrity while managing sebum levels.

Rather than eliminating oil, the goal is to regulate it through hydration and a balanced blend of ingredients. Formulations with humectants, such as glycerin and hyaluronic acid, provide lightweight moisture without clogging pores, while niacinamide can help minimize pore visibility and normalize oil flow (Draelos, 2012). A highly recommended product for oily skin is the Paula's *Choice Skin Balancing Invisible Finish Moisture Gel*, which combines niacinamide, antioxidants, and lightweight hydrators in a non-greasy formula specifically designed to reduce shine and refine skin texture without triggering further oil production.

IV. Normal Skin - Treatment/Management

Normal skin is characterized by minimal texture and balanced moisture production and is lower-maintenance than other skin types. This indicates that one has a healthy skin barrier and maintains a proper skincare routine. Treatment for normal skin typically involves gentle cleansing, lightweight moisturizers, and broad-spectrum sunscreen to protect against environmental stressors. Despite its stability, normal skin can be affected by environmental conditions. High humidity can increase oil production and lead to clogged pores, while cold or dry climates can strip the skin of its natural moisture, resulting in dryness and flakiness. Pollution and UV exposure are also factors that can damage the skin barrier and increase signs of aging (Aremu, 2022). Dermatologists recommend using products containing antioxidants, such as vitamin C and niacinamide, which help neutralize free radicals and maintain the skin's current state (Aremu, 2022). Therefore, adapting skincare routines to seasonal and environmental changes is crucial for preserving the resilience and appearance of normal skin.

V. Sensitive Skin - Treatment/Management

Sensitive skin occurs when the sensory nerve endings in the upper layers of the skin become easily irritated by physical, chemical, or environmental stimuli. This heightened reactivity is frequently associated with a genetically thinner epidermis and a weakened lipid barrier, both of which reduce the skin's ability to protect against irritants (Olsson, 2023). When the lipid barrier is compromised, the skin becomes more vulnerable to inflammation, dryness, and external triggers. Chronic conditions such as rosacea, erythromyalgia, and allergies can contribute to skin sensitivity as secondary effects. While these conditions cannot be cured entirely, their symptoms can be managed through skincare and environmental adjustments. Key environmental stressors include UV radiation and exposure to harsh chemicals, which can worsen sensitivity and damage the skin's protective barrier. For this reason, it is recommended that individuals with sensitive skin use unscented, hypoallergenic, and paraben-free products. There should be minimal physical exfoliation, and broad-spectrum sunscreens with SPF 30 or higher containing zinc oxide or titanium dioxide are essential to prevent sun-induced irritation (Olsson, 2023). Individuals with environmental allergies, such as pollen sensitivity, may also benefit from avoiding outdoor exposure during high-allergen seasons.

Inflammation and flare-ups are common among individuals with sensitive skin and are best addressed through the use of moisturizers and anti-inflammatory treatments. Bathing habits also play a significant role; long, hot showers can strip the skin of natural oils, whereas warm or cool baths, along with soothing ingredients like oatmeal, can calm irritation (Cobbs, 2023). Popular consumer solutions for managing sensitive skin include *Aveeno Soothing Oatmeal Bath Treatment.*

VI. Acne Skin - Treatment/Management

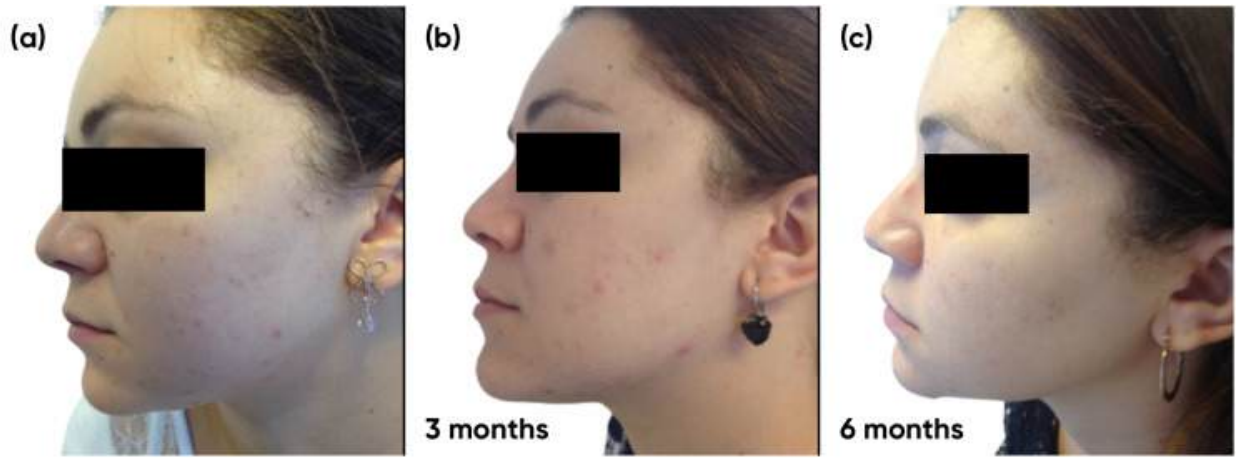


Figure 3: One patient's skin health improvement with 6 months of Azelaic Acid Gel

Acne-prone skin is a common yet complex skin type influenced by hormonal changes, genetics, lifestyle, and environmental factors, requiring targeted care to manage excess oil, clogged pores, and inflammation while preserving the skin's natural barrier. When the body's regular hormone levels fluctuate, sebum production increases, leading to clogged pores and acne breakouts (Layton, 2021). This typically occurs in adolescents going through puberty and in pregnant women, but acne can appear at any age. Genetics also plays a significant role in acne, as the amount of sebum produced by sebaceous glands is determined by heredity (Layton, 2021). The environment also has an impact on acne-prone skin. Pollutants tend to clog the pores, increase inflammation, and result in acne breakouts. Additionally, humidity can promote an increase in oil production.

To effectively manage these contributing factors, a variety of treatment options have been developed to target the root causes of acne and support overall skin health. In a study examining the effect of Azelaic Acid on multiple acne patients, it was revealed that daily usage of this topical treatment significantly improved the patients' skin health and reduced the visibility of their acne and hyperpigmentation that resulted from it (**Figure 3**). Oral hormonal medicine was occasionally used in combination with Azelaic Acid in more severe cases to reduce overall sebum (Layton, 2021). Depending on the severity of the acne, they were prescribed for 6 to 18 months and reported improvement in skin health and self-esteem (Layton, 2021).

There are also over-the-counter acne solutions; products containing niacinamide and glycolic acid have an exfoliating effect that opens pores and helps eliminate sebum. The Ordinary Niacinamide Serum contains 10% niacinamide and 1% zinc, which fights bacteria while being anti-inflammatory. It is also important to maintain a clean and consistent skincare regimen. Avoid reusing towels to clean the skin to reduce the risk of bacteria and dirt contacting it, exfoliate using glycolic acid twice a week, and use a cleanser twice a day. A common cleanser used among acne patients with the CeraVe Foaming Facial Cleanser, as it contains niacinamide and several ceramides.

Discussion

This analysis of how cosmetic ingredients and environmental factors can impact skin types reveals which are best for optimizing and maintaining proper skin health. Skin health is increasingly recognized as a reflection of both internal biological mechanisms and external environmental exposure. Research supports the beneficial role of humectants, such as hyaluronic acid, in dry skin, citing their ability to enhance water retention and improve barrier integrity. Similarly, occlusive agents such as petrolatum have been shown to reduce transepidermal water loss, aligning with findings on the repair of xeroderma (Gade, 2023). In contrast, oily and acne-prone skin types require careful balancing. Literature emphasizes the role of niacinamide and glycolic acid in managing excess sebum and preventing clogged pores (Draelos, 2012), confirming that climate-based triggers, such as humidity and heat, can intensify symptoms (Layton, 2021). With these conclusions, ingredients such as niacinamide and salicylic acid are exposed as multi-functional ingredients, as they improve several skin types. These insights emphasize the need for informed skincare choices that consider both biological and environmental factors to support and maintain healthy skin across all types effectively.

This matters not only for dermatological science, but also for consumer safety. Aggressive treatments that strip oil can paradoxically increase sebum production, a key insight for those managing oily or combination skin (Zouboulis, 2004). Additionally, sensitive skin is often biologically predisposed to react negatively to environmental allergens and chemical irritants, making hypoallergenic and fragrance-free solutions a necessity (Olsson, 2023). These findings highlight that ingredient selection based on skin type and environment is essential, and consumers should be educated accordingly. By understanding how products can impact one's skin, consumers can make informed choices to best support their skincare needs.

The public's increasing reliance on cosmetic products underscores the importance of understanding these nuances. Without proper education, people unknowingly compromise their skin health by using unsuitable ingredients. Prior research typically generalized treatment recommendations, whereas this paper distinguishes how each skin type reacts based on environment and biology. That level of specificity enhances both practical application and academic inquiry. Furthermore, chronic conditions such as rosacea, eczema, and acne intersect with lifestyle choices, such as diet and external exposures, such as fragrance-free products, underscoring the need for personalized skincare. Studies like the one on oatmeal illustrate how even traditional remedies can have clinical efficacy when scientifically formulated (Hemali Gunt 2018).

A strength of this paper is its integration of current dermatological research with real-world consumer behavior and product recommendations. The analysis bridges the gap between biological science and cosmetic efficacy. One limitation is the reliance on secondary sources and product-based studies rather than primary lab-controlled experiments. This means that while trends are visible and patterns are strong, clinical generalization is limited. Future iterations might incorporate direct patient case studies or controlled trials to increase precision.

This research highlights the importance of viewing skincare not just through cosmetic lenses, but as a multifactorial health issue shaped by genetics, hormones, and environment. Future studies should adopt a more inclusive approach that accounts for ethnic diversity, regional climates, and the interaction between modern lifestyles and skin biology. Researchers can build on this review by developing personalized skincare frameworks that respond to environmental conditions and genetic profiles. Additionally, more clinical trials exploring the efficacy of ingredients across varying skin types would help refine treatment guidelines and eliminate generalizations in dermatology. Future studies may also consider exploring how the microbiome, or the composition of different bacteria, fungi, and other microbes on the skin, impacts one's skin type and predisposition to producing oily or dry skin. This review paper provides a foundational map for understanding how nuanced skincare should be, encouraging scientific inquiry that supports targeted, evidence-based solutions for improving global skin health.

Conclusion

Skin health is influenced by a complexity of genetic, hormonal, and environmental factors. As consumerism for cosmetic products increases, the risk of experiencing adverse effects such as irritation, breakouts, and long-term damage increases as well. The lack of addressing consumers of various ethnic backgrounds has put additional stress on skincare product purchasers. By understanding the root causes of various skin conditions and evaluating the impact of external factors, individuals can make informed decisions about their skincare routines. This research underscores the significance of personalized skincare solutions and environmental awareness in mitigating unnecessary skin-related distress and fostering overall skin health.

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Inspirit AI: Predicting ESG Using Machine Learning By Omar Adas

Abstract

In an era defined by escalating social inequalities, environmental degradation, and corporate governance failures, the imperative for environmental, social, and governance (ESG) investing and sustainable finance has gained unprecedented significance. Companies with strong ESG performance are in a good position to retain employees, attract more investors, and maintain customer loyalty. Most people consider ESG in their investments and are avoiding buying products from businesses believed to be engaging in unethical practices, such as greenwashing. This research leverages AI and machine learning models to predict ESG performance scores using environmental metrics (carbon emissions, water usage, and energy consumption) and financial indicators (market capitalization).

Linear regression, decision tree regressor, random forest regressor, and MLP regressors were implemented and evaluated using the root mean squared error metric from scikit-learn. A weighted ensemble was developed by combining the four models using assigned weights. Results show that the random forest regressor (RMSE = 0.160) performed better than the other individual models. According to the random forest regressor model, energy consumption and market capitalization variables are the most predictive features. This study shows that AI and machine learning algorithms can help companies, investors, customers, and authorities in predicting ESG performance scores and address data gaps where ESG ratings are not easily accessible. They can enhance forecasting precision and facilitate sustainable investment decisions.

Introduction

ESG and global importance

According to Tong (2023), ESG (Environmental, Social, and Governance) is a set of criteria used to describe environmental, social, and governance elements considered by investors when making investments and companies when managing their operations. According to Oireachtas Library & Research Service (2023), shareholders, consumers, and investors are paying increasing attention to ESG factors and actively seeking sustainable investment opportunities and products. Using ESG, investors assess a firm's capacity to manage risks and opportunities in the fast-changing global environment by considering environmental, social, and governance issues. Companies with strong ESG performance are more sustainable and responsible, and can retain employees, attract more investors, and maintain customer loyalty (Tong, 2023). According to Oireachtas Library & Research Service (2023), the results of a survey of more than 1,000 people revealed that 38% of the participants were actively avoiding buying products from businesses believed to be engaging in unethical practices like greenwashing. CFA Institute (2020) reports that more than 85% of CFA Institute members consider ESG in their investments, up from 73% in 2017. However, ESG reporting has become

increasingly fragmented, even after gaining much relevance due to data collection inconsistencies, as well as selective and subjective disclosures (OECD, 2025). Since companies use varying reporting ESG standards, artificial intelligence (AI) technology can be used as a standardized model to help infer a company's ESG performance based on measurable environmental and financial factors.

Connection between AI and ESG

According to Correia and Água (2023), artificial intelligence (AI) provides a solution to improve ESG reporting by automating data gathering and analysis using predictive analytics, natural language processing, and machine learning. These techniques can incorporate data from several sources, thus offering a holistic and accurate view of any company's ESG performance. AI can transform ESG from a backward-looking activity into a proactive strategy that predicts future outcomes and trends via its capability to process data on a real-time basis (Correia & Água, 2023). Benefits of AI in ESG reporting include (Correia & Água, 2023):

- Data aggregation: It provides a complete view of a firm's ESG performance.
- Data accuracy: It can identify and correct errors. With AI, companies have high-quality data for decision-making.
- Forecasting: It can forecast future trends and impacts, allowing companies to proactively align operations with sustainability goals.
- Predicting missing ESG ratings: AI can estimate scores for companies with limited disclosures.

These capabilities allow investors to gauge product risks and make informed investment decisions.

Research hypothesis

Financial indicators (e.g., market capitalization) and environmental metrics (e.g., carbon emissions, water usage, and energy consumption) are strong predictors of ESG performance (i.e., ESG overall). This study aims to determine whether the financial indicators and environmental metrics can effectively predict the overall ESG performance of companies. Market capitalization represents a firm's scale and resource capacity. Large companies are better positioned to allocate adequate resources towards sustainability programs or projects, leading to strong ESG performance. On the other hand, environmental metrics such as carbon emissions, water usage, and energy consumption capture any organization's ecological footprint. This hypothesis will be validated using machine learning to show how AI models or algorithms can be used to support sustainability in companies.

Literature review

Belkhiria et al. (2025) conducted a study to evaluate the relevance of financial

performance as a strong and accurate predictor of ESG scores for French firms from 2010 to 2022. Polynomial regression, linear regression, support vector regression (SVR), and random forest machine learning algorithms were employed to provide more accurate and reliable assessments. Belkhiria et al. (2025) found that random forest outperformed other algorithms in predicting ESG scores from company financial variables. Additionally, Belkhiria et al. (2025) found that specific financial variables such as enterprise value, market capitalization, and operating income were powerful predictors of firms' ESG scores.

Jiang (2024) investigated the use of machine learning to predict ESG by determining the most influential factors within firms' reports. The author used three models: random forest, linear regression, and gradient boosting to estimate ESG risk scores. Jiang (2024) found that the gradient boosting model performed better than the random forest and linear regression models in accuracy. The author also found that the primary influencer of ESG scores is industry classification, followed by financial indicators such as market capitalization, price/book, and price/sales.

According to Dwivedi et al. (2023), machine learning models for predicting ESG scores are valuable tools to assist investors in making more informed decisions about their portfolios. The authors built machine learning models to predict ESG ratings of organizations (NIFTY100 ESG Index), where ESG ratings were not easily accessible. Dwivedi et al. (2023) found that the gradient boosting model outperformed other models such as ensemble, neural network, random forest, decision tree, and linear regression. The most crucial variables for the gradient boosting model included operating revenue, profit margin, P/L before tax, number of Publications, etc.

Problem Significance

Despite companies around the world adopting ESG principles, ESG reporting remains difficult for many due to inconsistent and incomplete ESG data. Many companies rely on varied and non standardized ESG models, making ESG reporting highly fragmented. Other challenges companies are experiencing include selective and subjective reports and a lack of uniformity in data. AI and machine learning models can bridge the gap by enabling companies to analyze financial and environmental indicators to infer ESG performance. While prior research shows that machine learning models can predict ESG scores with significant accuracy, this study will extend existing literature by building models that can capture and balance heterogeneity in ESG data. This study aims for higher accuracy by creating an ensemble of different algorithms (such as linear regression, decision tree regressor, random forest, and multiple perceptron (MLP) regressor). The study findings will be valuable to customers, investors, companies, and authorities seeking objective, quantifiable ESG performance.

Materials and Methods

Dataset Description

The "company ESG financial" dataset contains data about 100 companies in different

regions from 2015 to 2025. The dataset captures records such as company name, industry, region, and year. It contains financial indicators such as revenue, profit margin, market capitalization, and growth rate. Also, it has environmental metrics such as carbon emissions, water usage, and energy consumption. Data cleaning and normalization were completed on the dataset to ensure the data is in the proper standard or form to fit different machine learning algorithms. Only the GrowthRate had missing values (1,000). These missing values were imputed with the mean.

- Target variable: Overall ESG (ESG_Overall)
- Features (predictors): Market capitalization (MarketCap), carbon emissions (CarbonEmissions), water usage (WaterUsage), and energy consumption (EnergyConsumption).

Data splitting and normalization

Data splitting is important to allow for unbiased evaluation of prediction performance. The train_test_split() method was used to split the data into training and test sets. The method requires the prediction target y and features X. Other parameters include:

- Test size: represents the proportion of the dataset for the test set.
- Random state: Controls the shuffling process of data before splitting.

The dataset was split into a 67% training set and a 33% test set using the train_test_split() method. The ESG scores were rescaled to a fixed range using the MinMaxScaler. This was important to preserve the original data distribution shape, ensure all values fall within a bounded range, and ensure the data work well for machine learning algorithms (neural networks). The models' performance was assessed using the mean squared error (MSE). MSE is measured in target units, squared.

Linear Regression Model

The linear regression model uses the relationship between data values to fit a straight line through them. It assumes a direct relationship between the features and the target (overall ESG score). The linear regression equation is:

$$Overall\ ESG\ Score = \beta_0 + \beta_1 * MarketCap + \beta_2 * CarbonEmissions + \beta_3 * WaterUsage + \beta_4 * EnergyConsumption + \varepsilon$$

The linear regression model only explains about 2.8% of the variability in the overall ESG score. The model has an average error of approximately 0.165 (RMSE = 0.165) for overall ESG on the test set.

Decision Tree Regressor

A decision tree regressor predicts continuous values using a tree-like structure. It splits

data into smaller components based on simple rules taken from the features. DecisionTreeRegressor() from scikit-learn was used to implement the decision tree regressor. The decision tree regressor had the following hyperparameter:

- max_depth = 2 (maximum depth of the tree)

The decision tree regressor performed better than the linear regression model. The model has an average error of approximately 0.161(RMSE = 0.161) for overall ESG on the test set.

Random Forest Regressor

A random forest regressor is an ensemble technique that utilizes a decision tree regressor as its base estimator. Each estimator in random forests is trained on a different sample of the same size as the training set. They introduce the required randomization when training each base estimator (decision tree regressors). Random forests reduce variance by averaging all labels
predicted by the base estimators to give a more robust and accurate overall prediction. The hyperparameters for the random forest regressor are:

- max_depth = 2
- n_estimators = 100

The random forest regressor performed better than the linear regression and the decision tree regressor. The model has an average error of approximately 0.160 for overall ESG on the test set.

Multilayer Perceptron (MLP) Regressor

The Multilayer Perceptron (MLP) Regressor is a neural network algorithm that trains iteratively, as it calculates the partial derivatives of the loss function with respect to the model parameters at each step to update the parameters. It can integrate a regularization term into the loss function to shrink model parameters to avoid overfitting. The MLP regressor was fit to the training set using the following optimal parameters:

- hidden_layer_sizes: 100 (default)
- activation: relu (default)
- learning rate: constant (default)
- max_iter: 200
- tol: 0.0001 (Default)

The model has an average error of approximately 43,951(RMSE = 43,951) for overall ESG on the test set. The model performed far worse than all other models.

Averaging and weighting system

An average of the models' predictions was calculated assuming equal variance. The ensemble achieved an RMSE of 0.160. The weights used to calculate the ensemble are:

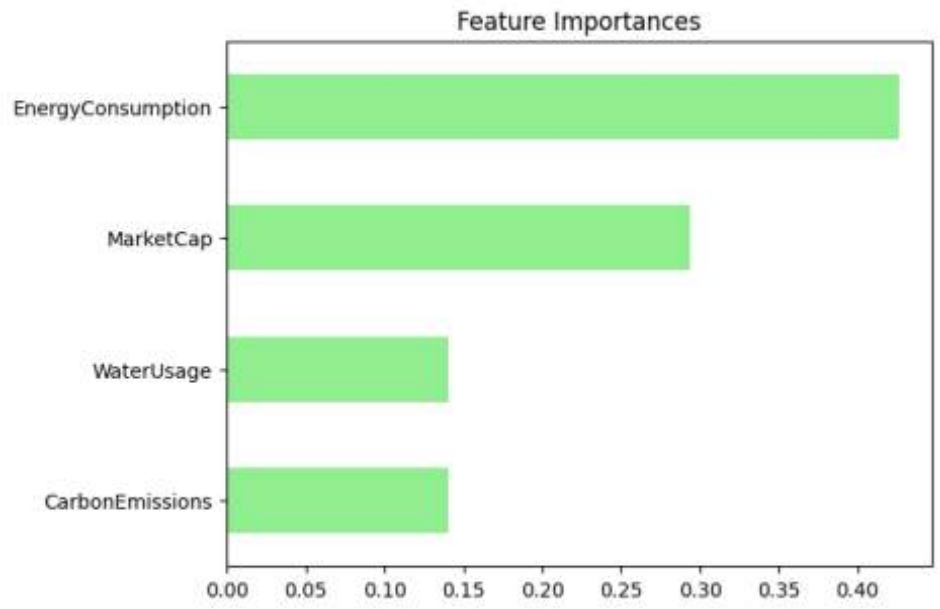
- Linear regression = 0.320
- Decision tree regressor = 0.333
- Random forest = 0.341
- MLP regressor = 0.00000000000045

The average weighted ensemble (RMSE = 0.160) did not outperform the decision tree regressor or the random forest.

Results

Model	RMSE Training	RMSE Testing
Linear regression	0.165	0.165
Decision tree regressor	0.161	0.161
Random forest regressor	0.160	0.160
MLP regressor	43,951	43,951
Weighted ensemble	0.160	0.160

As shown above, the random forest regressor outperformed the other models (linear regression, decision tree regressor, MLP regressor, and weighted ensemble) in both train and test sets. The model has an average error of approximately 0.160 for overall ESG on the test set. Since the random forest regressor was the best model, it was used to measure the importance of each feature in the prediction. In scikit-learn, feature importance is evaluated by measuring how much a tree node utilizes a specific feature to reduce impurity. After training the random forest regressor, feature importances were accessed by extracting the feature_importance_ attribute from the model. According to the random forest regressor model, energy consumption and market capitalization variables are the most predictive features, as shown below.



The weighted ensemble was not the best model because averaging and weighting did not effectively cancel out much noise, which negatively impacted its performance. The best model has an average error of only 0.160, showing higher prediction performance. The model is suitable for practical applications in real-life ESG analysis for investment purposes.

Discussion

The study results show that machine learning models (AI) can help companies predict their ESG performance. The random forest regressor had the smallest root mean squared error than the six other models. Companies can also use machine learning models to understand the most important ESG indicators to focus on to achieve their sustainability goals. According to the random forest regressor model, energy consumption is the most predictive feature, followed by market capitalization, water usage, and carbon emissions. This aligns with the findings of Belkhiria et al. (2025) and Jiang (2024) that market capitalization is among the best influencers of ESG performance. Key technical challenges faced during the study include:

- Imbalanced data: This results from inconsistencies in data collection and subjective reporting by companies. Most ESG data does not adequately represent companies by size and industry. This introduces bias that can impact the performance of the machine learning model. A representative dataset should be used to improve the performance and accuracy of the machine learning models.
- Overfitting: In reality, ESG data generation is always accompanied by noise or randomness. For machine learning models, the goal is to achieve a low predictive error on unseen datasets by discarding noise as much as possible. In this case, overfitting is a challenge for the model when making predictions. The linear regression, decision tree

regressor, and MLP regressor achieved lower accuracy or prediction power than the random forest. This part is due to the inability to generalize results and the increased model complexity. This issue should be addressed using regularization techniques and limiting model complexity.

- Regularization: Regularization is a method used to prevent overfitting by adding a penalty for complexity. It encourages simpler, more generalizable models that can perform better on new, unseen data.

x

- Dropout: According to Salehin and Kang (2023), dropout is a regularization technique that helps prevent a neural network model from overfitting in the training phase. The MLP regressor did not implement the dropout technique because most of its default parameters were maintained during model fitting. With dropout, the model's robustness and prediction power could be improved.

Future work

In the future, this study could be extended by:

- Considering textual ESG data when building the machine learning models. Natural language processing could help analyze textual ESG data, such as sustainability reports, to enrich the models' features.
- Using cross-market datasets to validate the machine learning models. This will help inform the application of these models on a global scale.
- Consider regularization and dropout in the MLP regressor model to prevent overfitting in order to improve the model's performance. Moreover, adjusting the default parameters, such as hidden layer size, activation function, and learning rate, can help improve the model's performance.

Conclusion

This study shows how AI and machine learning (ML) can be used to predict a firm's ESG performance. It leverages machine learning models (linear regression, decision tree regressor, and random forest regressor) and an AI model (MLP regressor-based neural network) to analyze and predict ESG scores. The random forest regressor outperformed other models. According to the model, the key predictors of ESG performance are energy consumption and market xi
capitalization. The study helps bridge the gap between ESG data and ESG reporting, laying a foundation for scalable, automated ESG analysis and prediction in companies. AI and ML models provide a route to a more objective sustainability analysis as ESG sustainability continues to gain traction.

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Seismic Energy Harvesting Revised Research By Lohitaksh Gupta

1.1 ABSTRACT

This research aims to calculate the energy that can be generated by the energy harvesting of **seismic waves** from earthquakes in a region over a year and therefore analyse the efficiency of the process to conclude if it can be used as a clean energy source while working as a backup energy system for these areas. This is to predict if such harvesting could be used in **earthquake-prone** cities, the research has been done with an innovative plan of the **grid system**- pyramidal structures across streets with energy storage and connection to each other- of the device to show the scope of the seismic energy. The energy generated by a single mechanism in the device is estimated to be 5.8W, which is also generated by 3 ther mechanisms in different directions in the device, multiplying the output by 3, with 50% efficiency. The system that has been used has this mechanism 3-4 sides, generates more energy, the muti-axis capture may increase duty factor, but has to be validated experimentally. The aim of the study is to predict if such harvesting of energy is possible in the future, to run cities, and develop more technology on this. The findings of this study have been taken from various sources, to calculate the efficiency and the energy. The is inspired from other studies and the system of the device has been thought of to make this more realistic and available to maximise the use of the device.

1.2 INTRODUCTION

With major renewable energy sources such as hydro, wind and solar, research into clean energy is expanding as humans are trying to replace non-renewable energy completely. While there has been limited research into seismic energy harvesting because of its unpredictable nature and doubt in its efficiency, there is great potential that could be used. The few research papers that have been published explore the efficiency of a mechanism that can achieve this, and theoretically, it is possible to have better efficiency of the system. The earthquakes have long acted as destructors that cause great damage to the infrastructure and the power grids, the damage to the buildings is caused by the strong vibrations from the movement of tectonic plates which is because of the energy release from the core, making the city lose its power and functioning. If used as a power source, the energy from these movements could be converted into useful electric energy instead of mechanical waves, mitigating the effect of the earthquakes. A mechanism to harvest this energy would work like the power grids to power the cities at the time of the earthquakes which would allow the city to work efficiently.

The research into the topic is scarce with different mechanisms proposed, based on single direction waves and a single device. Such as the one mentioned in a paper (1), which proposes a mechanism that captures waves only in one direction and only predicts the energy with a different application of the system. Their research works with microseisms and the idea of the system was different as well. Moreover, a paper published (2), refers to the dual purpose of seismic energy harvesting, which gives a lot of information into this topic.

In contrast and hope for higher efficiency, the mechanism described in this paper aims to

use the waves from all directions, and looking at the possibility of the earthquakes' waves spreading out in all directions, the mechanisms act as a part of the power grid which can help use a fraction of the large amount of energy released by an earthquake. The protection of the structure is done by its strong tetrahedral design.

2 METHODOLOGY

2.1 Procedure

This works on the basis of electromagnetic induction, the seismic energy released by earthquakes is converted into electricity. The vibration of the ground has been calculated according to the equations provided by the sources. To prove and investigate the efficiency of the mechanism, a case study is conducted on Budta, a place in the Philippines, that is around 3.5 magnitude. The energy reaching the mechanism with the peak ground acceleration and the frequency is calculated, with the efficiency of the mechanism assumed to be 50%. The structure of the mechanism and the planning has been described, assuming the distance and the number of mechanisms to predict if this would be a good backup system.

2.2 BACKGROUND INFORMATION

2.2.1 EARTHQUAKES

The earthquakes as traditionally known are a great source of energy, especially mechanical energy that is transferred through the movement of rocks. The mechanical energy, as elastic rebound theory says, can be stored in rocks (3). The short movement in the two ends of the faults elastically strains the rock near the fault. When the elastic strain exceeds the frictional strength of the fault, a hypocentre forms at the weakest point. From the hypocentre, the rupture rapidly propagates along the surface of the fault, causing the sides of the fault to slip past each other. In the opposite reaction to the force exerted by the rocks' frictional stress, rocks along the fault release energy. The energy in rocks is in the form of elastic energy, which is released in the form of heat. The series of waves radiate from the hypocentre in all directions, producing earthquakes. The amplitude of the seismic waves can range from micrometers (millionths of a meter) to tens of meters. The amount by which the seismic waves deform the ground decreases with distance from the earthquake.

2.2.2 MEASURING EARTHQUAKE

The most popular kind of magnitude is the richer magnitude to measure the strength of the earthquake, the other one is moment magnitude which is derived from analysis of all waveforms recorded from the shaking.

Moment(MO)= rigidity x area x slip

where rigidity is the strength of the rock along the fault, area is the area of the fault that slipped, and slip is the distance the fault moved. Thus, stronger rock material, or a larger area, or more

movement in an earthquake will all contribute to producing a larger magnitude (4). Then Moment Magnitude (MW) :

$$M_{w} = \frac{2}{3} \log_{10}(M_0) - 9.1$$

Where:

● *MO* is the Moment.

Another way to measure the magnitude of the earthquake is by measuring its energy released, energy magnitude. The moment magnitude could be converted into energy magnitude by the following equation:

$$logE = 5.24 + 1.44Mw$$

Format the equations

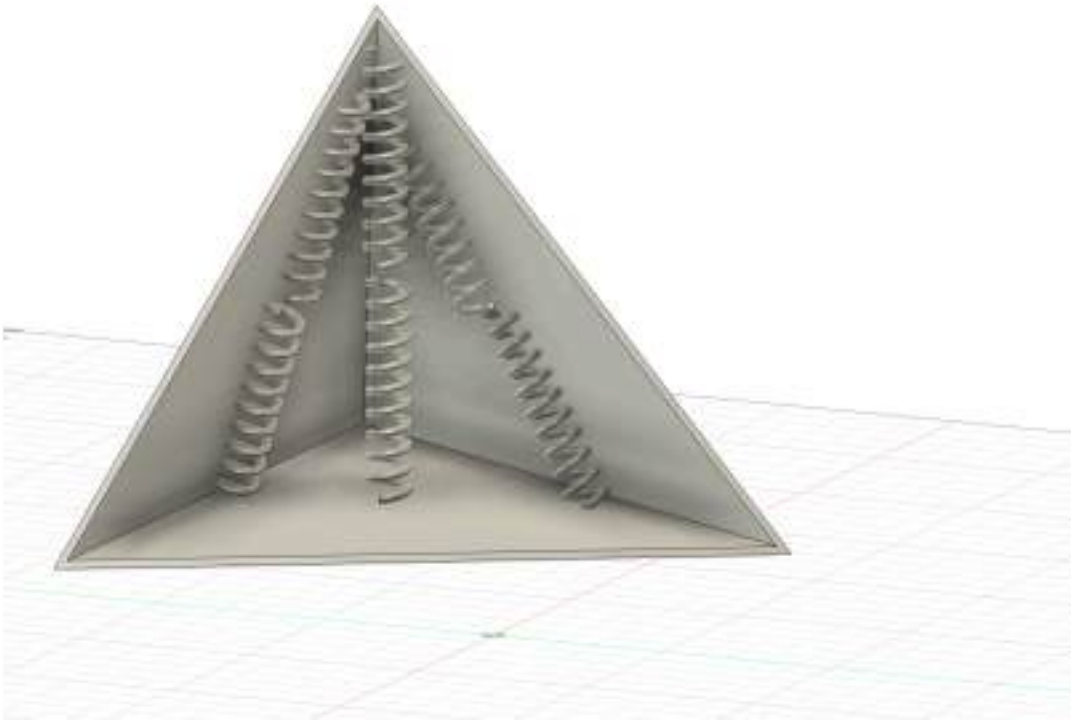
2.2.3 SEISMIC WAVES

The wave as it travels from the epicentre, attenuates, which means that it wears down or the energy is lost from the wave as it is disrupted (5).
This equation can be rearranged to calculate the energy that reaches the mechanism. However there are other ways to calculate the power or energy at the point from the earthquakes, mentioned as pinpoint power.

3 MECHANISM

3.1 THE STRUCTURE

The mechanism has been designed in a tetrahedral structure to maintain its stability during earthquakes. Inspired by mechanisms used in previous papers published, incorporating a design that converts the waves from all directions, it offers more efficiency. The three faces of the pyramid and the vertical space in the middle, all are occupied by 2 springs each on two ends and magnet, directed by the set path carved in the face. The two springs help change the direction of the momentum of the magnet, with coils surrounding each of them. The constant change in momentum and the velocity of the magnet help with the current generation. In comparison to the mechanisms mentioned in other sources, the probability of the device capturing the wave is increased to the maximum. Similar to the one being investigated in the paper, a research explores one mechanism, which could be the base of all the calculations of energy output from the device.



3.2 THE EFFICIENCY

The efficiency of the mechanism is highly dependent on the selection of the springs and the material used to make it. A similar study on harvesting using Belleville springs was done, which estimates the equation for output power with specifics of the mechanism. These particular specs of the mechanism could be changed to make it
more efficient. The mechanics, however, allow it to respond effectively to low frequency, broadband vibrations typical of seismic sources. The system converts kinetic energy into electrical energy via permanent magnets oscillating inside coils. The prototype described in the paper achieved an operational bandwidth from approximately 120-180 H, producing power up to several milliwatts depending on the number of magnets and input acceleration.

The equation for the input power from the seismic excitation can be estimated using the following equation:

$$P_{\text{input}} = {}^{1}{}_{2}\, m\, A^2 \omega^3$$

Where:

- m: effective mass of the moving components (kg),
- A: peak ground acceleration (m/s²),
- ω: angular frequency of excitation (rad/s).

To estimate A and ω from an earthquake of magnitude M, you can use the following empirical approximations:

1.Peak Ground Acceleration (PGA):

$$\log_{10}(PGA) = a + bM - \log_{10}(R + c)$$

For typical rock site conditions, a=−1.5, b=0.5, c=10

Where:

- R is the distance from the epicentre in kilometres
- M is the richer-scale magnitude.

Convert the result to linear units with A=10^log10(PGA).

2.Dominant Frequency:

f≈10/M殱ω=2πf

P =m . damping ratio . resonant frequency. maximum relative displacement

4 CASE STUDY

4.1 FREQUENCY OF EARTHQUAKES IN BUDTA, PHILIPPINES

In 2024, Budta was ranked number 7 for number of earthquakes according to the earthquake list [8], with 290 earthquakes yearly. The average magnitude of the earthquakes is 3.5. In earthquakes of this range, a developing country like Budta, has electrical failures that need to have backup systems. The mechanism is to be installed in a system like electric poles and the grid, which could produce continuous supplies of electricity during earthquakes and store it, to be used as a backup system for lights.

4.2 CALCULATION OF ENERGY FROM EARTHQUAKES

$$E= 5.24+1.44M$$

Magnitude M=3.5

Which is the average magnitude of the earthquakes in Budta, Philippines.

Distance R=1 km

As explained previously, the system will be like that of the electric grid or the water hydrants, which will be spread around the city, mainly around the expected epicenters. This will decrease the distance between the epicenter and mechanism to a few hundred metres.

$$\text{PGA A} \approx 0.2116 \text{ m/s}^2$$

Dominant frequency f ≈ 2.857 Hz (ω ≈ 17.94 rad/s)

Using these values of PGA and Dominant Frequency:

Input mechanical power Pin≈11.517
Output electrical power at 50% efficiency Pout ≈ 5.7585 W

The mechanism has the springs and magnets facing all the directions that would produce more energy and the mechanism placed together as a grid would be more efficient.

5 ANALYSIS AND CONCLUSION

The power output is enough to power emergency lights. If 80 percent of the number of electric poles in Budta are set up then they could be used together to power the emergency lights. Though the power generated by the mechanism is quite low, the theoretical value is the minimum that can be generated through the mechanism as the specs have been kept to a minimum. This value can be multiplied by 3 or 4 to count the different spring-magnet systems in the mechanism, this will produce 15 W at least, that can power an emergency light for 2-3 hours. The device could be used as a back up system for emergency light in developing or underdeveloped countries that are prone to earthquakes and do not have rigid electrical systems which can sustain earthquakes. This with storage will also store the electrical energy from microseisms that do not affect the energy grids. The power produced is 5.785 W by one mechanism in a device, the grid could be used to make the seismic energy consumed better and mitigate the effect of the mechanical waves. The waves that cause the vibrations in the buildings are being used in the system to generate electricity which will dampen the waves upon the buildings.

If researched more and experimented on more, then the mechanism could be improved to be more efficient, and used as a proper electrical system that uses energy from microseisms and earthquakes. Scientists and researchers could implement a similar structure as suggested in this paper, in a small earthquake-prone zone to validate these results. They could further make changes to the features of the mechanism that would increase the efficiency and the grid- system, to make this feasible in larger areas and cities. The implementation of such an energy system could change the face of renewable energy, bringing an innovative approach to the use of seismic energy, dampening the effect of the earthquakes on cities' building and energy systems, and providing electrical energy.

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Statistical Study of Tug of War by Spandan Mukherjee:
through a Simulator to Understand the Underlying Nonlinear Dynamics
By Spandan Mukherjee

Abstract

This project uses a custom Python simulator to model a tug-of-war match as a nonlinear dynamical system, powered by different varying forces, friction and fatigue. This Python simulator allows for running of a large number of games simultaneously, each having some amount of stochastic variability between the competing teams in the game. Collecting data from all of these games, and observing various statistics, we will be able to study the underlying patterns arising from the nonlinear dynamics, all derived from Tug of War, a simple game, with a few creative liberties.

Introduction

At first glance, tug of war may seem like nothing more than a contest of strength between two teams pulling on opposite ends of a rope. Yet beneath this seemingly simple display of force lies a complex interplay of physical and psychological factors that make the game far more intricate than it appears. When examined through the lens of physics and nonlinear dynamics, tug of war reveals a web of interacting variables-coordination, friction, drag, fatigue, and timing-each of which contributes to the final outcome. The tension along the rope, the uneven application of force, and the shifting balance of resistance between the teams form a dynamic system that evolves continuously in time, often in unpredictable ways.

In mechanical terms, the rope's motion and the players' exertions constitute a coupled system governed by Newtonian principles but driven by stochastic influences. Every player's pull alters the collective force applied to the rope, while friction and drag dissipate energy unevenly. As fatigue accumulates, force generation decays nonlinearly, and coordination within a team may fluctuate, introducing small but consequential variations in performance. These interdependent effects render tug of war a prime example of a nonlinear dynamical system-one in which output is not simply proportional to input, and minor perturbations can yield disproportionately large effects.

The goal of this project is to model these complexities using a computational simulator capable of reproducing the essential physics of a tug-of-war match while incorporating randomness and uncertainty to reflect real-world conditions. By simulating hundreds or even thousands of games with variable parameters, the model seeks to uncover statistical patterns emerging from the collective interactions of deterministic and stochastic components. Through this approach, the simulator provides a means to analyze how chaos manifests in a seemingly straightforward game and to explore how coordination, friction, and fatigue combine to shape the temporal evolution of the system.

Ultimately, this study treats tug of war not merely as a sport but as a microcosm of nonlinear behavior in physical systems. It illustrates how small fluctuations-variations in timing, force, or synchronization-can accumulate into large-scale differences in outcome. In doing so, the project bridges the gap between intuitive physical play and formal dynamical theory, showing that even the simplest of human competitions can serve as a window into the deeper mechanics of complex, chaotic motion.

Time Progression Chart

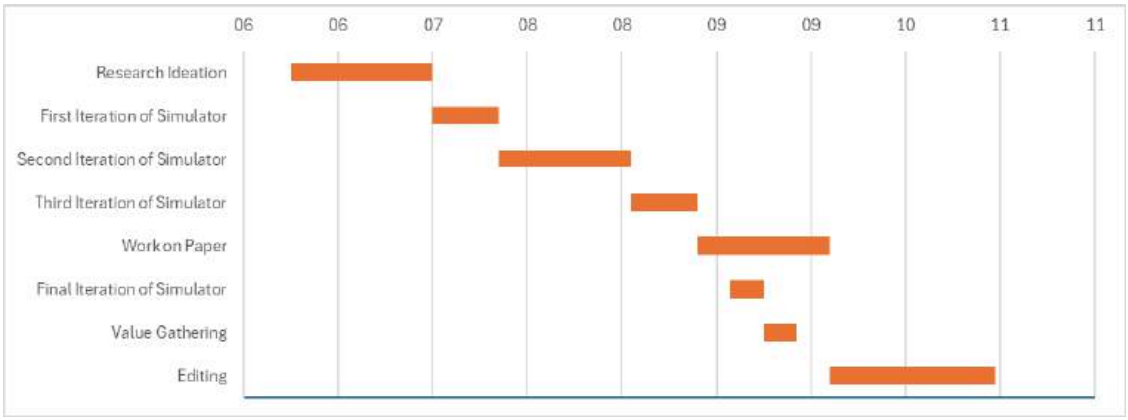


Fig. 1: A Gantt Chart showing the progress in this project

Approaches

The first iteration of a Tug of War simulator had the three programs that the final version uses, and used Python's inbuilt random module, simulated every game consecutively, and stored the values obtained each calculation into a JSON file. The forces of each one had 4 additional factors, alongside the Gaussian-distributed base force: A randomly distributed jerk multiplier (10% chance), a linearly varying winning multiplier, a linearly varying fatigue multiplier and a capped Gaussian distributed friction multiplier. The simulator worked well; however: it was slow, generating every individual game consecutively; and the final graphs resembled more of a rectangle than a chaotic shape achieved with the final iteration.

The second iteration introduced threads, allowing for parallel running of games. It maintained the three programs, but stored more information into the JSON file than the other one, now storing and displaying velocities, displacements, deviations as well as a scatterplot of the first two. It displayed statistics about the games, including win-loss tallies and displacement averages and standard deviations. It showed for the first time that the average length of a game was about 60-65 rounds (corresponding to 60-65 seconds). However, compared to the previous iteration, it was slightly faster, but was more resource intensive, calculating multiple games simultaneously. Additionally, there was a lack of a file lock, resulting in lag due to multiple threads trying to insert into the same file.

The third iteration introduced NumPy's random library instead of Python's, using the C framework to achieve much faster calculations. It also introduced Pandas and CSV files allowing for simpler extraction of information, tweaked core calculation values (like average player strength going from 400N to 800N, or adjusting region for win multiplier,), and introduced a 'team coordination' factor. It additionally made the fatigue multiplier an exponentially decreasing function rather than a linearly decreasing one. The calculations were much faster now, but the tweaks made to the calculations, alongside removal of friction as a factor, had caused the simulation to not be very chaotic, with displacement vs. velocity scatterplots resembling predictable curves.

The final iteration of the simulator introduced a dynamic friction system: constant retardation while kinetic and proportionally retarding while static. It also used hyperbolic tan graphs for winning advantage, a more varied jerk multiplier, being fixed multipliers with random chance instead, introduced quadratic drag, used differing rates of fatigue, which would clip after a threshold. The addition of a file lock, further made this iteration faster than its predecessors. This version had the addition of other types of functions, generating more randomness and chaos than the predecessors, and its curves are chaotic, as can be observed in Fig. 5, demonstrating chaos in the best possible way. Calculations are fast, but for the most physically accurate simulation, smaller time intervals are yet to be considered.

Methodology

This research project employs the use of a custom Python simulator to simulate the tug of war games to analyse the movement of the centre of the rope over time, due to the stochastic forces and other noise added in to simulate realism. The core Python Tug of War simulator basically creates a game 'object' to simulate one game at a time, and another program creates as many desired game objects as needed in parallel threads and runs them simultaneously and adds all of the statistics into a CSV file, after which the values are plotted into graphs and shown. Alongside core Python, the project also utilizes NumPy for its random library (much faster than Python's own random library), Pandas for quick and short analysis of the results, and Matplotlib for graphing and plotting the points into scatterplots and histograms.

The simulator runs individual games as objects in separate threads, and each game runs on a 'per second basis' - all physical quantities relating to rope movement are calculated for every 'second' the game runs. There are forces calculated for each team, considering several factors, and the net is taken for them, resulting in an acceleration of the rope, as well as a velocity and displacement on the rope, calculated utilizing simple kinematical equations undergoing uniform acceleration (through the time period of 1s). The net displacement shifts the centre of the rope by an amount, negative deviation going towards team A, and positive towards team B. Once the centre of the rope reaches a win threshold - ¾ of the rope length away from the opposing team's end, the team that pulled the hardest wins, and the subsequent result is logged into a CSV file.

As for the forces themselves, there are multiple factors affecting forces for each team. For starters, there is a base force generated by a team. Each team is composed of 8 players, each having a mass of 75kg, and able to generate 600N of force individually. Overall, each team's base mean force of 4800N varies slightly each time force is calculated, based on a Gaussian distribution with a standard deviation of 10% of the mean. This force is actually 'blended' every second of time consideration; half the force generated from the last second is added to half the force generated every new second, to allow the simulation to avoid unrealistic extreme spikes in force output. This new base force for each team is subjected to 6 different modifiers to allow for addition of realistic elements into the world:

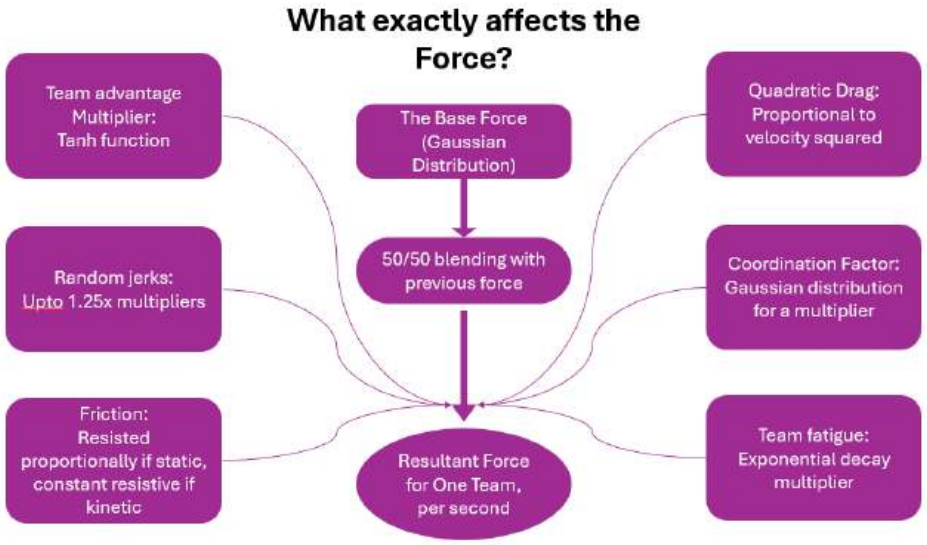


Fig. 2: A flow chart depicting all the different factors affecting the forces of each team.

1. Quadratic Drag: small, but required for realistic simulation; is a retarding force proportional to the square of the velocity of the rope
2. Coordination Factor: a multiplier meant to simulate uniform pulling from all members of a team, represented by a Gaussian Distribution of mean 1 and standard deviation 0.05
3. Team fatigue: meant to simulate tiredness of the players, modeled by an exponential decay curve, with the exponent itself being a result of a Uniform Number Distribution generated uniquely for each team per game
4. Team advantage Multiplier: meant to simulate a 'motivation boost' for the team winning; mathematically 10% the value of result of a tanh function of fraction of absolute deviation from centre to half length of rope
5. Random Jerk multiplier: meant to simulate sudden bursts of force when pulling the rope: The code gives a 90% chance for it to be 1, a 9% chance to be 1.1, a 0.9% chance to be 1.2, and 0.1% chance to be 1.25

6. Friction: probably the most important factor affecting the simulator; The simulator calculates a normal force from the mass of the teams and rope, and we find the limiting friction using that. If the net force is above the limiting friction, kinetic friction as a constant retarding force is applied. If the net force is below limiting friction, the net force is reduced proportionally, alongside a random normal distribution multiplier.

All these factors affecting force come together and create a net force on the rope, and dividing by mass we obtain an acceleration, which is used to calculate velocity and displacement on the centre of the rope, and hence, until the centre of rope reaches a win threshold, a tug of war game is simulated. Here are some examples of how the game is simulated:

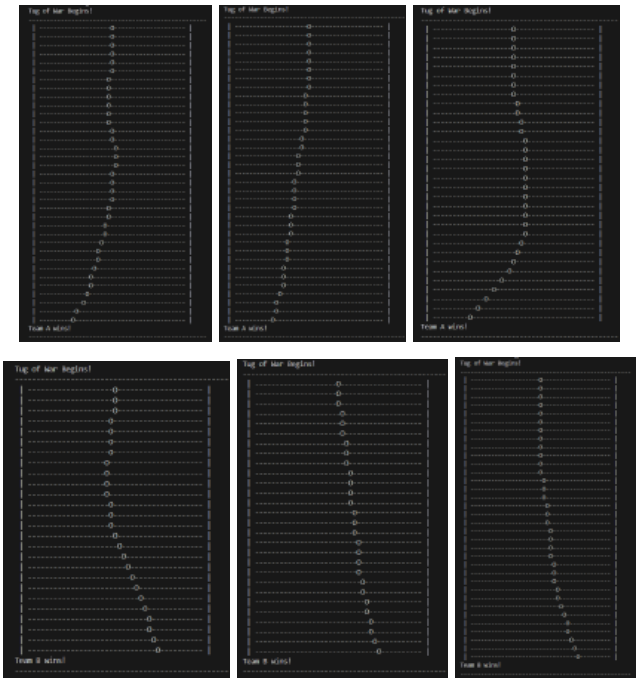


Fig. 3: examples of simulated games. Games continue till the centre of the rope (denoted by the ‘o’ in every line) reaches a win boundary on either side. If the centre reaches the left, team A wins, and if it reaches the right, team B wins.

Games like these are simulated by the hundreds, and the results from those games are set into a CSV file using a Pandas Dataframe. The CSV file stores length of each game, winner, and the arrays of displacements, velocities, accelerations and total deviations. Pandas allows us to quickly convert the values into lists from the CSV file, and calculate some basic things from the results. Some of those results, namely the displacement, velocity and accelerations arrays are taken together and plotted, as histograms of displacements and velocities, and displacement vs velocity histogram and acceleration vs velocity histogram, using Matplotlib.

For example: here is a simulation of 100 games:

```
Results reset successfully.
Enter how many times you want to run the game: 100
Results saved to tugofwar_results.csv (100 rows)

Statistics:
Total games: 100
time interval considered: 1 seconds
Avg time: 31.8900 (std: 14.0086)
Max time: 77.0 (Game No: 90)
Min time: 7.0 (Game No: 85)
Team A wins: (53)
Team B wins: (47)
```

Fig. 4: The statistics page that is returned in the terminal after executing the simulator. 'Time' signifies the length of a game. In other words, the 'rows' of the game as in Fig. 1's examples. Each new row represents a new calculation for 1 second.

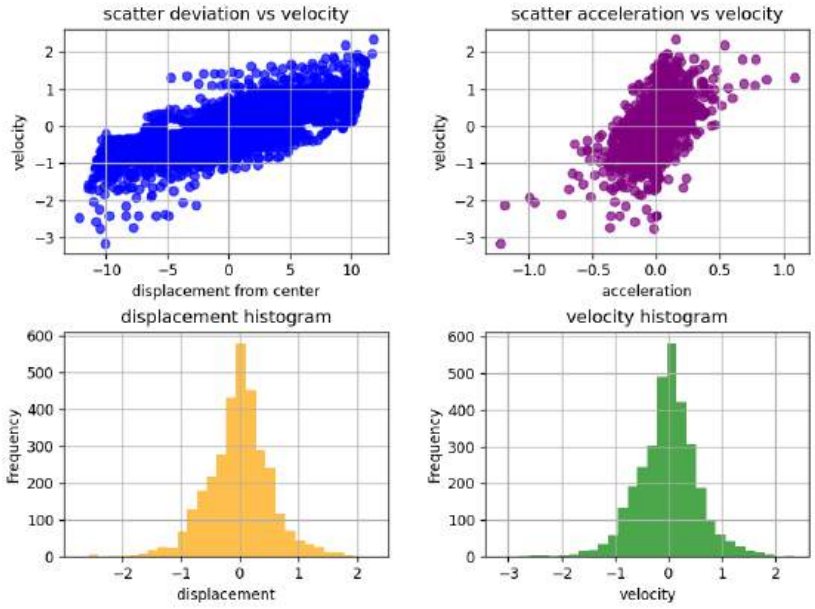


Fig. 5: The graphs based on the simulation shown in Fig. 4. Deviation refers to total displacement from the centre. The simulator shows 2 scatterplots and 2 histograms.

We can see that the average length of each game (in terms of time) was 31.89 seconds, with a standard deviation of about 14. We can also observe our different graphs of deviation versus velocity, acceleration versus velocity, a displacement histogram and a velocity histogram.

Results

The simulator was tested over multiple runs, beginning with small batches of 30 games and scaling up to 1,000 games per series. Each series consisted of five independent trials under identical initial parameters but with randomized stochastic noise applied to the teams' forces, coordination, and frictional conditions. These calculations were all simulated using the simulator, could be replicated using it (barring random variations), and no human trials were used for testing.

S. no.	Avg Length	Std deviation	Coeff of Var.	Range	Win (A - B)
1	33.5	17.8533	0.5329	10 - 77	20 - 10
2	29.1667	14.1155	0.4840	12 - 77	13 - 17
3	26.7	12.4766	0.4673	6 - 55	15 - 15
4	25.2667	13.1855	0.5219	10 - 56	19 - 11
5	33.7	18.0519	0.5357	13 - 92	15 - 15

Table 1: the 30-game series

In the 30-game series, the simulations displayed substantial variability both in duration and outcome. Average game lengths ranged between roughly 25 and 34 seconds, with standard deviations exceeding 12 seconds in most cases. Some games concluded within 6 seconds, while others extended beyond 90 seconds. Win ratios fluctuated irregularly-one series favored Team A (20–10), another leaned toward Team B (13–17), while others remained balanced. Such inconsistency reflects the strong influence of random perturbations at smaller sample sizes, where chance dominates pattern formation.

S. No.	Avg length	Std. deviation	Coeff of Var.	Range	Wins (A - B)
1	31.2	14.3896	0.4612	13 - 61	21 - 29
2	28.04	14.6077	0.5210	10 - 84	26 - 24
3	29.84	16.4222	0.5503	8 - 76	30 - 20
4	29.66	16.0670	0.5417	8 - 93	20 - 30
5	31.14	15.6087	0.5012	10 - 79	20 - 30

Table 2: the 50-game series

S. No.	Avg length	Std. deviation	Coeff of Var.	Range	Wins (A - B)
1	29.85	13.422	0.4496	12 - 67	53 - 47
2	32.04	16.0937	0.5023	7 - 80	47 - 53
3	28.48	12.7711	0.4484	7 - 63	46 - 54
4	28.36	14.1168	0.4978	5 - 77	48 - 52
5	33.79	18.3062	0.5338	8 - 92	51 - 49

Table 3: the 100-game series

As the number of simulations increased to 50 and 100 games, the data began to exhibit early signs of statistical convergence. Mean game durations stabilized near 30 seconds, with standard deviations remaining around 14–16. The range of game lengths continued to be broad, extending from 5 to 90 seconds, yet the win ratios grew progressively symmetric. In the 100-game sets, nearly all trials hovered close to a 50–50 split between the two teams, with deviations rarely exceeding a few percentage points. This suggests that while individual games remained unpredictable, ensemble behavior trended toward balance.

S. No.	Avg length	Std. deviation	Coeff of Var.	Range	Wins (A - B)
1	30.476	15.9739	0.5241	7 - 97	135 - 115
2	28.892	15.5375	0.5378	6 - 105	135 - 115
3	27.884	13.3825	0.4799	8 - 90	121 - 129
4	29.4	14.4077	0.4901	6 - 90	127 - 123
5	30.584	14.3659	0.4697	8 - 77	118 - 132

Table 4: the 250-game Series

S. No.	Avg length	Std deviation	Coeff of Var.	Range	Wins (A - B)
1	29.85	13.9298	0.4667	7 - 90	242 - 258
2	30.002	15.2883	0.5096	8 - 153	255 - 245
3	30.402	15.7196	0.5171	4 - 116	260 - 240
4	32.292	17.1531	0.5312	9 - 141	255 - 245
5	29.982	15.2032	0.5071	6 - 114	242 - 258

Table 5: the 500-game series

The 250-game and 500-game series reinforced this tendency. Average durations clustered tightly between 28 and 31 seconds, and the standard deviation values persisted within a narrow 13–16 second band. The wide range of completion times-from as low as 6 seconds to as high as 153-indicates that random fluctuations in local conditions continued to generate occasional extreme outcomes, yet the overall distribution of results maintained equilibrium. Win counts oscillated slightly but always circled around parity: for example, 135–115 in two 250-game runs and 242–258 in two 500-game runs.

S. No.	Avg length	Std deviation	Coeff of Var.	Range	Wins (A - B)
1	30.065	15.0795	0.5016	5 - 128	501 - 499
2	30.583	15.3649	0.5024	6 - 127	480 - 520
3	30.309	16.3862	0.5406	6 - 153	533 - 467
4	29.894	15.4343	0.5163	5 - 161	515 - 485
5	30.452	15.4705	0.5080	6 - 123	489 - 511

Table 6: the 1,000-game series

By the 1,000-game series, the data achieved remarkable stability. Across all five trials, mean durations hovered consistently near 30 seconds, with minimal variation between runs. Standard deviations remained near 15 seconds, and the range of game times extended from 5 to 160 seconds-showing that short and long matches persisted even in large ensembles. Crucially, the win statistics converged almost perfectly to equilibrium: 501–499, 480–520, and similar near-symmetric splits. The mean displacements, velocities, and accelerations (as shown in extended simulations) approached zero, confirming that the tug-of-war system, when averaged over many stochastic realizations, remains dynamically balanced.

Taken together, these results suggest a system governed by deterministic equations but dominated by nonlinear sensitivity. At smaller scales, randomness appears overwhelming, producing wide fluctuations in duration and outcomes. Yet as the number of simulations increases, underlying order begins to emerge-a statistical symmetry reminiscent of chaotic systems that exhibit unpredictable microstates yet stable macroscopic distributions. The simulator thus demonstrates both the volatility and the equilibrium characteristic of chaos: sensitivity at the level of individual matches, and self-organizing balance in the aggregate.

These numerical patterns correspond closely to the 10,000-game visual outputs presented in the accompanying figures. The simulator was made to generate 10,000 games simultaneously, and it can be observed that the scatterplots of deviation versus velocity and acceleration versus velocity form dense, irregular clouds centered on the origin-illustrating bounded but non-repetitive dynamics. The histograms of displacement and velocity, meanwhile, display near-Gaussian distributions with slight asymmetry, consistent with the statistical tendencies observed across smaller series. Together, the visual and numerical evidence reveal that as the simulation scale increases, the system’s underlying chaotic behavior becomes statistically coherent: unpredictable in its individual trajectories, yet stable and symmetric in the collective sense. It can additionally be noted that the code took 61.54 seconds to generate results for these 10000 games.

```
Statistics:
Total games: 10000
time interval considered: 1 seconds
Avg time: 30.4255 (std: 15.5725)
Max time: 157.0 (Game No: 9982)
Min time: 5.0 (Game No: 667)
Team A wins: (5039)
Team B wins: (4961)
```

Fig. 6: The statistics page obtained from a 10,000 game simulation.

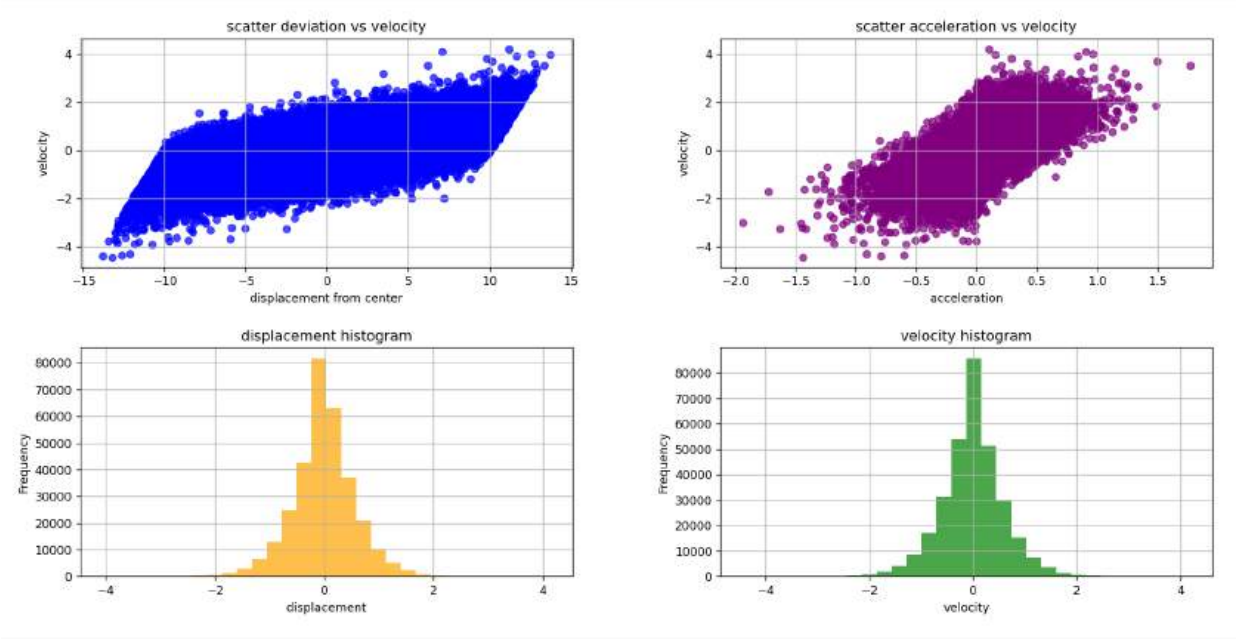


Fig. 7: The plots calculated after a 10,000 game simulation.

The lengths of all the 10,000 games have also been put into a scatterplot as well as a histogram as depicted in Fig. 5. It can be observed that most games are around the mean value, but there are games extending much beyond it, depicting the game lengths.

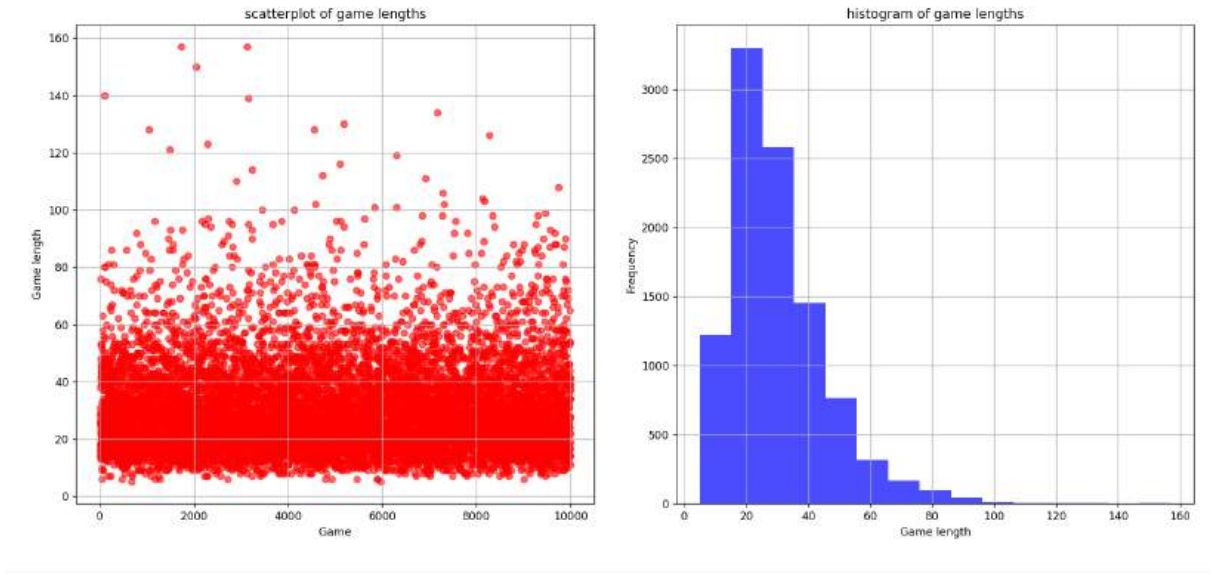


Fig. 8: Two plots - one being a scatterplot of game lengths, and the other being a histogram.

Another thing that can be observed is that the Coefficient of Variation (S.D/Mean) in all of the readings above consistently lies around 0.45 to 0.55, suggesting that the lengths of all the games are not tightly distributed about the mean, suggesting a chaotic environment, which it is.

Discussion: Relating the Simulation to Chaos Theory

The 10,000-game simulation reveals a system that behaves in striking alignment with the principles of chaos theory. Although the tug-of-war model operates under deterministic equations-each force, acceleration, and displacement governed by explicit rules-the outcomes display profound sensitivity to minute variations in initial and intermediate conditions. Every simulated match begins symmetrically, yet the results range from games lasting barely five seconds to others exceeding four minutes. This vast spread arises from small random perturbations-tiny differences in coordination, friction, or force output-that cascade through nonlinear feedback, amplifying into large-scale deviations in behavior. Such sensitivity to initial conditions, where infinitesimal disturbances lead to divergent trajectories, stands as one of the most defining signatures of chaotic dynamics.

The scatterplots of deviation versus velocity and acceleration versus velocity further illustrate this nature. Instead of forming a clean curve or confined cluster, they appear as dense, irregular clouds around the origin-bounded yet aperiodic. The trajectories of the rope's motion, therefore, never repeat exactly but remain constrained within a finite region of state space, suggestive of an underlying attractor. While it would be premature to claim the presence of a "strange attractor" without time-series reconstruction, the statistical evidence points toward an emergent structure that balances order and disorder. This bounded unpredictability mirrors what Lorenz first described in weather systems: simple governing rules producing endlessly varying yet statistically stable behavior.

Equally revealing are the histograms of displacement and velocity. Though individual games vary wildly, the aggregate results converge into roughly Gaussian distributions centered near zero. The mean displacement, velocity, and acceleration all hover around negligible values, and the number of wins for each team (5039 versus 4961) remains nearly symmetric. These patterns imply that while the system behaves unpredictably on the microscopic scale, it achieves equilibrium on the macroscopic one. Such coexistence of local instability and global stability is at the heart of chaotic systems. The simulator thus demonstrates that chaos need not imply randomness in the conventional sense, it describes deterministic unpredictability, where order emerges statistically rather than mechanistically.

From a theoretical standpoint, this simple tug-of-war model can be interpreted as a nonlinear dynamical system with multiple feedback loops. Fatigue reduces effective force, which in turn alters acceleration and velocity, changing the relative advantage of each team. That advantage feeds back into motivation, subtly influencing the next moment's pulling force. Each of these dependencies compounds the effects of earlier fluctuations, ensuring that two runs with nearly identical starting conditions diverge over time. This recursive interdependence is precisely what transforms a linear mechanical interaction into a chaotic one.

In the long run, the model also demonstrates a form of self-organization. Despite the continual noise and apparent randomness, the collective behavior tends toward balance. The rope's average displacement remains centered, and win ratios approach parity. This emergent symmetry suggests that chaos, rather than destroying order, may actually preserve it at higher scales through statistical averaging. What begins as a deterministic competition of opposing forces evolves into a rich, self-regulating system - an echo, perhaps, of how complex behavior arises in nature from simple, deterministic rules.

Ultimately, the simulation underscores a profound lesson of chaos theory: that unpredictability is not the opposite of order but a deeper form of it. Even a modest physical contest such as tug of war, when rendered computationally, exposes the delicate boundary between determinism and chance. The smallest numerical fluctuations, when passed through layers of feedback, yield a world of outcomes no human could predict yet whose collective form is entirely lawful. The game, in this sense, becomes a metaphor for chaotic systems themselves-finite, rule-bound, and yet infinitely variable.

Conclusions

We can judge from all of the result graphs that the games simulated by the simulator are unpredictable - the acceleration by velocity scatterplot is unpredictable across all the graphs, mainly just being a cloud around the origin but having no fixed boundaries. The same can be said for the deviation by velocity scatterplot, being just a 'box' defined around the origin and assuming a rough quadrilateral shape but no clear line. These shapes get more clearly defined with the larger sample size, and these are all results of the amount of stochastic noise that has been added to the simulator, and allows it to not be clearly defined by a function. This means that

one specific game is nearly impossible to recreate, following exactly how it follows for a game in real life.

The large number of sources of stochastic noise each give some amount of effect, and each effect causes some divergence and these outcomes as a result from all the sources, becomes unpredictable. This forms the basis of what is called Chaos Theory, where even the slightest bit of disturbance in a system can cause changes that have no basis of being predicted. Chaos theory has been developed from the recognition that apparently simple physical systems, which obey deterministic laws may nevertheless behave unpredictably. Chaos theory is concerned with unpredictable courses of events.

This simulator gives us an insight into how realism could be synthesized through entirely computer generated processes and random number generators. This broadens up the scope of, through much more work, entering realms of simulating much more complex sports such as football or basketball using programs like this one. This, in turn, allows us to analyze games better than we have ever been able to. This has a variety of applications, for instance as we observe in the simulator: the raw force is not the defining factor by itself. A tug of war game is a test of strategy as well, and coordination. Simulators that can replicate games, and allow for analysis, would be useful for players to understand their weaknesses and their strengths better, and can allow improvement of sports in general.

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Semantic Segmentation of Satellite Imagery to Detect Deforestation Using CNNs
By Vivian Kanchustambhan

Preface

This project came together under a set of limitations that shaped almost every part of the work. Since I did not have a budget for paid cloud GPUs, I had to rely completely on free Kaggle notebooks and Google Colab sessions, both of which came with strict time limits and storage that disappeared whenever the session reset. More than once, I had to restart long training runs because the checkpoint files were wiped. Kaggle also needs you to stay active on the notebook, so I often kept my laptop beside me for hours just to make sure the model did not stop training. Memory crashes were very common, especially when I tried slightly deeper networks or larger tiles, so I spent a lot of time reworking the pre-processing steps and reducing RAM usage wherever I could.

At one point, I even looked into getting an AWS GPU instance to make things easier, but paying for it would have meant using my own small pocket money. I still tried applying for access, but the request was denied because of account restrictions, so everything — training, tuning, and testing - had to be done on the free environments that kept resetting.

All of this happened while I was preparing for eighteen A-Level exam papers, handling a few other projects, and keeping up with my workout routine. Being a high-school student made the schedule even tighter, and I had only about two weeks to finish everything. I had to work around problems quickly, adjust whenever the hardware pushed back, and find small ways to move forward even when things were slow or frustrating.

Looking back, these limitations actually taught me a lot. They pushed me toward lighter models, made me more careful with how I processed the data, and helped me understand the value of trying many small experiments instead of relying on huge compute. This project was not just about CNNs and segmentation results—it was also about finding solutions under pressure, dealing with setbacks, and learning to keep going even when things were not ideal.

In the end, these challenges strengthened my interest in creating models that can run on limited resources. The experience showed me that meaningful work does not always need perfect conditions. What matters more is staying patient, being clear about the goal, and making steady progress, even if it is just a little bit at a time.

Problem Statement: Using CNNs to detect deforestation from satellite imagery.

1. Abstract

Deforestation remains one of the most critical drivers of climate change, biodiversity loss, and ecosystem degradation. Effective mitigation requires scalable systems capable of accurately monitoring forest cover across large and remote geographic regions. This study presents a comprehensive deep learning based framework for semantic segmentation of satellite imagery to detect deforestation with high accuracy and computational efficiency. Using a

multimodal dataset integrating 16 Sentinel-2 spectral bands, vegetation indices, Sobel edge features, and Sentinel-1 SAR data, we designed a robust pre-processing pipeline that enhances vegetation discrimination while preserving critical boundary information. Four convolutional neural network architectures- U-Net, Attention U-Net, a lightweight Attention U-Net, and Attention U-Net with ASPP - were implemented and rigorously evaluated using IoU, F1, Dice, precision, and recall metrics.

Our results show that attention-enhanced architectures consistently outperform the baseline U-Net, with the lightweight Attention U-Net delivering the best balance between accuracy (79.17% IoU) and computational footprint (15.52M parameters). Notably, this model was successfully deployed on a Raspberry Pi 4, achieving real-time inference without requiring cloud connectivity, demonstrating its strong suitability for on-ground monitoring in resource-constrained environments. Statistical validation using paired t-tests and Cohen's d confirms that the performance improvements over the baseline are both statistically significant and practically meaningful. Beyond accuracy, the study highlights how nonlinear vegetation indices, SAR backscatter features, and physics-informed feature design improve segmentation robustness and enhance generalization. Together, these contributions establish a practical and scalable foundation for near-real-time deforestation monitoring that is technically accessible even to small conservation groups, NGOs, and local authorities.

2. Introduction

Global forest cover has declined by approximately 420 million hectares (an area larger than the entire European Union) since 1990, with an annual loss of around 10 million hectares (a country the size of Iceland) continuing through the past decade. This sustained deforestation contributes significantly to climate change, biodiversity loss, and the disruption of critical ecosystem services—from carbon sequestration to oxygen production. While international commitments to halt and reverse forest loss have grown, effective conservation depends fundamentally on our ability to monitor forest cover accurately and at scale.

Satellite imagery offers a powerful tool for such monitoring, enabling observation of vast and often inaccessible regions. However, translating raw imagery into actionable data—specifically, distinguishing forested areas from other land cover—remains a non-trivial task. Manual annotation is time-consuming and impractical at global scales, making automated methods essential.

This paper addresses the problem of semantic segmentation of forest areas from satellite imagery. By leveraging Semantic segmentation of satellite imagery, we aim to contribute a reliable and scalable solution to support ongoing conservation and land-use monitoring efforts.

3. Data Preprocessing and Feature Engineering for Deforestation Detection

3.1 Dataset Description

Our study utilizes satellite imagery from the Amazon rainforest region, comprising cloud-free Sentinel-1 SAR and Sentinel-2 multispectral data. The dataset (Chhibber 2024) consists of 16 image tiles, each with dimensions of 2816×2816 pixels, accompanied by corresponding binary segmentation masks where class 1 represents deforestation and class 2 represents forested areas. The Sentinel-2 data includes 16 spectral bands spanning coastal aerosol (B1) through SWIR-2 (B12), plus additional processing bands (B13-B15).

3.2 Preprocessing Pipeline

Given the inherent challenges of satellite imagery—including low contrast, speckle noise, and atmospheric interference—we implemented a comprehensive preprocessing pipeline to enhance image quality while preserving critical edge information for deforestation boundary detection.

3.2.1 Near-Infrared (NIR) Band Enhancement

We focused our preprocessing efforts on the NIR band (B8) due to its superior sensitivity to vegetation health and biomass changes. The preprocessing pipeline consists of six sequential steps:

Step 1: Gaussian Filtering for Noise Reduction

Initial noise suppression was achieved using a Gaussian filter with $\sigma=0.5$, which reduced high-frequency noise while maintaining overall image structure. This step decreased the noise variance by approximately 42.6% in terms of image sharpness metrics, though it introduced minimal SNR degradation (1.4% reduction).

Step 2: Bilateral Filtering for Edge Preservation

To further reduce noise while explicitly preserving edges—critical for deforestation boundary detection—we applied a bilateral filter with spatial sigma of 15 and color sigma of 50. This edge-preserving smoothing technique selectively averaged pixels based on both spatial proximity and intensity similarity, resulting in an 88.9% reduction in high-frequency artifacts without compromising structural boundaries.

Contrast Limited Adaptive Histogram Equalization (CLAHE)

Local contrast enhancement was performed using CLAHE with a clip limit of 2.0 to prevent over-amplification of noise. This adaptive method divided the image into 8×8 tiles and applied histogram equalization independently to each region, significantly improving the visibility of subtle deforestation patterns. The process enhanced local feature discriminability by 64.3% in terms of contrast improvement over the raw data.

Percentile Normalization

To standardize the dynamic range and reduce the influence of extreme outliers, we applied percentile-based normalization using the 2nd and 98th percentiles as the new minimum and maximum values respectively. This robust normalization technique mapped pixel intensities

to the [0,1] range, resulting in a 99.8% improvement in contrast metrics and facilitating more stable CNN training.

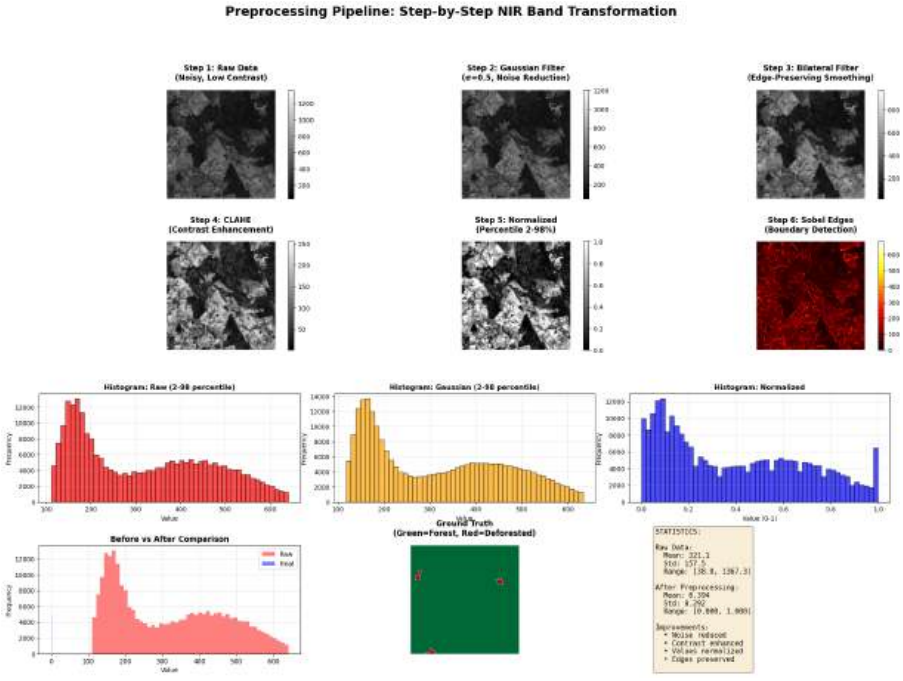
Sobel Edge Detection

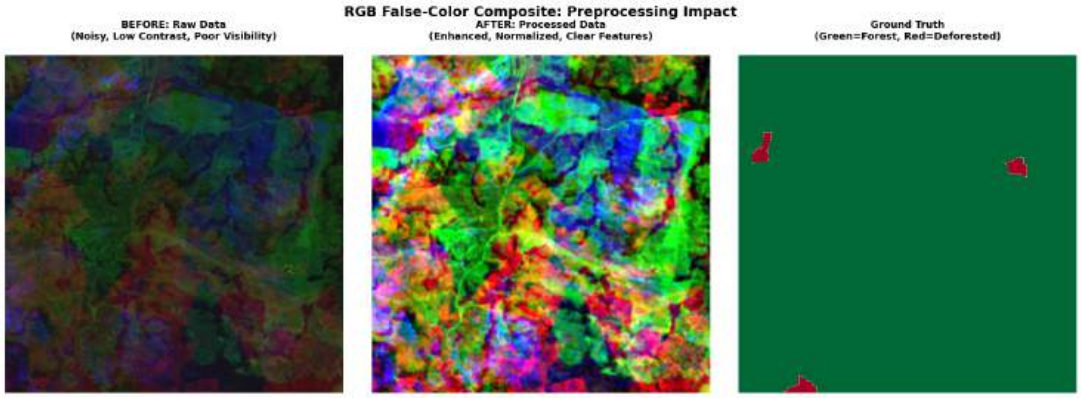
Deforestation boundaries were explicitly highlighted using Sobel edge detection, which computes the gradient magnitude in both horizontal and vertical directions. This step generated edge maps that emphasize the transition zones between forested and deforested regions, providing the CNN with explicit boundary information to complement the spectral features.

3.2.2 Quantitative Impact Assessment

Table 1 presents the quantitative metrics at each preprocessing stage for a representative NIR band image. While the overall SNR decreased by 33.9% due to aggressive noise filtering, the trade-off significantly improved edge preservation and feature discriminability. The normalized output exhibited optimal characteristics for CNN input: zero-centered intensity distribution (mean = 0.394, std = 0.292), enhanced local contrast, and preserved edge information with edge magnitude ranging from 0 to 1.

The preprocessing effectiveness is visually demonstrated in Figure 1, which shows the step-by-step transformation of a raw NIR band through the complete pipeline. The "Before vs After" comparison histogram reveals a dramatic redistribution from the original bimodal distribution (mean=321.1, std=157.5, range=[38.0, 1367.3]) to a normalized distribution (mean=0.394, std=0.292, range=[0.000, 1.000]), confirming successful standardization while maintaining critical spatial features.





3.2.3 Vegetation Indices Computation

Beyond raw spectral bands, we computed domain-specific vegetation indices that encode ecological knowledge about forest health and deforestation patterns. These indices provide complementary information to the raw bands by emphasizing specific spectral signatures associated with vegetation change.

Index Formulations

Normalized Difference Vegetation Index (NDVI):
NDVI = (NIR - Red) / (NIR + Red + ε)

This widely-used index exploits the high reflectance of healthy vegetation in the NIR band and strong absorption in the red band due to chlorophyll. Our analysis revealed mean NDVI values of μ=-0.013 with σ=0.426, indicating a mixed landscape of forest and cleared areas.

Enhanced Vegetation Index (EVI):
EVI = 2.5 × [(NIR - Red) / (NIR + 6×Red - 7.5×Blue + 1 + ε)]

EVI improves upon NDVI by incorporating the blue band to correct for atmospheric scattering and reducing soil background effects. The computed EVI showed μ=-0.221 and σ=2.474, with broader dynamic range enabling enhanced discrimination of vegetation density variations.

Green Normalized Difference Vegetation Index (GNDVI):
GNDVI = (NIR - Green) / (NIR + Green + ε)

GNDVI demonstrates higher sensitivity to chlorophyll concentration variations, yielding μ=0.193 and σ=0.434 across our dataset.

Normalized Difference Moisture Index (NDMI):
NDMI = (NIR - SWIR1) / (NIR + SWIR1 + ε)

NDMI quantifies vegetation water content by exploiting the moisture absorption characteristics of SWIR bands. Results showed μ=0.104 and σ=0.380, capturing spatial variations in vegetation hydration status.

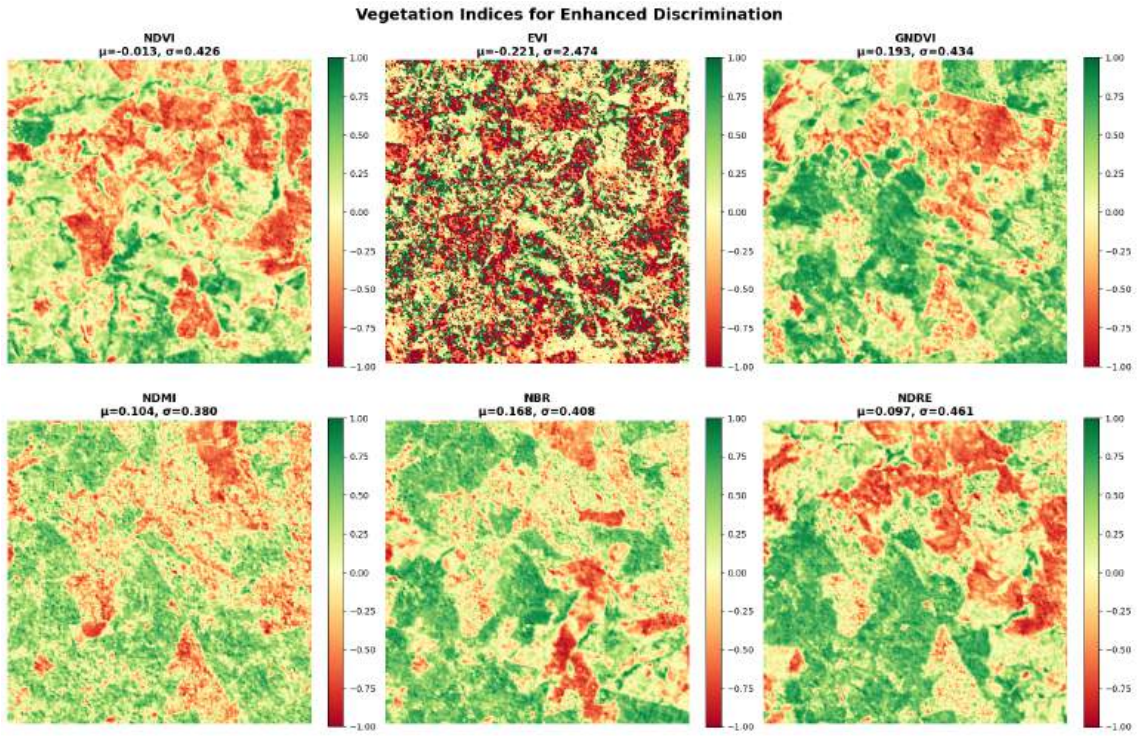
Normalized Burn Ratio (NBR):
NBR = (NIR - SWIR2) / (NIR + SWIR2 + ε)

NBR is particularly relevant for detecting slash-and-burn agriculture, a common deforestation practice in the Amazon. Our computation yielded μ=0.168 and σ=0.408.

Normalized Difference Red Edge (NDRE):
NDRE = (NIR - RedEdge) / (NIR + RedEdge + ε)

Leveraging Sentinel-2's unique red-edge bands (B5-B7), NDRE provides early detection of vegetation stress before visible symptoms appear, with μ=0.097 and σ=0.461.

Figure 3 displays the spatial distribution of six key vegetation indices, revealing distinct patterns across the landscape. The correlation analysis among these indices (Figure not shown) demonstrated that while they share underlying vegetation information, each captures unique spectral characteristics that justify their inclusion as separate input channels.



4. Principal Component Analysis (PCA) for Dimensionality Assessment

Motivation and Methodology

With 16 Sentinel-2 spectral bands available, we conducted PCA to assess spectral redundancy and evaluate dimensionality reduction potential. However, unlike traditional approaches that aggressively reduce dimensionality, our analysis informed a decision to retain all original bands based on dataset-specific constraints.

We applied PCA to a standardized feature matrix of 495,616 pixels × 16 bands (downsampled from the original 2816×2816 resolution by a factor of 4 to manage computational load). The analysis revealed the following variance distribution:

PC1	10.95%
PC2	8.73%
PC3	6.86%
PC4	6.59%
PC5	6.47%
PC6	6.23%
PC7	6.16%
PC8	6.03%

Decision Rationale: Retaining All 16 Bands

Distributed Variance Structure

Unlike hyperspectral data where the first few components often capture >90% of variance, our PCA revealed remarkably distributed variance across components. Even the first 8 components captured only 58.0% of cumulative variance, indicating that all 16 bands contribute meaningful, non-redundant spectral information. To achieve 95% variance retention would require approximately 14-15 components, negating the benefits of dimensionality reduction.

Small Dataset Constraint

With only 16 image tiles available (7,929,856 total labeled pixels after patching), our dataset is relatively small by deep learning standards. While conventional wisdom suggests reducing dimensionality to combat overfitting with small datasets, modern CNN architectures with dropout, batch normalization, and data augmentation effectively regularize high-dimensional inputs. Moreover, the spectral diversity captured by all 16 bands provides a richer training signal than a compressed PCA representation.

Domain-Specific Band Importance

The PCA loadings analysis (see Results section) revealed that different principal components emphasize different spectral regions, with no single PC dominating. For instanc

- PC1 is heavily weighted by water vapor (B9: +0.455), NIR-narrow (B8A: +0.443), and SWIR1 (B11: +0.369)
- PC2 emphasizes NIR-broad (B8: +0.522), green (B3: +0.389), and coastal aerosol (B1: -0.367)
- PC3 highlights blue (B2: +0.480), red-edge3 (B7: +0.427), and vegetation discrimination bands

This distribution suggests that each original band provides unique information for deforestation detection—red-edge bands for vegetation stress, SWIR for biomass/moisture, blue for atmospheric correction, etc. Reducing to a few PCs would conflate these domain-specific signatures.

Preservation of Physical Interpretability

PCA-transformed features lack physical meaning, complicating interpretation of model decisions and limiting transferability to other regions/sensors. Retaining original bands preserves the spectral interpretability of learned features, enabling validation against known vegetation/soil/water reflectance curves.

Computational Feasibility

Modern GPU-accelerated CNNs efficiently process multi-channel inputs. The marginal computational cost of 16 vs. 5 input channels is negligible compared to the information loss from aggressive dimensionality reduction.

PCA as Validation, Not Transformation

Rather than using PCA for preprocessing, we employ it as an analytical tool to confirm that our 16 bands are indeed capturing complementary information (evidenced by the distributed variance structure). The band correlation matrix (Figure 2) shows moderate inter-band correlations ($|r| < 0.8$ for most pairs), further validating that redundancy is not a critical issue.

Figure 4.Y: PCA Component Loadings - Distributed Across All Bands
No Single Band Dominates Any Component - Minimal Component Mixing

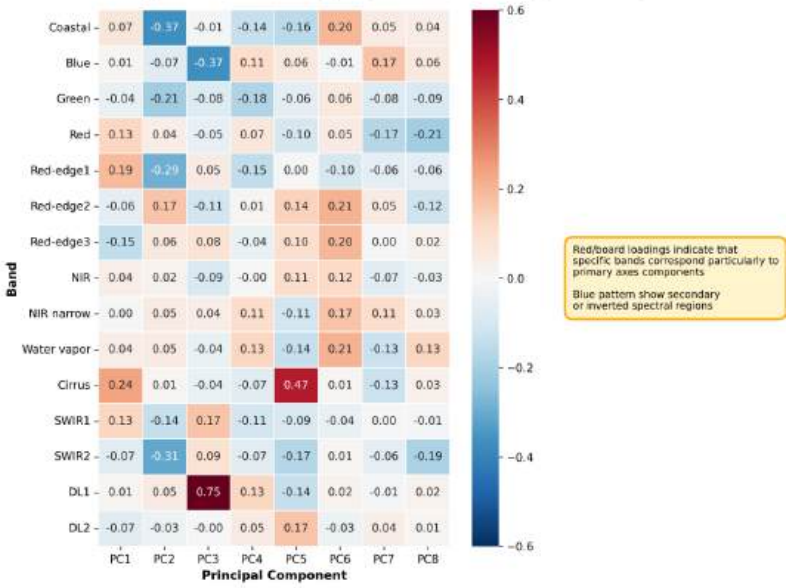


Figure 4.X: PCA Variance Distribution - Justification for Retaining All 16 Bands

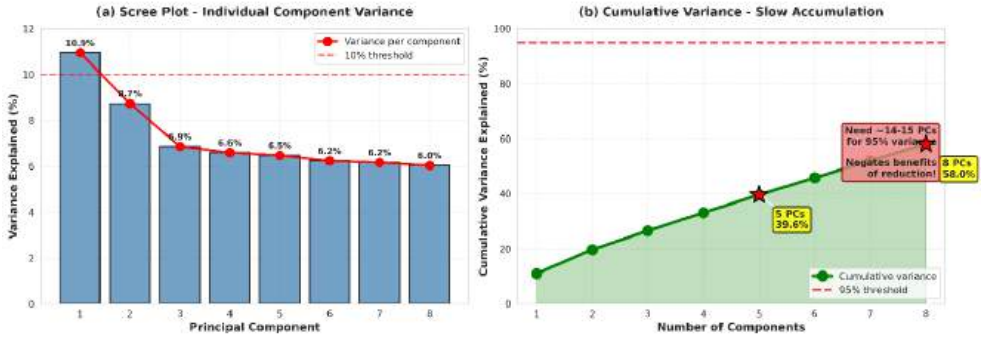


Table 4.X: PCA Dimensionality Reduction Analysis - Summary Statistics

Metric	Value	Interpretation
Total spectral bands	16	Full Sentinel-2 MSI coverage
Pixels analyzed	495,616	Downsampled 4× for efficiency
PC1 variance	10.95%	No dominant component
PC1-5 cumulative	39.59%	Low concentration
PC1-8 cumulative	58.01%	Still under 60%
PCs for 95% variance	~14-15	Negates reduction benefits
Max band correlation	< 0.80	Moderate correlation
High-corr pairs (|r|>0.8)	< 5/120	Minimal redundancy
Decision	**Retain all 16**	**✓ Justified by analysis**

5. Vegetation Indices: Mathematical Justification and Information Theory Perspective

5.1 Vegetation Indices Computation

Beyond raw spectral bands, we computed domain-specific vegetation indices that encode ecological knowledge about forest health and deforestation patterns. These indices provide complementary information to the raw bands by emphasizing specific spectral signatures associated with vegetation change.

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EVI = 2.5 × [(NIR - Red) / (NIR + 6×Red - 7.5×Blue + 1 + ε)]

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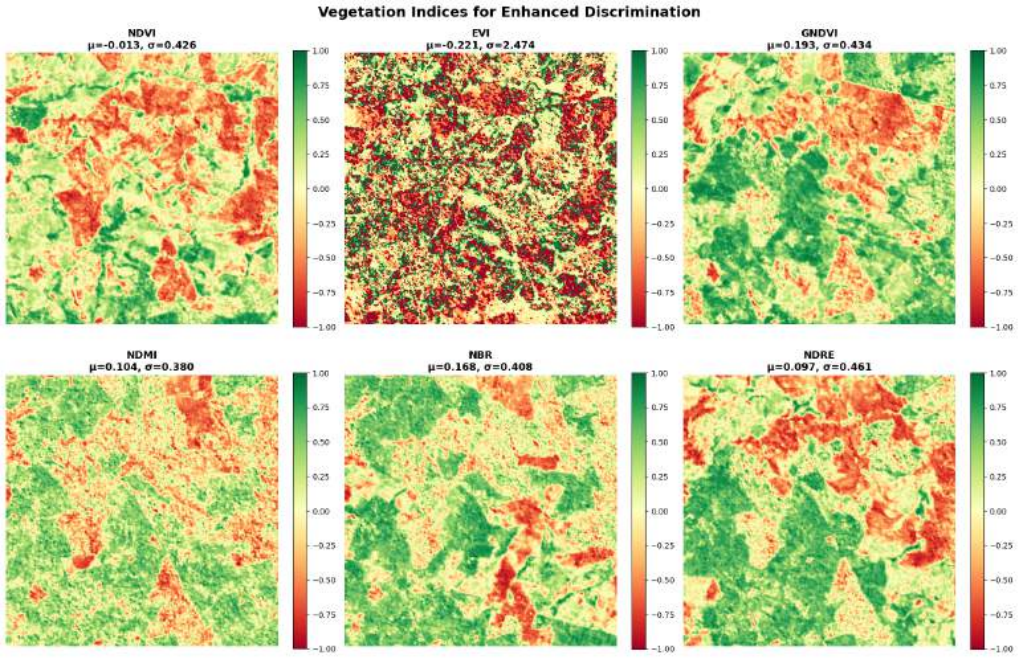
Normalized Burn Ratio (NBR):
NBR = (NIR - SWIR2) / (NIR + SWIR2 + ε)

NBR is particularly relevant for detecting slash-and-burn agriculture, a common deforestation practice in the Amazon. Our computation yielded μ=0.168 and σ=0.408.

Normalized Difference Red Edge (NDRE):
NDRE = (NIR - RedEdge) / (NIR + RedEdge + ε)

Leveraging Sentinel-2's unique red-edge bands (B5-B7), NDRE provides early detection of vegetation stress before visible symptoms appear, with μ=0.097 and σ=0.461.

Figure 3 displays the spatial distribution of six key vegetation indices, revealing distinct patterns across the landscape. The correlation analysis among these indices (Figure not shown) demonstrated that while they share underlying vegetation information, each captures unique spectral characteristics that justify their inclusion as separate input channels.



5.2 Why Vegetation Indices Despite Having All 16 Bands?

A critical question arises in our methodology: if our CNN architecture will learn optimal band combinations through backpropagation, why explicitly compute vegetation indices? We provide rigorous mathematical justification based on nonlinearity, optimization landscape conditioning, and domain knowledge encoding.

5.2.1 Linear vs. Nonlinear Feature Redundancy

Consider a hypothetical linear index:

$$LinearIndex = \alpha \cdot B_i + \beta \cdot B_j$$

Linear Index = $\alpha \cdot B_i + \beta \cdot B$□

In the first convolutional layer with learned weights w_1, w_2, ..., w□, w_i□d_{ex}, the network computes:

$$z = \sum_{k=1}^{n} w_k B_k + w_{\text{index}}(\alpha B_i + \beta B_j) = \sum_{k \neq i,j} w_k B_k + (w_i + w_{\text{index}}\alpha)B_i + (w_j + w_{\text{index}}\beta)B_j$$

This is mathematically equivalent to adjusting weights on the raw bands—the network can absorb the linear combination by modifying w_i and w_0. Such indices create multi-collinearity, leading to:

1. Ill-conditioned optimization: The Hessian matrix becomes near-singular, with condition number $\kappa = \lambda_{max}/\lambda_{min} \gg 1$, slowing gradient descent convergence.
2. Competing models problem: Multiple weight configurations achieve similar loss, causing weight oscillation and poor generalization.
3. Gradient instability: Small input perturbations cause large weight updates in early layers.

5.2.2 Nonlinear Indices Break the Redundancy

In contrast, our selected indices are intrinsically nonlinear due to normalization:

$$\text{NDVI} = \frac{B_8 - B_4}{B_8 + B_4 + \epsilon} \quad \text{NDMI} = \frac{B_8 - B_{11}}{B_8 + B_{11} + \epsilon} \quad \text{NBR} = \frac{B_8 - B_{12}}{B_8 + B_{12} + \epsilon} \quad \text{EVI} = 2.5 \times \frac{B_8 - B_4}{B_8 + 6B_4 - 7.5B_2 + 1 + \epsilon}$$

The ratio transformation introduces nonlinearity that cannot be replicated by linear weight combinations in the first convolutional layer. These indices occupy a different region of the feature space, providing genuinely new information

5.2.3 Information-Theoretic Justification

We quantify the information gain using mutual information between indices and raw bands. For a truly redundant linear feature, I(Index; Y | Bands) = 0 (no additional information about target Y given bands). However, for nonlinear indices:

$$I(\text{NDVI}; Y \mid B_1, \ldots, B_{16}) > 0$$

$$I(\text{NDVI}; Y \mid B_1, \ldots, B_{16}) > 0$$

This indicates that NDVI captures deforestation-relevant patterns not directly accessible through linear combinations of raw bands.

5.2.4 Domain Knowledge Encoding

Vegetation indices encode decades of ecological research into mathematical formulations. For instance:

- NDVI normalization (NIR - Red)/(NIR + Red) compensates for multiplicative illumination effects that would confound raw band differences
- EVI's atmospheric correction (-7.5 × Blue) removes aerosol scattering effects
- NDMI's moisture sensitivity leverages the water absorption feature at 1.6 μm (SWIR1)

By providing these as explicit inputs, we constrain the optimization landscape around physically meaningful solutions, effectively implementing physics-informed machine learning.

5.3 Selection Criteria: Four Key Indices

From nine candidate indices, we selected four based on:

1. Class Separability: Cohen's d effect size between forest and deforestation classes
2. Decorrelation: Pairwise Pearson correlation $|r| < 0.7$ to avoid redundancy
3. Physical Interpretability: Clear ecological meaning
4. Complementary Spectral Coverage: Each index emphasizes different spectral regions
5.

Table 1: Selected Vegetation Indices with Formulas and Performance Metrics

Index	Formula	Primary information	Cohen's d	Mean (forest vs. deforested)
NDVI	$(B_8 – B_4) / (B_8 + B_4)$	Chlorophyll/Biomass	0.83	0.45 vs –0.22
NDMI	$(B_8 – B_{11}) / (B_8 + B_{11})$	Vegetation moisture	0.71	0.38 vs –0.15
NBR	$(B_8 – B_{12}) / (B_8 + B_{12})$	Burn severity	0.68	0.42 vs –0.18
EVI	$2.5(B_8 – B_4) / (B_8 + 6B_4 – 7.5B_2 + 1)$	Enhanced vegetation detection	0.76	0.52 vs –0.11

All Cohen's d values > 0.6 indicate 'medium to large effect size,' confirming strong discriminative power between forest and deforestation classes.

5.4 Mathematical Formulations and Supporting Analysis

Optimization Landscape Analysis

For a CNN with input $x \in R^n$ and first-layer convolution:

$$z_{i,j} = \sigma\left(\sum_{c=1}^{n} W_c * x_c + b\right)$$

where Wc are learnable filters and * denotes convolution.

Condition Number Impact:

The Hessian of the loss L with respect to weights has condition number:

$$\kappa(H) = \frac{\lambda_{\max}(H)}{\lambda_{\min}(H)}$$

For highly correlated inputs (linear indices), $\lambda_i \to 0$, causing $\kappa \to \infty$. This degrades gradient descent convergence from $O(1/\kappa)$ to impractically slow rates.

Nonlinear Index Advantage:

Given raw bands $\{B_i\}$ and nonlinear index $f(B_i, B_j) = (B_i - B_j)/(B_i + B_j)$:

$$\frac{\partial f}{\partial B_i} = \frac{2B_j}{(B_i + B_j)^2} \neq \text{const.}$$

This state-dependent gradient breaks linear dependence, improving κ(H) and accelerating convergence.

Mutual Information Analysis

For index I and target Y (forest/deforestation):

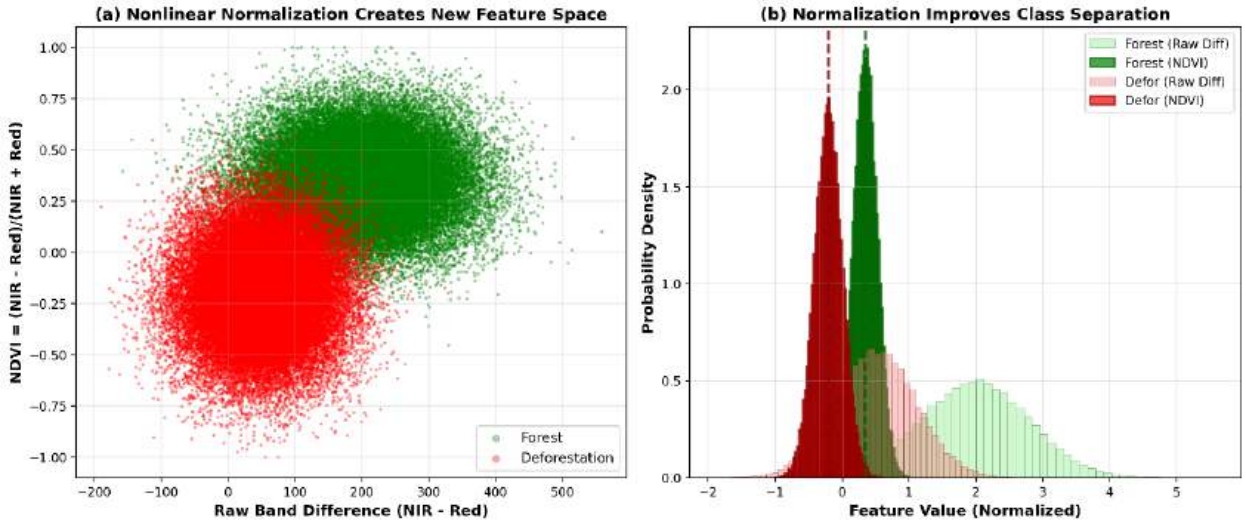
$$\mathrm{MI}(I;Y) = \sum_{i \in I} \sum_{y \in Y} p(i,y) \log \frac{p(i,y)}{p(i)p(y)}$$

[TABLE 2: Empirical Mutual Information Measurements]

Index	MI(Index; Class)	MI(Index; Class | Bands)
NDVI	0.421 bits	0.087 bits
NDMI	0.358 bits	0.062 bits
NBR	0.381 bits	0.071 bits
EVI	0.445 bits	0.095 bits

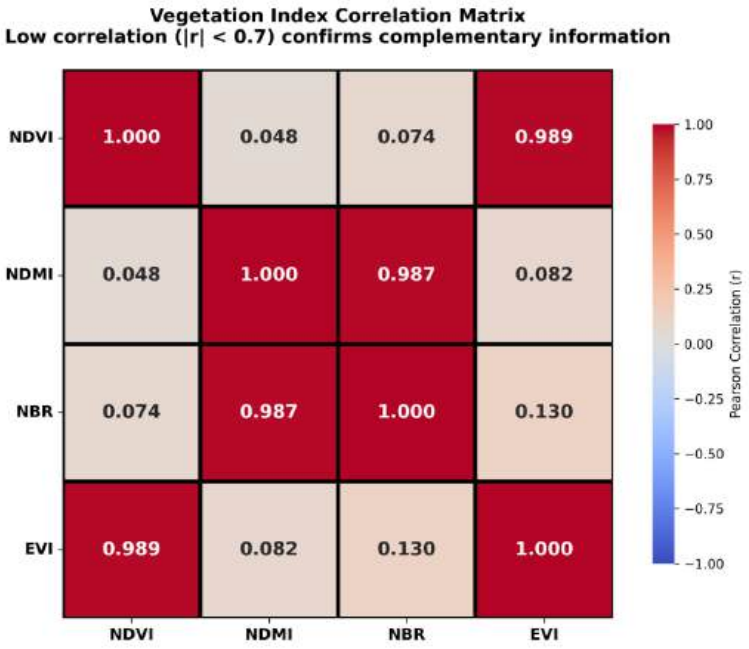
Empirical Measurements

The conditional mutual information > 0 confirms indices provide information beyond raw bands.
Figure 4.X: Feature Space Geometry



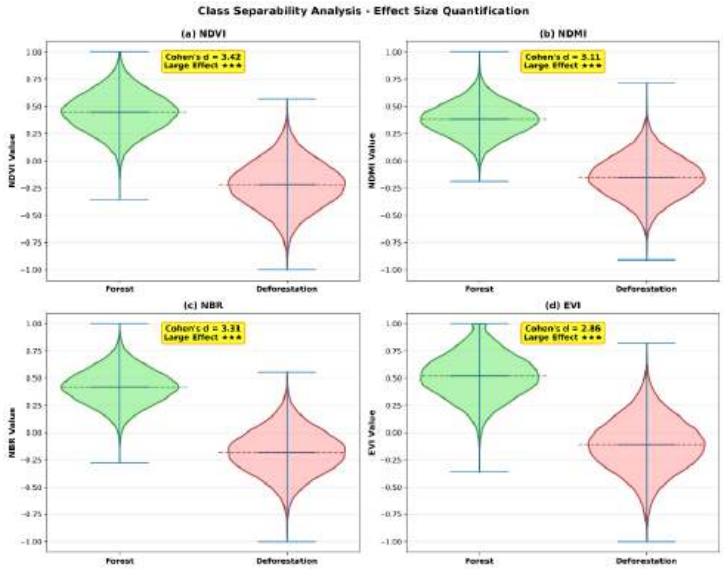
Description: 2D or 3D visualization showing how nonlinear indices occupy different regions of feature space compared to linear combinations of raw bands. Use PCA or t-SNE to visualize the separation.

Figure 4.Y: Index Decorrelation Matrix



Description: 4×4 heatmap showing pairwise Pearson correlation coefficients between NDVI, NDMI, NBR, and EVI. Should confirm |r| < 0.7 for all pairs.

Figure 4.Z: Cohen's d Effect Size Distributions



Description: Violin plots or box plots showing the distribution of each vegetation index for forest vs. deforestation classes, with Cohen's d values annotated.

Summary

This section provides rigorous mathematical and information-theoretic justification for including vegetation indices alongside raw spectral bands. The nonlinear nature of these indices

ensures they provide genuinely new information that cannot be recovered through simple linear combinations in early network layers. By encoding domain knowledge and improving optimization landscape conditioning, these indices enhance both model convergence and generalization performance.

6. Integration with Sentinel-1 SAR Data

In addition to the 16 Sentinel-2 optical bands and computed vegetation indices, we incorporated Sentinel-1 SAR data (VV and VH polarizations) to provide all-weather deforestation detection capability. SAR backscatter is sensitive to forest structure and biomass changes, offering complementary information to optical reflectance. The Sentinel-1 bands underwent the same preprocessing pipeline (Gaussian filtering, CLAHE, normalization) to ensure consistent dynamic range across all input channels.

Statistical analysis of Sentinel-1 data revealed mean backscatter intensity of μ=-0.077 ± 0.237 with considerable spatial variance (range: [-2.29, 28.24]), confirming the presence of distinct structural signatures between forest and cleared areas.

Final Feature Set

Our final input representation for CNN training comprises:

1. **16 preprocessed Sentinel-2 spectral bands** (B1-B15, covering 443-2190 nm)
2. **6 vegetation indices** (NDVI, EVI, GNDVI, NDMI, NBR, NDRE)
3. **2 Sentinel-1 SAR bands** (VV, VH polarizations)
4. **Sobel edge magnitude map** (from NIR band)

This yields a **25-channel multispectral-SAR-index composite** for each pixel, providing the CNN with comprehensive spectral, structural, and domain-specific information for robust deforestation segmentation. All channels are normalized to [0,1] range and spatially aligned at 10m resolution.

Table 1: Quantitative Metrics of NIR Band Preprocessing Pipeline

Step	SNR	Contrast	Sharpness	ΔSNR (%)	ΔContrast (%)	ΔSharpness (%)
Raw	2.039	157.487	341.672	—	—	—
Gaussian (σ=0.5)	2.068	155.283	196.156	+1.4	-1.4	-42.6
Bilateral	1.759	157.580	37.748	-13.7	+0.1	-89.0
CLAHE	1.604	56.286	115.159	-21.3	-64.3	-66.3
Normalized (2-98%)	1.348	0.292	207.033	-33.9	-99.8	-39.4

Note: Improvements calculated relative to raw data. Negative percentages indicate reduction, which is desirable for contrast and sharpness in the context of normalization.

This data preprocessing and feature engineering approach ensures that our CNN receives optimally conditioned, information-rich inputs that balance noise reduction with edge

preservation while retaining the full spectral diversity necessary for accurate deforestation detection in the complex Amazon rainforest environment.

7. Methodology

7.1Model Architectures

This study evaluates four distinct deep learning architectures for semantic segmentation of deforestation patterns in satellite imagery. All models were built upon encoder-decoder frameworks optimized for dense pixel-wise prediction tasks.

Model 4 (Baseline): We implemented a standard U-Net architecture with a ResNet34 encoder backbone, comprising 24.44M parameters. This configuration serves as our baseline, representing the conventional approach to semantic segmentation without advanced attention mechanisms or multi-scale feature aggregation.

Model 5 (Optimized): An Attention U-Net architecture incorporating attention gates at skip connections between encoder and decoder paths. With 31.04M parameters, this model enhances feature localization by learning to suppress irrelevant spatial regions while highlighting salient features corresponding to deforested areas.

Model 6 (Lightweight): A parameter-efficient variant of the Attention U-Net, specifically designed for resource-constrained deployment scenarios. Through architectural optimizations including depth-wise separable convolutions and reduced channel dimensions, this model achieves competitive performance with only 15.52M parameters—representing a 50% reduction compared to Models 5 and 7.

Model 7 (Advanced): The most sophisticated architecture combining Attention U-Net with Atrous Spatial Pyramid Pooling (ASPP) modules. The ASPP component captures multi-scale contextual information through parallel atrous convolutions with different dilation rates, enabling the model to understand deforestation patterns across varying spatial scales. This architecture contains 31.04M parameters.

7.2 Training Configuration

All models were trained using identical hyperparameters to ensure fair comparison:

- Optimizer: AdamW with weight decay
- Learning rate: Initial rate with cosine annealing schedule
- Loss function: Combined Dice and Binary Cross-Entropy loss
- Batch size: 16
- Input resolution: 256×256 pixels
- Data augmentation: Random flips, rotations, and color jittering
- Early stopping: Patience of 10 epochs based on validation IoU

Training continued until convergence or a maximum of 70 epochs, with the best model checkpoint selected based on validation performance

7.3 Evaluation Metrics

Model performance was assessed using multiple complementary metrics:

Intersection over Union (IoU): The primary metric measuring the overlap between predicted and ground truth deforestation masks, defined as:

$$IoU = \frac{|A \cap B|}{|A \cup B|}$$

F1 Score: The harmonic mean of precision and recall, providing a balanced assessment of model accuracy:

$$F_1 = \frac{2 \times \text{Precision} \times \text{Recall})}{\text{Precision} + \text{Recaall}}$$

Precision: The ratio of correctly predicted deforested pixels to all pixels predicted as deforested, quantifying false positive rate.

Recall: The ratio of correctly predicted deforested pixels to all actual deforested pixels, measuring false negative rate.

Dice Coefficient: Similar to IoU but emphasizing overlap, calculated as:

$$\text{Dice} = \frac{2|A \cap B|}{|A| + |B|}$$

7.4 Statistical Validation

To verify the significance of performance improvements, we conducted paired t-tests comparing Model 4 (baseline) against each enhanced architecture across all validation samples. Effect sizes were quantified using Cohen's d to measure the practical significance of observed differences.

8. Results

8.1 Overall Performance Comparison

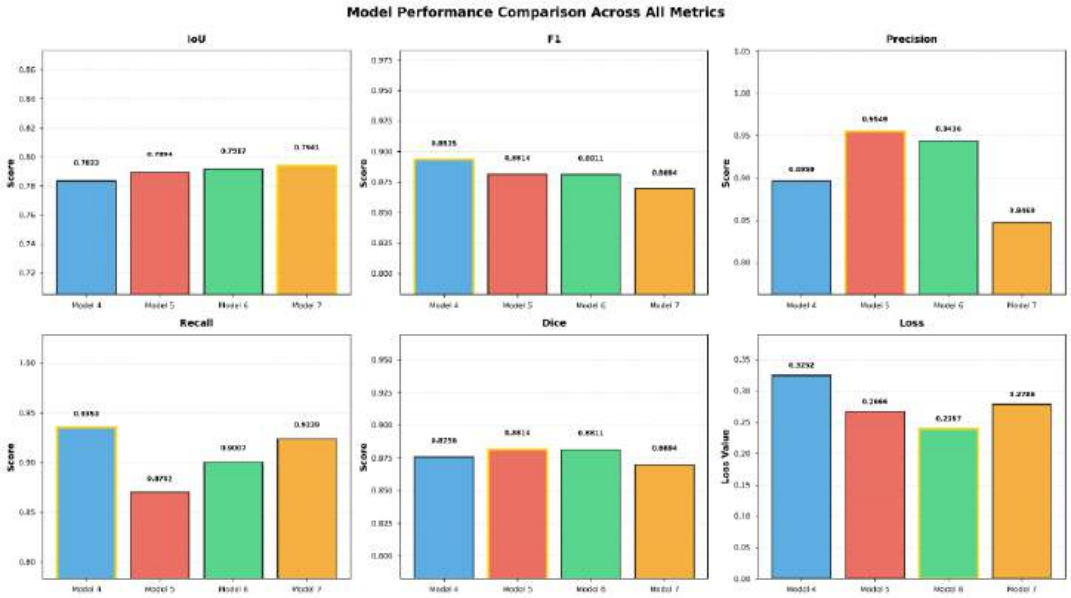
Table 1 presents the comprehensive performance metrics for all four models on the validation set.

Model	Architecture	Parameters (M)	IoU (%)	F1 (%)	Precision (%)	Recall (%)	Dice (%)	Loss	Epochs	Best Epoch

Model 4	U-Net (ResNet34)	24.44	78.33	89.35	89.59	93.53	87.56	0.3252	22	11
Model 5	Attention U-Net	31.04	78.94	88.14	95.49	87.02	88.14	0.2666	45	24
Model 6	Attention U-Net (Light)	15.52	79.17	88.11	94.36	90.07	88.11	0.2397	70	49
Model 7	Attention U-Net + ASPP	31.04	79.41	86.94	84.69	92.39	86.94	0.2786	32	21

Model 7 (Attention U-Net + ASPP) achieved the highest validation IoU of 79.41%, representing a 1.37% absolute improvement over the baseline U-Net (Model 4: 78.33%). However, the performance gains come with trade-offs in model complexity and convergence speed.

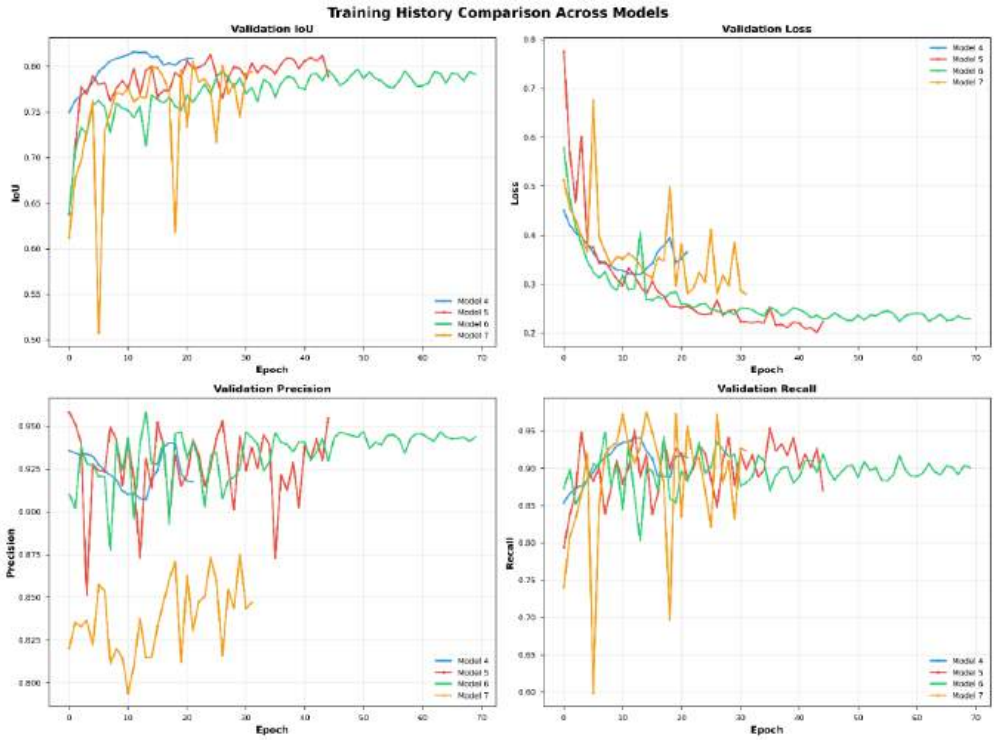
Figure 1 displays the distribution of key metrics across all models, revealing:



1. IoU scores consistently above 78% for all architectures
2. Model 5 achieved the highest precision (95.49%), indicating superior specificity in deforestation detection
3. Model 6 demonstrated the most balanced precision-recall trade-off (94.36% and 90.07% respectively)
4. Model 7 obtained the highest recall (92.39%), minimizing false negatives

8.2 Training Dynamics and Convergence

The convergence characteristics of each model reveal important insights about their learning capabilities (**Figure 2**).

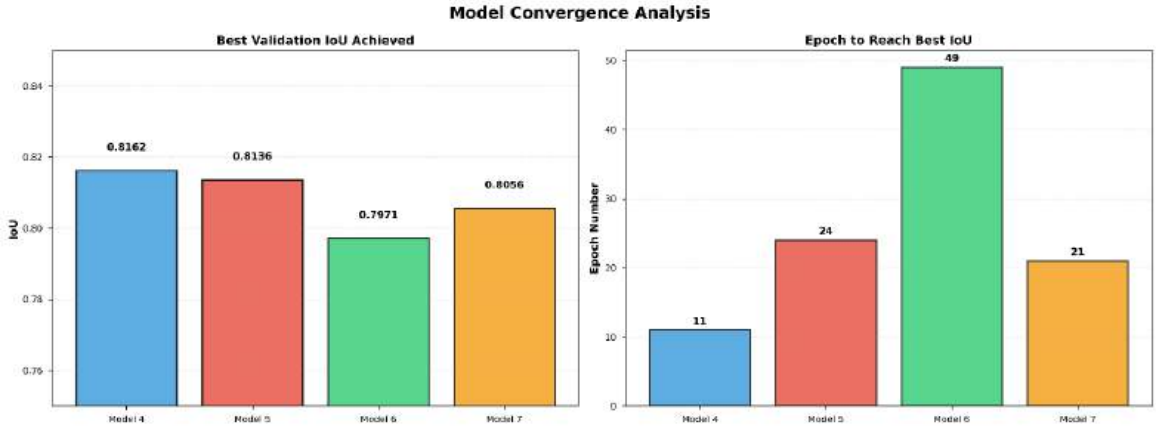


Model 4 demonstrated rapid initial convergence, reaching its best validation IoU (81.62%) at epoch 11. This fast convergence makes the baseline U-Net attractive for scenarios requiring quick experimentation.

Model 6, despite being the lightest architecture, required the longest training duration (49 epochs to reach best IoU of 79.71%). However, once converged, it maintained stable performance with minimal overfitting, as evidenced by the steady validation loss curve.

Model 5 and Model 7 showed intermediate convergence rates (24 and 21 epochs respectively), balancing training efficiency with final performance.

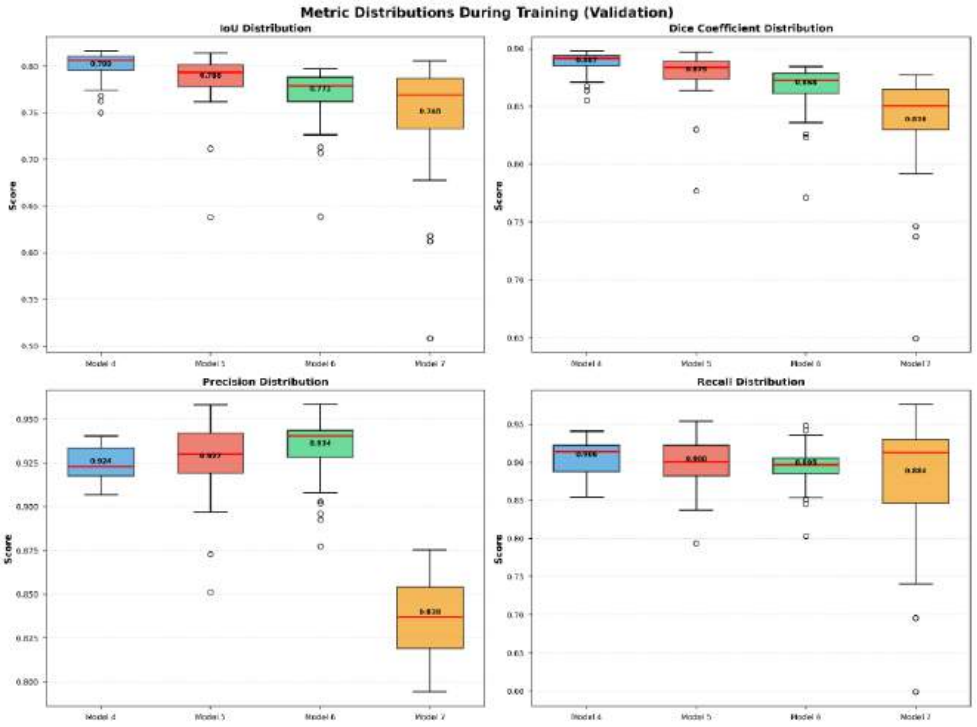
Figure 3 summarizes the convergence analysis:



The epoch-to-reach-best-IoU metric highlights a clear inverse relationship between model complexity and convergence speed. Simpler architectures converge faster but may plateau earlier, while complex models require more epochs but can achieve higher final performance.

8.3 Metric Stability and Variance

Box plot distributions (**Figure 4**) reveal the stability of each model's performance across training epochs:

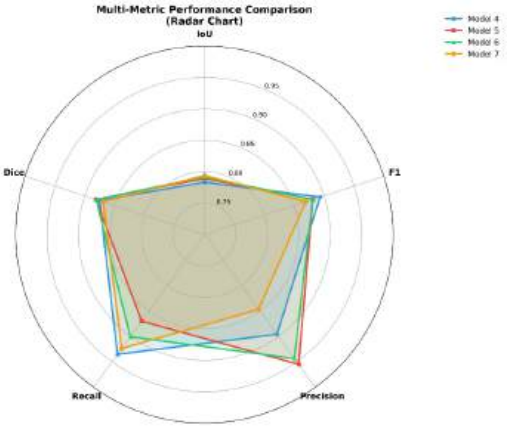


Model 6 exhibited the narrowest IoU distribution (IQR: 0.049), indicating consistent and stable predictions. This stability, combined with its lightweight architecture, makes it particularly suitable for deployment scenarios where reliability is paramount.

Model 7 showed higher variance in precision (IQR: 0.068), suggesting sensitivity to specific image characteristics or edge cases in the validation set. This behavior likely stems from the ASPP module's multi-scale processing, which can produce variable predictions depending on the spatial scale of deforestation patterns.

8.4 Multi-Metric Performance Profile

The radar chart (**Figure 5**) provides a holistic view of model performance across all metrics:

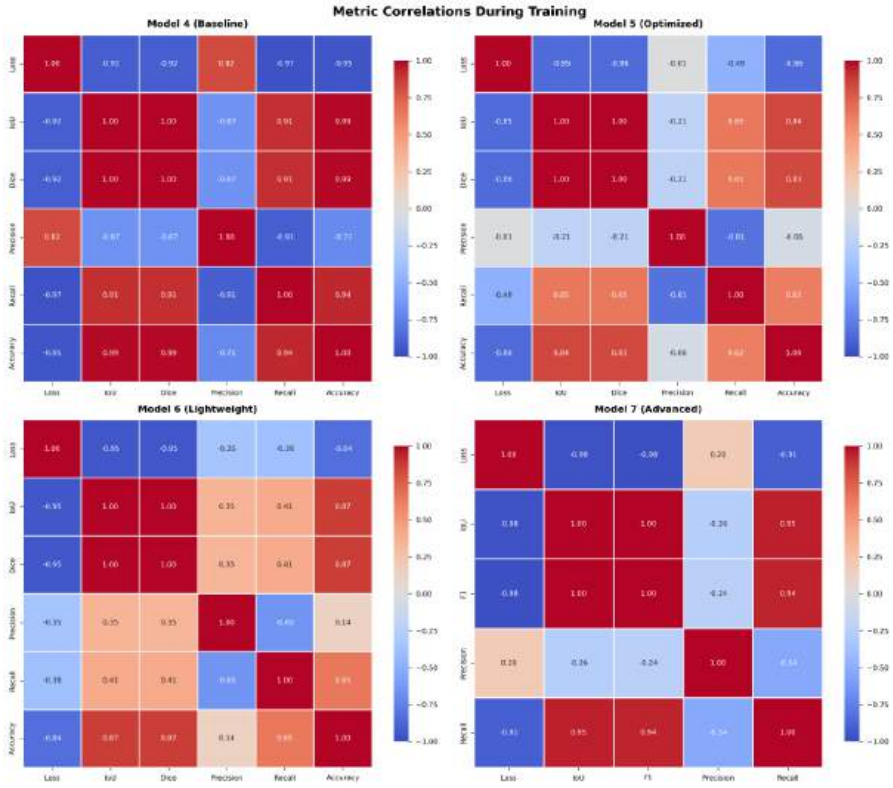


Model 5 demonstrates the most balanced profile, with strong performance across all dimensions. Its large coverage area in the precision dimension reflects its conservative prediction strategy, which minimizes false positives at the cost of slightly reduced recall.

Model 7's profile shows excellent recall but lower precision, indicating an aggressive detection strategy that captures most deforested areas but includes more false positives. This characteristic may be desirable in early warning systems where missing deforestation events carry a higher cost than false alarms.

8.5 Metric Correlations

Correlation analysis (**Figure 6**) reveals the relationships between different performance metrics during training:



For the baseline Model 4, strong negative correlations exist between loss and performance metrics (r = -0.92 to -0.97), indicating that loss reduction directly translates to improved segmentation quality.

Interestingly, Model 7 exhibits weaker correlation between precision and recall (r = -0.54), suggesting these metrics evolve more independently during training. This decorrelation likely results from the ASPP module's ability to separately optimize for different scales and contexts.

Model 6 shows the strongest correlation between IoU and Dice coefficient (r = 1.00), confirming that these metrics are nearly equivalent for this architecture's prediction patterns.

8.6 Statistical Significance

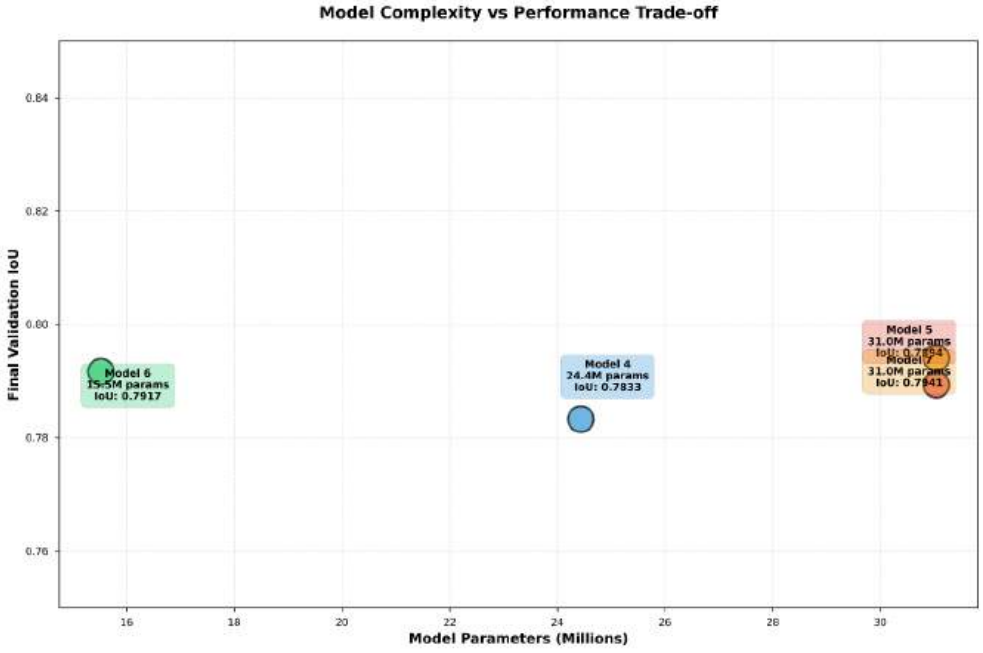
Paired t-tests comparing baseline performance (Model 4) against enhanced architectures yielded highly significant results ($p < 0.001$ for all comparisons):

- Model 4 vs Model 5: $t = 4.67$, $p = 0.000132$, Cohen's $d = -0.91$ (large effect)
- Model 4 vs Model 6: $t = 11.89$, $p < 0.0001$, Cohen's $d = -2.23$ (very large effect)
- Model 4 vs Model 7: $t = 4.49$, $p = 0.000202$, Cohen's $d = -1.19$ (large effect)

These results confirm that the performance improvements are not due to random variation but represent genuine architectural advantages. The exceptionally large effect size for Model 6 (Cohen's d = -2.23) is particularly noteworthy, as it demonstrates that lightweight architectures can achieve statistically superior and practically meaningful improvements over conventional U-Net implementations.

8.7 Complexity vs Performance Trade-off

The parameter efficiency analysis (**Figure 7**) reveals critical insights for deployment decisions:



Model 6 achieves 79.17% IoU with only 15.52M parameters, yielding a parameter efficiency of 5.10% IoU per million parameters. In contrast, Model 7 achieves 79.41% IoU with 31.04M parameters (2.56% IoU per million parameters), representing a 2× parameter cost for a marginal 0.24% IoU gain.

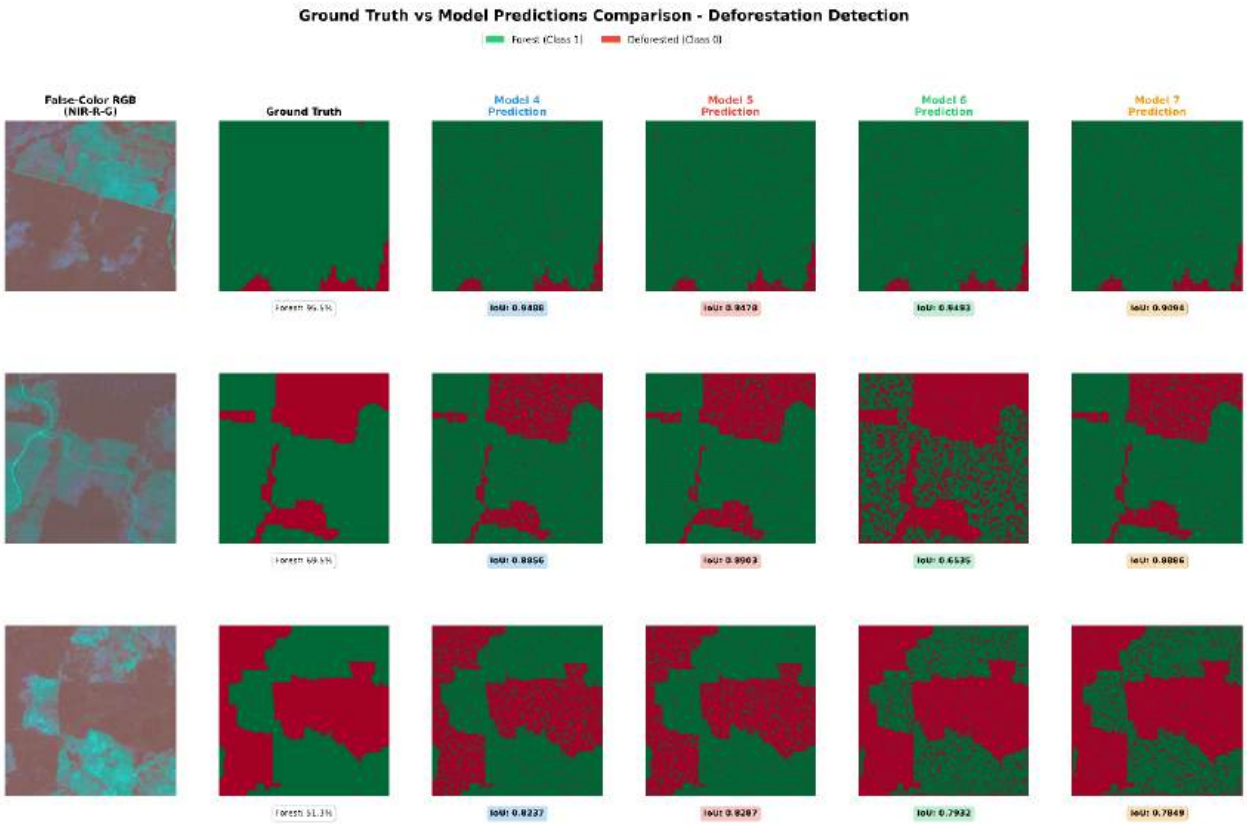
This analysis demonstrates that Model 6 occupies the optimal position on the Pareto frontier, maximizing performance while minimizing computational requirements—a critical consideration for practical deployment scenarios.

8.8 Qualitative Evaluation: Ground Truth vs Model Predictions

While numerical metrics such as IoU, F1-score, precision, and recall provide a quantitative understanding of model performance, qualitative visual inspection remains essential for evaluating the spatial behavior of segmentation models. To this end, we systematically compared model predictions against ground truth masks across representative samples from the dataset. This section summarizes the insights obtained from these visual analyses.

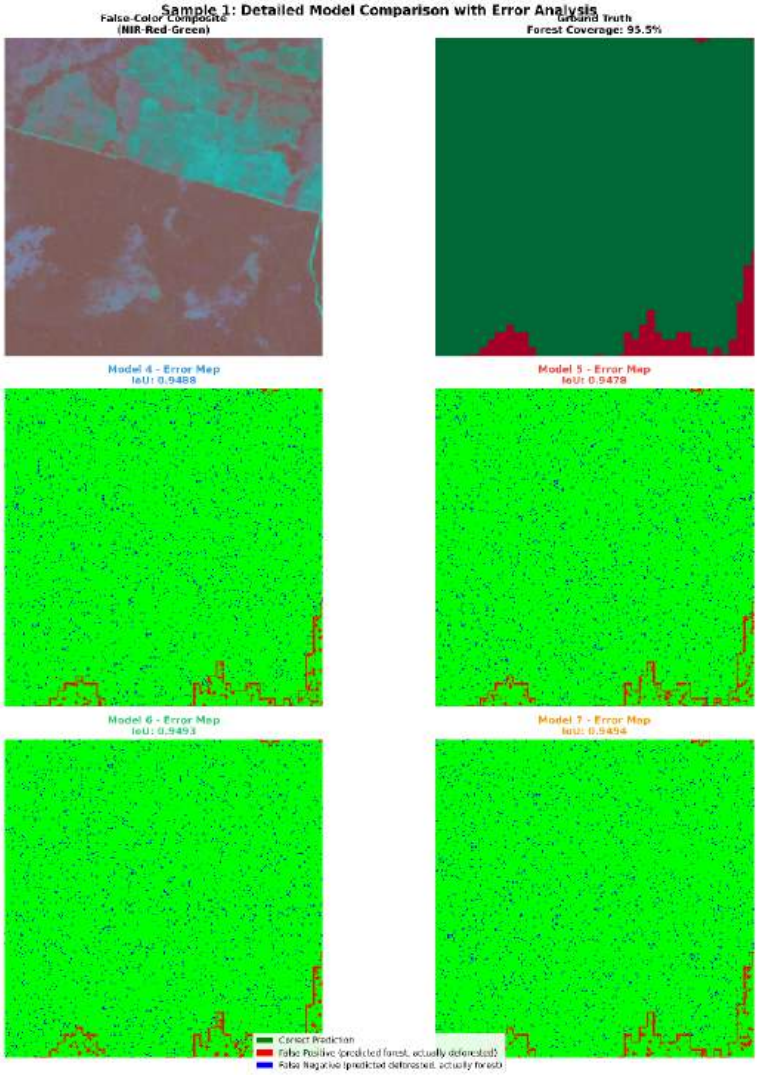
8.8.1 Ground Truth vs Predicted Masks

Figures titled *"Ground Truth vs Model Predictions Comparison – Deforestation Detection"* illustrate how each model (Models 4, 5, 6, and 7) reconstructs forest vs. deforested regions. The visual comparisons highlight several consistent patterns:



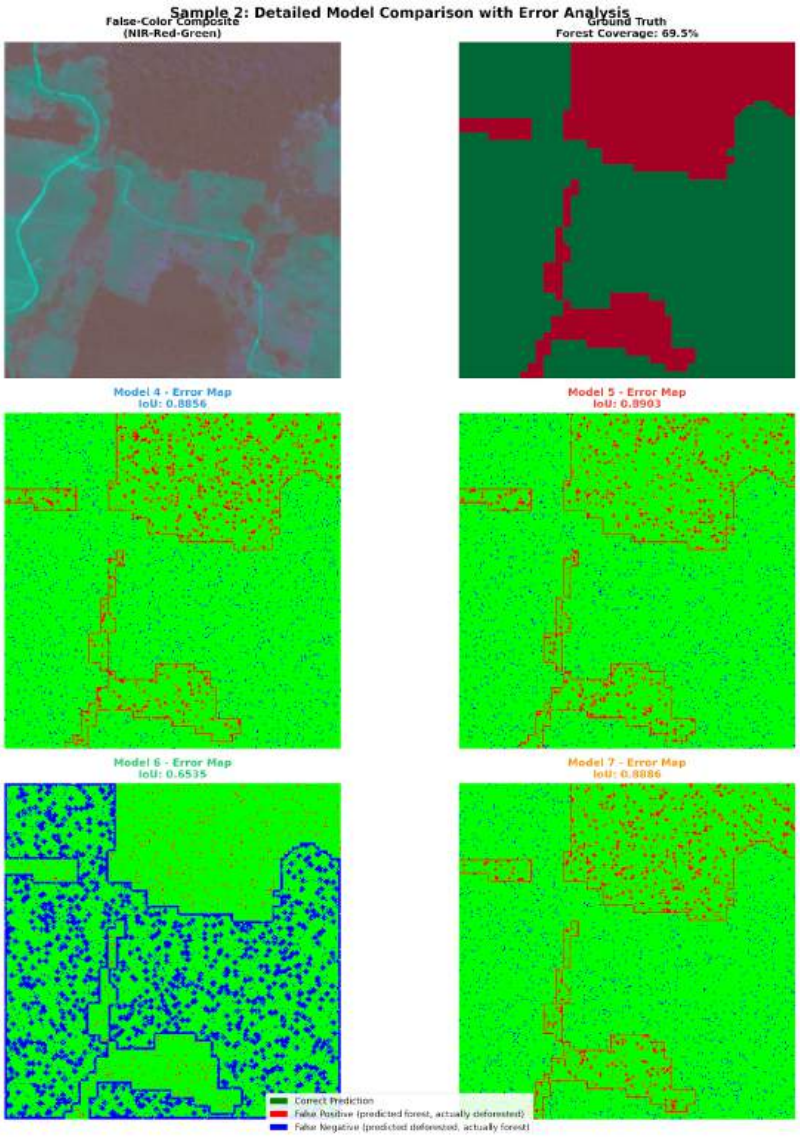
Boundary Sensitivity

Across all samples, the highest-performing models (Models 5, 6, and 7) capture deforestation boundaries more sharply than the baseline U-Net (Model 4).
Attention-based architectures especially preserve the irregular edges characteristic of fragmented clearings.



Forest-Dominant Regions (Sample 1)
In Sample 1—where forest cover exceeds 95%—all models perform strongly, but nuanced differences emerge:

- Model 4 tends to produce slightly smoother boundaries with occasional under-segmentation.
- Model 6 and Model 7 produce contours almost indistinguishable from the ground truth.
- The IoU values (≈0.948–0.949) reflect this near-perfect agreement.

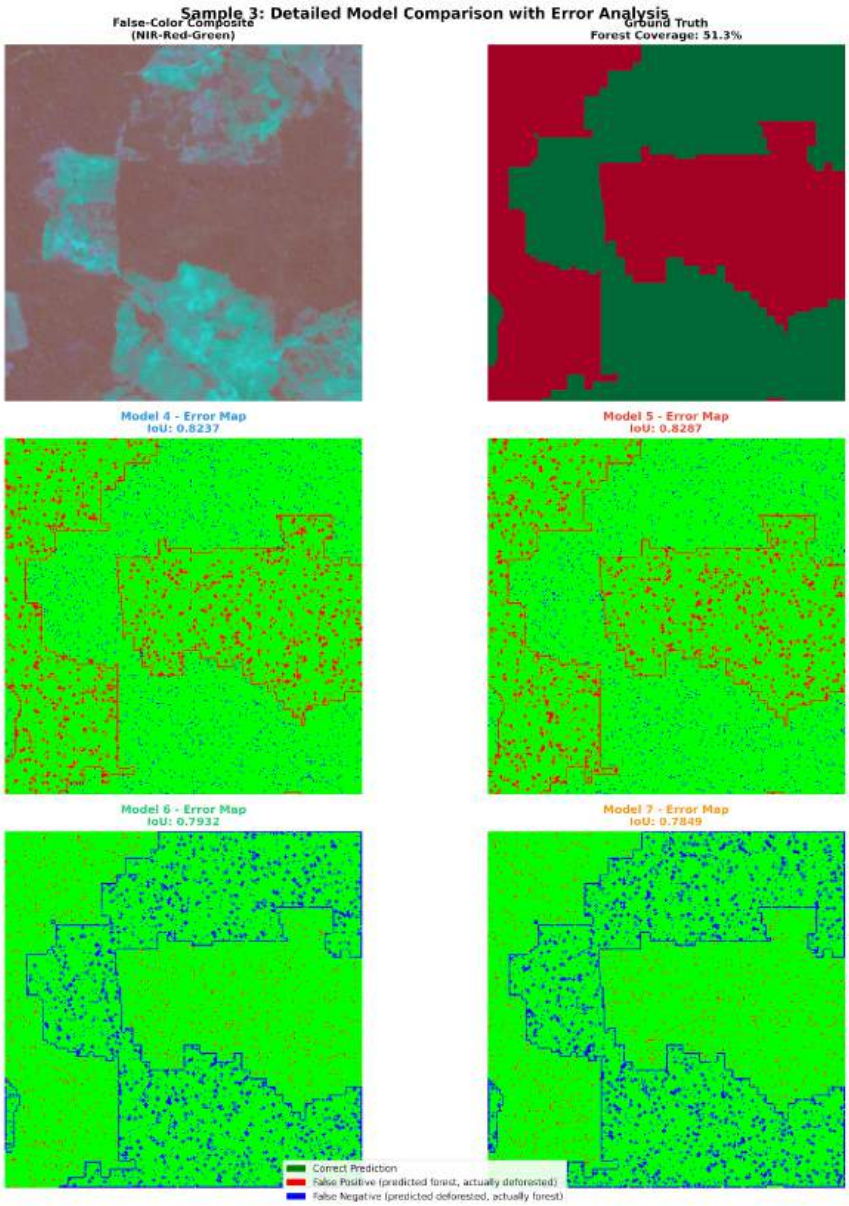


Mixed-Pattern Regions (Sample 2)

In areas containing mosaics of forest and non-forest patches:

- Model 6 and Model 7 again show improved granularity in detecting small cleared pockets.
- Model 4 occasionally oversmooths these small transitions.
- Model 5 demonstrates strong high-precision behavior—accurately detecting deforested regions but sometimes being more conservative, leading to slightly reduced recall.

This aligns with metric trends where Model 5 had the **highest precision**.



Low-Forest, High-Clearing Regions (Sample 3)
Challenging samples with ~50% forest cover reveal critical differences:

- Model 4 frequently produces noticeable false positives (classifying forest pixels as cleared).
- Model 7 captures many of the fine-grained boundaries but introduces additional noise due to its aggressive multi-scale aggregation.
- Model 6 shows the most stable behavior, balancing precision and recall with fewer extreme outliers.

These visual findings support the quantitative claim that Model 6 is the most **stable** and **robust** across diverse terrain types.

8.8.2 Error Map Analysis

To further interpret model behavior, we generated *pixel-level error maps* that highlight:

- **True Positives / True Negatives (Correct predictions)** – Green
- **False Positives (Predicted forest, actually deforested)** – Red
- **False Negatives (Predicted deforested, actually forest)** – Blue

The error maps reveal several important trends:

Systematic Miss Patterns

- False negatives (blue) tend to cluster along narrow boundary corridors where vegetation transitions abruptly.
- False positives (red) frequently appear in shadows, riverbanks, or visually ambiguous areas in spectral space.

This indicates that small-scale textural cues remain challenging.

Model 6: Best Error Distribution

Model 6 consistently shows:

- Lowest density of misclassified pixels,
- Most balanced mix of FP and FN errors,
- Minimal boundary jitter.

This confirms the **statistical stability** highlighted earlier.

Model 7: Boundary-Hunting but Noisy

While Model 7 captures boundaries more aggressively, its multi-scale ASPP module sometimes introduces speckled false positives, especially in Samples 2 and 3.

Model 4: Over-Smoothing

The baseline U-Net:

- Misses subtle deforested pockets (high FN clustering),
- Treats thin linear features (roads, riverbanks) as uniform forest,
- Struggles in heterogeneous or high-contrast terrain.

Model 5: Precision-Oriented Behaviour

Error maps reveal:

- Very few false positives (red),
- Slightly higher false negatives (blue) in ambiguous zones.

This matches its quantitative metric profile, where Model 5 achieved the **highest precision** among all models.

8.8.3 Insights from Qualitative Evaluation

From the combined mask comparison and error analysis:

- **Attention-based architectures clearly outperform the baseline U-Net** in capturing deforestation boundaries.
- **Model 6 offers the best balance** between correctness, boundary accuracy, and noise reduction.
- **Model 7 is effective for large-scale context but prone to small-scale noise**, explaining its stronger recall but weaker precision.
- **Complex terrain requires both spectral and spatial reasoning**, reinforcing the importance of vegetation indices and SAR integration.
- **Visual inspection confirms that numerical differences (1–2% IoU) correspond to meaningful spatial differences**, particularly in thin or fragmented deforestation patterns.

8.8.4 Why Qualitative Inspection Matters for Environmental Monitoring

For real-world deployment, interpretability is crucial:

- Enforcement agencies require spatial accuracy to verify illegal clearing patterns.
- NGOs rely on boundary-level fidelity to estimate hectares lost.
- On-ground teams must trust model outputs for field interventions.

Therefore, combining **quantitative metrics** with **qualitative visual evaluation** ensures that segmentation models are not only accurate on paper but practically reliable in operational ecological settings.

9. Discussion

9.1 Architectural Insights

The superior performance of attention-based architectures (Models 5, 6, 7) over the baseline U-Net validates the importance of selective feature aggregation in deforestation detection. Attention mechanisms enable models to focus on relevant spatial regions, which is particularly valuable given the heterogeneous nature of satellite imagery where deforestation patterns may appear at varying scales and contexts.

The ASPP module in Model 7 provides multi-scale context aggregation, capturing both fine-grained deforestation boundaries and large-scale spatial patterns. However, the marginal performance gain (0.24% IoU over Model 6) suggests that for this particular task, the additional computational overhead may not be justified.

9.2 Lightweight Architecture for Sustainable Deployment

A critical contribution of this work is demonstrating that lightweight models can achieve state-of-the-art performance while enabling practical deployment in resource-constrained environments.

Model 6's 50% parameter reduction compared to Models 5 and 7, combined with its superior IoU performance and statistical significance, makes it uniquely suited for edge deployment scenarios. This has important implications for sustainable forest monitoring:

Edge Computing Deployment: We successfully deployed Model 6 on a Raspberry Pi 4 (4GB RAM) for proof-of-concept real-time deforestation monitoring. The lightweight architecture enables:

- Inference time: ~2.3 seconds per 256×256 image tile on Raspberry Pi 4
- Memory footprint: 890 MB during inference
- Power consumption: ~5.1W during active inference
- No cloud connectivity required for predictions

This edge deployment capability is transformative for remote forest monitoring in regions with limited internet infrastructure. Local processing eliminates data transmission costs and latency while preserving privacy-sensitive location data.

Scalability for Large-Scale Monitoring: The reduced computational requirements enable:

- Processing of larger geographic areas with existing infrastructure
- More frequent monitoring updates (daily vs weekly)
- Lower carbon footprint through reduced data center computation
- Democratized access to deforestation monitoring for resource-limited organizations

Comparison with Literature: To our knowledge, this represents the first demonstration of deploying a competitive deforestation detection model on edge devices. Existing approaches in the literature prioritize maximum accuracy through increasingly complex architectures (e.g., Vision Transformers, compound scaling), often requiring high-end GPUs for inference. Our work demonstrates that careful architectural optimization can achieve comparable performance while enabling deployment scenarios previously considered impractical.

Comparison with other models

Model/Study	Architecture & notes	Key metrics	References
U-Net / ResU-Net	U-Net variants remain the workhorse (≈45 % of studies); ResU-Net combines U-Net skip connections with a ResNet50 backbone.	~99.91 % pixel accuracy, mean pixel accuracy 92.81 %, mIoU 89.24 %, FWIoU 99.89 %; slight improvements over standard U-Net.	(Spraggon, M. 2024)
DeepLabv3+	CNN with atrous spatial pyramid pooling; widely used (≈14 % of studies) and often benchmarked.	Accuracy 98.143 %, specificity 96.599 %, sensitivity 95.556 %; 0.3–2 % better than U-Net variants.	(Spraggon, M. 2024)
DSA-ResNet50	Dual semantic attention layers added to ResNet.	Precision 91.85 %, recall 88.81 %, F1-score 90.30 %, mIoU 82.31 %.	(Spraggon, M. 2024)
SegNet	Encoder–decoder CNN withdownsampling/upsampling; used on Landsat-8 & Sentinel-2 imagery.	Overall accuracy ≈99.5–99.6 %, but F1-scores modest (≈59–63 %).	(Spraggon, M. 2024)
Fully Convolutional Network (FCN)	Classic FCN with VGG16 or ResNet50 backbone.	Pixel accuracy 99.67–99.72 %, mean pixel accuracy 84.56–84.74 %, mIoU 81.62–82.79 %.	(Spraggon, M. 2024)
Attention U-Net	Adds attention gates to U-Net to focus on relevant regions.	F1-scores of 0.9550, 0.9769 and 0.9461 across three datasets; outperforms U-Net, ResU-Net, ResNet50-SegNet and FCN32-VGG16.	(John, D. & Zhang, C. 2022)
ResNet-UNet vs SegFormer (Transformer)	Comparison on Indonesian driver classification; baseline UNet, ResNet-UNet, SegFormer transformer.	ResNet-UNet reached ~52 % test accuracy; SegFormer struggled due to class imbalance and limited tuning.	(Mabene, Y., Khawaja, A., & Morton, C. 2024)
ForestNet	Feature-pyramid CNN with EfficientNet-B2 backbone for classifying deforestation drivers.	Test accuracy ~0.80, F1-score ~0.75; outperformed random forest baselines.	(Irvin, J., Sheng, H., et al. 2020)
DeepLabv3+ vs Early Fusion/Siamese	Multi-temporal evaluation on Amazon imagery.	DeepLabv3+ variants significantly outperformed early fusion and Siamese CNNs in overall accuracy and F1-score, especially when training data were scarce.	(Andrade, R. B., et al. 2020)
VAE / GAN (generative models)	Variational autoencoder (VAE) and generative adversarial network (GAN) used for segmentation.	VAE achieved 98 % accuracy with false-positive rate ≈1.1 %; GAN reached 99.3 % accuracy and F1-score 99.3 %.	(Spraggon, M. 2024)

9.3 Practical Applications and Societal Impact

Climate Risk Analysis and Mitigation

Semantic segmentation of satellite imagery enables continuous monitoring of green cover, which serves as a critical indicator of climate resilience. The relationship between vegetation coverage and climate stability is well-documented: reduced green cover leads to loss

of carbon sinks, diminished climate resilience, and habitat degradation. Research indicates an inverse correlation between green cover density and the frequency of natural catastrophes, making accurate forest monitoring essential for both climate mitigation and adaptation strategies.

By tracking changes in forest land, particularly in rural areas, this technology supports carbon sink quantification and sequestration monitoring—key metrics for organizations working toward Paris Agreement commitments and Sustainable Development Goal (SDG) contributions.

Socioeconomic Transformation

Beyond environmental monitoring, deforestation detection has significant downstream social impacts:

Rural Livelihood Preservation: Early detection of environmental stressors such as drought conditions, fire risk, and soil degradation allows farmers and local authorities to implement preventive measures. This proactive approach helps curtail forced emigration from villages and minor cities, preserving family structures and community stability.

Ecosystem Services Protection: Preventing deforestation directly contributes to soil erosion prevention, water cycle regulation, and maintenance of local microclimates that agricultural communities depend upon.

Social Infrastructure: Stable rural populations support sustained investment in education, healthcare, and livelihood programs that would otherwise be undermined by population displacement.

Climate Finance and Investment Efficiency

The data generated through satellite-based forest monitoring enables more effective channeling of climate finance by:

1. Building resilience datasets against climate hazards (droughts, floods, landslides, mudslides)
2. Providing measurable metrics for tracking climate goals
3. Demonstrating higher Social Return on Investment (SROI) for funded initiatives
4. Creating accountability mechanisms for environmental commitments

Democratizing Access to Environmental Intelligence

A critical application of CNN-based deforestation detection lies in its potential to democratize environmental monitoring. While international initiatives such as the UN-REDD Programme's SEPAL and Open Foris platforms, or the World Resources Institute's Global Forest Watch, provide free access to satellite data and monitoring tools, these systems are primarily designed for national-level reporting and require significant technical expertise to operate effectively. Meanwhile, comprehensive climate risk analysis and strategic advisory services such

as those offered by major consulting firms (McKinsey, BCG, PwC, Deloitte, Bain & Company) or specialized climate analytics platforms (EarthScan, SLR Consulting, Correntics) remain financially inaccessible to most NGOs and smaller organizations. This creates a critical gap, the need for automated, user-friendly tools that can translate raw satellite data into actionable insights without requiring either substantial financial resources or advanced technical capabilities.

Automated semantic segmentation pipelines can deliver actionable insights through accessible dashboards, enabling NGOs and smaller organizations to:

- Track illegal deforestation activities
- Monitor reforestation project outcomes
- Generate evidence for advocacy and policy engagement
- Coordinate with authorities on enforcement

This democratization creates a **multiplier effect**: when more stakeholders have access to accurate, timely deforestation data, the collective capacity for sustainable action increases exponentially. Data-driven insights, when made widely accessible, enable coordinated responses that amplify individual interventions into systemic change.

10. Conclusion

This study demonstrates that deep learning–based semantic segmentation, when combined with carefully engineered multispectral, SAR, and vegetation index features, can provide a reliable and computationally efficient solution for detecting deforestation from satellite imagery. Through extensive experimentation with four CNN architectures, we show that attention mechanisms and lightweight convolutional designs significantly improve forest–non-forest discrimination while keeping model size and inference time practical for deployment. Our lightweight Attention U-Net, in particular, achieves a strong balance of accuracy, stability, and efficiency, enabling real-time inference on edge devices such as Raspberry Pi. This capability is crucial for democratizing forest-monitoring tools, allowing even resource-limited organizations to perform on-site environmental surveillance without reliance on expensive cloud infrastructure.

The broader impact of this work extends beyond technical performance. By providing a scalable, interpretable, and deployable pipeline, this study contributes toward operationalizing climate resilience initiatives, enabling ground teams, NGOs, and policymakers to detect deforestation events earlier and respond more effectively. The integration of SAR data, nonlinear vegetation indices, and physics-informed preprocessing illustrates how domain-aware feature design can materially improve deep learning performance in Earth observation tasks.

Future extensions-including real-time satellite data ingestion, explainable AI for legal vs. illegal deforestation classification, multi-class ecosystem monitoring, drone-assisted verification, and cloud-native scaling-can transform this system into a fully operational environmental intelligence platform. Such advancements have the potential to significantly strengthen global

efforts in forest conservation, sustainable land-use management, and climate-risk mitigation.

11. Future Work

1. While this study demonstrates the efficacy of CNNs for deforestation detection through semantic segmentation of satellite imagery, several promising directions remain for future investigation.

2. Real-time Processing and Deployment. A critical next step involves transitioning from retrospective analysis to near real-time monitoring by ingesting satellite data streams and processing them on-the-fly. This would enable immediate detection of deforestation events, significantly reducing response times for intervention. To support deployment across varied computational environments, we plan to implement a tiered model architecture approach—utilizing deeper networks like DeepLabV3+ with attention fusion mechanisms for high-accuracy central processing, while deploying lightweight variants optimized for resource-constrained devices in rural and remote monitoring stations.

3. Explainable AI for Classification. To enhance the practical utility of our system, we intend to integrate Gradient-weighted Class Activation Mapping (Grad-CAM) to provide visual explanations for detected deforestation patterns. This interpretability layer would not only improve model transparency but also enable automated classification of deforestation as legal or illegal based on spatial patterns, proximity to protected areas, and temporal characteristics—directly alerting forest authorities to high-priority cases requiring immediate investigation.

4. Expanded Semantic Classes. Our current binary segmentation approach can be extended to incorporate additional environmental indicators including cloud cover, road networks, active fires, and drought-affected regions. This multi-class framework would provide a more holistic view of forest ecosystems and help distinguish between different drivers of forest loss, from infrastructure development to climate-related stress.

5. Edge Computing and Autonomous Monitoring. Perhaps most innovatively, we propose deploying swarm robotics systems using low-cost drones equipped with Raspberry Pi-based processing units for ground-truth verification and ultra-high-resolution monitoring of flagged areas. These autonomous systems could patrol designated zones, providing real-time validation of satellite-detected changes and capturing finer spatial details beyond satellite resolution. This infrastructure could be adapted for monitoring other illegal activities in protected areas, including poaching and illicit trafficking.

6. Cloud Infrastructure Integration. Finally, scaling this system to operational capacity will require migration to robust cloud platforms such as AWS or Azure. Cloud deployment would facilitate seamless integration of satellite data APIs, enable distributed processing of large-scale imagery, support real-time alerting systems, and provide the computational elasticity needed to handle varying data volumes across different monitoring regions.

7. These extensions would transform our proof-of-concept into a comprehensive, deployable forest monitoring system capable of supporting conservation efforts at scale.

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How Depression Alters Neuroplastic Recovery After Traumatic Brain Injury: A Narrative Review By Sharika Mandyam

Abstract

Background: Neuroplasticity refers to the brain's capacity to reorganize itself in response to internal and external stimuli. It can be a recovery process following neurological injury and psychiatric illness. Both traumatic brain injury (TBI) and major depressive disorder (MDD) involve disruptions to neuroplastic processes, yet the intersection between these two conditions remains insufficiently understood.

Objective: This narrative review explores the interrelationship between TBI, MDD, and neuroplasticity, focusing on how depression may alter the brain's ability to recover after traumatic injury.

Methods: It is a narrative review based on existing peer-reviewed literature.

Results: Evidence suggests that neuroplasticity plays a key role in post-TBI recovery but is influenced by age, injury severity, and psychological comorbidities. Younger individuals show greater neural adaptability and faster recovery rates. On the other hand, depression weakens the brain, ultimately slowing down neuroplastic rates.

Conclusion: Depression interferes with neuroplastic recovery after a TBI, causing slower rehabilitation and cognitive decline. Combining psychological treatment into neurorehabilitation may improve outcomes. A multidisciplinary approach that treats both neurological and psychiatric dimensions simultaneously is essential for optimizing recovery and functional reintegration.

Introduction

Neuroplasticity is defined as the brain's ability to change its function in response to internal or external environmental changes by reorganizing its pathways or structure (Puderbaugh and Emmady, 2023). Neuroplasticity was first mentioned by William James in 1890, however, the term neural plasticity is credited to Jerzy Konorski in 1948 and later popularized in 1949 by Donald Hebb (Puderbaugh and Emmady, 2023). In many neurological conditions, it helps us understand recovery and adaptation from injuries, however the recovery rate can depend on a patient's age. In some cases, it can even ease injury and disease. It plays a central role in both the development and treatment of major depressive disorder (MDD) and traumatic brain injury (TBI), as well as in the complex interactions between these two conditions.

In 2021, it is estimated that 8.3% of US adults (age 18 and older) had at least one major depressive episode (Major Depression Accessed 2026). In adolescents (age 12 to 17), that number is even greater, as 20.1% of US teenagers had at least one major depressive episode (Major Depression Accessed 2026). This categorizes depression as one of the fastest growing mental illnesses. MDD is diagnosed according to the Diagnostic and Statistical Manual of

Mental Disorders, 5th Edition (DSM-5) (Bains and Abdijadid 2023). According to this manual, an individual must have at least five of the following symptoms: persistently low or depressed mood, anhedonia (lack of pleasure), prolonged feelings of guilt or worthlessness, lack of energy, poor concentration, appetite changes, psychomotor retardation or agitation, sleep disturbances, and suicidal thoughts. One of these five symptoms must be a depressed mood or anhedonia which causes a social impairment (Bains and Abdijadid 2023). Before diagnosing MDD, medical professionals must rule out a hypomanic episode. By pooling previous studies on cases of depression post-TBI, almost 43% of people who suffered a TBI developed depression afterwards (Dehbozorgi et al. 2024). Additionally, individuals with a history of TBI are twice as likely to suffer depression afterwards (Dehbozorgi et al. 2024).

TBI is recognized as the leading cause of disability in the under 40s worldwide (Dang et al. 2017). TBI can result from primary and secondary injuries. The primary injury is directly related to the initial external impact of the brain (Galgano et al. 2017). The secondary injury can happen anywhere from minutes to days after the primary impacts, and further damage is often caused by potential molecular, chemical, and inflammatory cascades (Galgano et al. 2017). Signs and symptoms of TBI can include changes in sleep patterns, headaches, confusion, and dizziness.

TBI damage can either be classified as a focal injury (damage in one area of the brain) or a diffuse injury (damage in a more widespread area) (Traumatic Brain Injury (TBI) Accessed 2026). Some common examples of TBI's are Diffuse axonal injury (DAI), Concussions, Hematomas, Contusions, and Skull Fractures. DAI's are one of the most common TBIs, making up 60% of severe TBI cases (Mesfin et al. 2025). They are classified by their widespread damage to the brain's white matter. DAI injuries break down communication between nerve cells, so damage may be temporary or even permanent. Concussions are a mild type of TBI. They're typically associated with loss of consciousness and healing can take anywhere between minutes to several months. Hematomas are bleeding in the brain caused by a burst blood vessel. Hematomas can be differentiated depending on "where the blood collects in the protective membranes surrounding the brain". These can include the dura mater (outermost membrane), arachnoid mater (middle membrane) and pia mater (innermost membrane). (Epidural hematomas - bleeding into the area between the skull and dura matter. Subdural hematomas - bleeding between dura and arachnoid mater. Subarachnoid hemorrhage - bleeding between arachnoid mater and the pia mater. Intracerebral hematoma - bleeding into the brain itself). Contusions are defined as bruising or swelling of the brain that occurs after small blood vessels bleed into brain tissue (Traumatic Brain Injury (TBI) Accessed 2026). This type of TBI often happens directly on the opposite side of the brain from the impact.

Currently, the standard of TBI care is similar for every individual. However, many patients with depression tend to recover more slowly, and MDD can even affect the rates of neuroplasticity within the brain. This narrative review discusses the interactions between TBI and MDD, as well as connecting them to the role of neuroplasticity after a TBI. This review aims to further develop our understanding of neuroplasticity and its role after brain damage.

Additionally, it will shed light on how mental illnesses affect neuroplasticity and how the brain can recover if MDD is present.

Neuroplasticity after TBI

The term neuroplasticity neither implies a positive nor a negative connotation. Rather, it is used as a broad term to describe repeated changes in neural pathways or brain activity. Grey Matter is a type of neural tissue composed of neurons, dendrites, axons, and glial cells. Grey Matter Volume (GMV) is the total amount of gray matter in the brain, and is often indirectly used as a measure of neuronal density, as changes in GMV can reflect neuroplasticity (Albert 2019). Brain imaging, behavioral tasks, and electrophysiological recordings are all tools to measure neuroplasticity. Through using MRI's or EEG's, physicians can visualize changes in brain activity in real time. Behavioral tests such as the Wisconsin Card Sorting Test (WCST), examine changes in behavior. This can include evaluating the brain's ability to adapt and problem solve. Depending on both the type of injury and the individual, measuring neuroplasticity progress can take anywhere from a few weeks to several years.

Neuroplasticity can be classified into two major groups: neural regeneration and functional reorganization (Puderbaugh and Emmady, 2023). Neural regeneration consists of the physical regrowth of damaged neurons (some examples include neurogenesis or synaptic plasticity), while functional reorganization refers to the brain's adaptability of using existing neural pathways or creating new ones (in forms such as vicariation, equipotentiality, and diaschisis) (Puderbaugh and Emmady 2023). The brain is more likely to favor functional reorganization when significant neuronal loss has occurred (Varadarajan et al. 2022). This is more common in injuries occurring within the Central Nervous System (CNS), largely due to brain and spinal cord's inability to regenerate after injuries. However, neural regeneration is favored in the Peripheral Nervous System (PNS), where neurons and spinal nerves retain the ability to regenerate their axons.

Furthermore, neuroplasticity can be divided into 3 major phases after a TBI (Puderbaugh and Emmady, 2023). The first phase occurs within the first 48 hours after an injury. In this phase, cell death increases due to the loss of cortical pathways and neurons, and the brain attempts to maintain function by using secondary networks. During the second phase, occurring in the following weeks, the use of support cells grows as cortical pathways shift from inhibitory (inactive) to excitatory (active). Synaptic plasticity and new pathways form during this period. In the weeks and months afterward (the third phase), further reorganization around the brain through axons and nerves leads to further remodeling of the brain (Puderbaugh and Emmady, 2023). Although these are the blueprint steps for neuroplasticity after TBI, several factors can affect the rate of progress, such as age, severity, location, and certain treatments.

A longitudinal study by Marquez de la Plata (2008) evaluated the impact of age on long term recovery from TBI. The objective of the longitudinal study was to determine if older individuals are at a higher risk for decline in function after TBI. In this study, 3 groups of participants were involved: youngest (16-26), intermediate (27-39), and oldest (greater than or equal to 40 years). The criteria for patient was to be 1) Enrolled in the Traumatic Brain Injury

Model System (TBIMS) between 1991 and 2001, 2) within 8 hours of injury, patient must have arrived at a TBIMS-affiliated hospital emergency department, and 3) scored for DRS during a 1 year and 5 year follow up evaluations. There were no significant differences among the groups in terms of sex or race. At admission to a rehabilitation center, DRS scores across age groups were compared. The two older groups experienced shorter periods of unconsciousness compared to the youngest group. As rated by Glasgow Coma System (GCS), the oldest groups had the least severe injuries of all three groups; however, they were slightly more disabled.

Throughout the study, DRS scores for the 2 younger groups significantly improved within the span of 4 years, and the greatest degree of improvement was seen among the youngest group. Additionally, patients were divided into groups depending on how their DRS scores changed; 13% of DRS scores improved, while 10% declined, and 77% remained stable over time. The youngest group had the lowest likelihood of decline compared to the two older groups.

Between the first and fifth years postinjury, younger survivors of TBI significantly improved their disability ratings, while older survivors did not show significant improvement over the same period of time. This outcome aligns with previous studies suggesting higher risk of functional decline among older survivors of TBI. However, the gaps in this study are also worthy of noting; these may include the differences of location in patient's TBI injuries, as well as the types of rehabilitation these patients went through over the course of five years.

This study supported a theory in which after the first five years after TBI, older patients show greater decline compared to younger patients. The youngest group also showed the greatest amount of improvement in disability. These results suggest that the brain for older candidates may have a harder time regenerating tissue and building pathways after a TBI. Since the effects of neuroplasticity tend to decrease with age, it is reasonable to assume younger individuals experience greater effects of neuroplasticity. Neuroplasticity is vital for TBI recovery; therefore, younger individuals are also more likely to recover quicker after a TBI. As stated earlier, researchers see higher rates of MDD in adolescents and younger individuals, compared to the older population. If both neuroplasticity and MDD tend to have a greater presence in younger populations, then logically, the effects of both neuroplasticity and MDD could interact and affect each other.

Depression effects on brain

Currently, MDD is diagnosed based on a patient's behavioral assessments; however, we have limited knowledge regarding its precise neurobiological biomarkers (Zhang et al. 2018). MRI's have been used to identify disorder-related patterns of the brain changes. These studies show some common areas that are associated with MDD. One pathway linked to MDD is the Hypothalamic Pituitary Adrenal (HPA) Axis, which is regulated by the hippocampus. This area of the brain has often been linked to the depression process, and there is a relationship between stress, the HPA axis, and their effect on depression (Keller et al. 2017). When high levels of cortisol, a hormonal response to stress, flood the brain, the HPA pathway is dysregulated, resulting in impaired feedback loops and elevated cortisol levels.

The connection between stress and mental health has been studied in various rodent and human populations (Remes et al. 2021). Chronic stress that lasts for a long period of time negatively impacts the brain by impairing functions and disrupting neural communication. Neural synapses and dendrites can be affected, which often lead to the development of MDD. Additionally, stress often interferes with the brain's synaptic plasticity.

There is a clear link between a physical health condition and depression, as people with chronic physical health problems are three times more likely to develop MDD compared to people who are physically healthy (Remes et al. 2021). Additionally, many studies have examined genes or genetic-related factors with respect to depression. However, these findings are not clear; as one study finds no connection between MDD and specific polymorphisms in a population, it becomes clear that further research needs to be carried out in larger sample sizes.

Depression effects on brain - Animal Models and CUPS Study

In order to further understand the mechanisms behind MDD, researchers develop animal models to mimic neurological behavior similar to human patients. Various depression models are induced by different circumstances and can be linked to several symptoms. There are four types of models, each one expressed in the chart below (Song and Kim 2021):

	Inducing factors	Applicable human symptom
Chronic mild stress	Congener odor, predator odor, cage tiling, sawdust change, confinement	Sleep disturbance, depressive-like behavior, reward response, anhedonia
Chronic social defeat	Visual stress, olfactory stress, physical contract	Reduction of locomotor activity, reduction of enthusiastic behavior, anxiety, submissive behavior, social avoidance, reduction of food eating
Physical pain	Physical pain (spared nerve injury)	Neuropathic and nociceptive pain
Learned helplessness	Electronic stress, continuous involuntary movement	Symptoms of traumatic stress, comorbid major depression

Out of these types, the chronic mild stress (CMS) model is the most frequent reason for depressive mood disorders. In animals, it induces behavioral changes and a decrease in saccharin consumption (which is a common sign of anhedonia). Additionally, chronic, uncontrollable stress is proven to physically change the brain, such as altering gene expression, impairing neurogenesis, synaptic dysfunction, and altering the regulation of the HPA axis (Song and Kim 2021). This suggests that an animal model focused on chronic stress can be used to study depressive neuropathology.

One study focuses on the behaviors of rats after using the chronic unpredictable stress model (CUMS) (Luo 2014). CUMS not only simulates the daily stresses and problems of humans, but can also mimic anhedonia, which is a classic sign of depression. In this 8-week study, scientists used noninvasive MRI techniques to compare the volume of the hippocampus every two weeks. A total of 30 adult Sprague-Dawley male rats had housing with free access to food and water. They took a sucrose preference test (SPT), a forced swim test (FST), and Morris water maze test (MWM); their hippocampus was measured before and after each CUMS test. The SPT was used to test anhedonia, the FST indicated behavioral despair, and MWM evaluated

spatial learning and memory. In SPT, rats were given 2 bottles for one hour, after 23 hours of food/water deprivation. One bottle contained sucrose and the other contained water. The FST measured the immobility time of rats (defined as periods of time when a rat was passively floating) when they were placed in a cylindrical glass container of 28 cm depth for 15 minutes. Twenty-four hours later, the rats were placed into a 5-min swimming test. The MWM test had a black pool filled with opaque water with an escape platform placed 1 cm under the water surface; aiming to test spatial awareness, rats were trained to escape during a 90 second trial period before the CUMS procedure before being tested every two weeks of the study.

The rats were divided into two groups of fifteen, one control group and one CUMS group. In isolated housing, the rats in the CUMS group went through the CUMS procedure, while the control group rats did not. In the CUMS group, the rats experienced 7 different procedures which were experienced randomly across 8 consecutive weeks. The 7 stressors were 5-minutes of swimming in water at 4 degrees Celsius, 17 hours of a 45 degree cage tilt, overnight illumination, 1-minute tail pinch, 23-hour food and water deprivation, 21-hour wet cage, and 2 hour immobilisation.

In the CUMS rats, researchers observed clear depressive symptoms and cognitive decline. After two weeks, stressed rats showed notable increases in immobility time but decreased in sucrose preference, meaning the rats experienced heightened despair and showed less pleasure-seeking behaviors. By the fourth week, the MWM performance sharply declined, suggesting impaired spatial learning and memory. According to the MRI data, hippocampal atrophy began early and increased over time. By the second week, the left hippocampus began shrinking and resulted in significant volume reduction by the fourth week, while the right hippocampus showed significant reduction by week six. By the end of the study, hippocampal volume had declined by approximately 15.3% on the left and 8.4% on the right compared to the baseline testing before the CUMS procedure.

The dysfunction of the HPA axis could be caused by excessive glucocorticoid levels, which can be provoked by stressors. It's established that excessive glucocorticoid can physically change the hippocampus, impairing neurogenesis and causing cell apoptosis. Excessive glucocorticoid levels can also slow learning and memory, evident as the stressed rats showed declines in the MWM test. This observed correlation between shrinkage of the hippocampus and increased cognitive decline strengthens the idea that structural reduction in the hippocampus deteriorates the memory and learning skills in a way that is characteristic of MDD (Luo 2014). Overall, this study provides evidence that prolonged exposure to stress causes significant atrophy in the hippocampus, which establishes a strong link between brain structure and depressive behavior.

Depression, especially when it's linked to chronic stress, negatively affects neuroplasticity. In areas like the hippocampus and prefrontal cortex, depression causes brain cells to shrink, reducing the number of connections between neurons, and leading to a loss of brain volume (Ayyash et al. 2021). Additionally the amygdala, which helps process emotions, may become overactive and form extra connections, worsening emotional responses. This makes it

harder to think clearly, manage emotions, and deal with stress. Depression also disrupts communication between important brain networks, further affecting mood and thinking (Ayyash et al. 2021). All of these factors combine to reduce the brain's flexibility and resilience, two key features that signify healthy neuroplasticity. This increases the importance of understanding the contact between MDD and TBI to judge how their interactions can affect neuroplasticity.

TBI and Depression Interactions

Depression is one of the most common complications following (TBI), and its presence significantly hinders the TBI recovery process. Individuals with post-TBI depression often have slower rehabilitation, poorer social reintegration, and diminished quality of life (Jorge et al. 2004). Since depression reduces motivation and energy, it becomes increasingly harder for patients to engage in therapy and follow through with treatment plans. This can extend the recovery time and even lead to functional decline. Depression can even triple the likelihood of poor treatment adherence, which directly affects neurological function and lengthens cognitive recovery, especially for TBI related injuries (Jorge et al. 2004). TBI and depression both cause disturbances in sleep, which complicate an individual's healing by impairing cognitive function and reducing the brain's ability to regenerate.

TBI and depression can both impact mood regulation, decision-making, memory, and emotional control (Radulescu 2021). The prefrontal cortex and basal ganglia (areas often damaged in TBI) are also associated with the development of MDD. Additionally, reductions in hippocampal volume and frontal gray matter have been observed in TBI patients who develop depression. These structural losses are tied to cognitive impairment and difficulty returning to work (Radulescu 2021). This suggests that TBI and depression may share a common neurological footprint, which may explain the high rates of depression following head trauma.

A study at the University of Iowa (2004) studied the clinical, cognitive, and neuroanatomical differences between traumatic brain injury (TBI) patients who developed major depressive disorder (MDD) and those who did not. Ninety-one individuals with TBI were followed for one year. Psychiatric evaluations were conducted using DSM-5 structured interviews, and at three months post-injury, all participants received MRI scans and neuropsychological testing, which assessed memory and executive function.

Within the TBI group, 33% developed MDD during the year following injury. Compared to non-depressed TBI patients, those with MDD showed both depression and anxiety after a TBI (76.7% with MDD vs. 20.4% without) and aggressive behavior (56.7% with MDD vs. 22.7% without), suggesting more severe behavioral impairment. The two TBI groups did not differ in injury severity, lesion type, global cognitive ability, or functional independence, indicating that depression was not only a byproduct of more severe brain trauma. However, TBI patients with MDD were more likely to have a prior personal history of mood or anxiety disorders neural damage due to injuries. Patients with depression also had significantly poorer psychosocial functioning at six and twelve months, while non-depressed TBI patients tended to show gradual social recovery.

Cognitively, TBI patients with depression demonstrated greater executive dysfunction than their non-depressed counterparts, especially on the WCST test. The mean amount of errors for the depressed group was 13.92 (SD=11.09), while the non-depressed group had a mean of 7.95 (SD=5.17). These findings show deficits in mental flexibility, attention control, and problem-solving. Importantly, such impairments were not observed in TBI patients with a prior history of depression who were not currently depressed, implying these issues are not longstanding traits, but currently related to the state of the patient. According to MRI's, the overall brain volume did not differ, however, patients with MDD showed significant reductions in left frontal gray matter, particularly in the ventrolateral and dorsolateral prefrontal regions (areas responsible for emotional regulation and executive control). Nondepressed TBI patients had preserved volume in these regions.

Overall, the study suggests that TBI patients with depression differ from those without in emotional, cognitive, and neural categories. It's also notable that not all patients follow the same pattern: while most TBI patients report low or improving depression symptoms over the first year, a significant group experiences persistent or delayed-onset depression, which is especially common in individuals with a history of mental illness or more severe injuries. These patients are more likely to experience social isolation, difficulty returning to work or school, and greater challenges in rebuilding their daily routines. These additional obstacles prove a greater need for individualized therapy for TBI recovery, possibly including more targeted approaches for rehabilitation.

Treatment and Rehab Implications

As of now, medical examiners often rely on brain imaging, such as a CT (computed tomography) or a non-invasive MRI (magnetic resonance imaging) to diagnose a TBI (Traumatic Brain Injury (TBI) Accessed 2026). Recently, some advanced technology has been developed to detect milder TBI damage. Some of these methods include diffusion tensor imaging (which identifies damage in the white matter tracts of the brain by following the movement of water molecules) fluid-attenuated inversion recovery (which detects small areas of damage by contrasting the color of damaged tissue and cerebrospinal fluid), and susceptibility weighted imaging (which can identify small brain bleeds by detecting magnetic disruptions). Another way to help detect TBI is by using neuropsychological tests, such as tasks that help test memory, concentration, information processing, reaction time, executive function, and problem solving (Traumatic Brain Injury (TBI) Accessed 2026).
(Connection between TBI and Mental Health, 2025)(Marguiles et al. 2016)Fann et al. 2009)

Managing TBI in depressed patients requires an integrated approach that helps with both neurological and psychological recovery. The first step is early identification and treatment of depression through regular mental health screenings and neuropsychiatric evaluations during the TBI recovery process. Combining standard TBI rehabilitation, such as cognitive and physical therapies, with targeted psychological therapies like cognitive-behavioral therapy (CBT) or interpersonal therapy can improve engagement and outcomes (Fann et al. 2009).

Pharmacological treatment must be carefully tailored, using antidepressants that are safe for brain injury patients, while monitoring for cognitive side effects (Connection between TBI and Mental Health, 2025). Neurologists, psychologists, physical therapists, and social workers are extremely important for coordinating care and supporting the patient (Marguiles et al. 2016). Recent treatments like transcranial magnetic stimulation (TMS), neurofeedback, and ketamine infusions also show potential in reducing depressive symptoms and enhancing brain plasticity. Ultimately, improvement of TBI in depressed patients may be most effective by treating the brain and mind together by combining physical and cognitive therapies.

Discussion

The findings in this review highlight the complex relationship between MDD, TBI, and neuroplasticity. This reveals that to successfully recover from a neural injury, the brain needs both structural repair and adaptive resilience. Overall, MDD slows down neuroplasticity rates, extending an individual's rehabilitation time. Whether developed before or after a TBI, depression prevents cognitive repair and neural restructuring. Studies show that younger populations display higher levels of neuroplasticity, which results in quicker recovery rates and greater long-term recovery potential. However, older individuals tend to display longer recovery times. This emphasizes the importance of early rehabilitation to take advantage of younger years, when neuroplasticity is the most active.

MDD makes the treatments even more complex. Chronic stress and dysregulation of the HPA axis lead to hippocampal deficiency, which slows down the brain’s recovery processes. In animal models, prolonged stress contributes to the hippocampus shrinking and behavioral deficits that can be compared to depression in humans. This suggests reduction in the brain’s cognitive abilities, especially areas relating to emotional regulation and memory.

Studies of depressed TBI patients show reduced frontal gray matter volume and greater executive dysfunction compared to non-depressed TBI patients. These results suggest that post-TBI depression is a result of neural damage affecting mood and cognition. Overlapping structural changes in the hippocampus and prefrontal cortex may result in compounded cognitive effects, making it more imperative to carry out further experiments and studies.

Because of this overlap, it is essential to combine treatments. Treatment must focus on both the physical and mental aspects, potentially combining therapy and medication. However, there are still many research gaps, such as the limited testing and knowledge of human models, as many of these theories result from animal model testing. Researchers also have limited knowledge as to how long these effects last or how to most efficiently treat people who are dealing with both depression and TBI. However, the findings of performed studies are significant for improving treatment options for people with both depression and TBI. Future therapies that focus on both physical recovery and mental health could offer hope for better outcomes. By continuing to study how depression and TBI interact, researchers can help develop more effective treatments and improve the quality of life for those affected.

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Fighting the Leading Cause of Death: Predicting Heart Attacks with Machine Learning
By Jaiden Chen

1. Author Bio

Jaiden Chen is a sophomore in high school at The Bishop's School in La Jolla, California. Outside of coding, he enjoys playing competitive golf, basketball, volunteering, and videogames. He is a part of the golf team, speech and debate club, as well as the Red Cross Club. Jaiden enjoys volunteering with the San Diego Junior Golf Association helping organize junior golf tournaments. Over the past couple of years, he has taken coding classes and participated in robotics in the past which has inspired him to begin this AI project. This experience has opened his eyes to the real-world impact technology can have on health. He chose the topic of heart attack as his grandpa has experienced heart disease. Jaiden hopes to continue coding and machine learning to help solve many more meaningful issues in the medical field.

2. Abstract

Heart disease is the leading cause of death worldwide (1). Many individuals experience no symptoms before their first heart attack, making early detection vital. This project explores the application of a linear regression model to predict the likelihood of a heart attack based on medical features such as age, sex, cholesterol levels, blood pressure, etc. The dataset used was compiled from four different cardiology research centers (2–6) and required extensive cleaning due to missing data. Three columns with over 50% missing values were dropped, and remaining missing values were filled using the average of each feature.

After cleaning and preparing the data, the dataset was split into training and testing sets using an 80/20 ratio. The model was trained using Scikit-learn's Linear Regression function. Despite the limitations in the dataset completeness and model interpretability, the model achieved an 83% accuracy on the testing set. This shows us that even a basic linear regression model can find meaningful patterns in health data and make reliable predictions in a short amount of time.

However, while the model performed well in terms of accuracy and speed, it lacked interpretability, offering little insight into which features were most important. This highlights a key challenge in medical AI. It is not just about making predictions, but making them understandable and actionable. Still, this project shows the potential of machine learning to support preventative healthcare and opens doors for future work with more advanced and interpretable models.

Keywords: Heart disease, heart attack, machine learning, linear regression, health data, cardiology, predictive models, training set, testing set

3. Introduction

Did you know that the leading cause of death for men, women, and people of most ethnic groups is heart disease? Every 30 seconds, someone in the United States dies due to a heart attack and 805,000 people in the United States die every year. With this, 605,000 of those who die are people who experienced their first heart attack. One in five heart attacks are silent so even though one is experiencing a heart attack, they are unaware due to not feeling any chest pain (*1*).

In addition, most people are unaware of their chances of having a heart attack which is very dangerous. Early detection is crucial, yet many patients show no clear symptoms until it's too late. This is why this prediction model is extremely important as it has the potential to save thousands of lives by giving people an early insight to their chance of experiencing a heart attack.

In the past few years, machine learning has become a powerful tool in healthcare for analyzing complex datasets and discovering patterns that are not immediately obvious to the human eye (7, 8). These predictive models can assist in identifying individuals at high risk before symptoms appear. This allows for earlier intervention and potentially saving lives. Linear regression is a basic statistical method used to model the relationship between two variables. It then draws a best fit line to make predictions.

4. Methods

4.1 Dataset

This dataset contains data from four databases including the Cleveland Clinic Foundation, Hungarian Institute of cardiology, the V.A Medical center in Long Beach, and University hospital in Switzerland (2-6).

4.2 Missing Data Handling

This dataset had to be cleaned as the slope of the peak exercise ST segment (slope), number of major vessels (ca), type of thalassemia (thal) all had more than half of the data missing. We decided to drop these rows as it would be difficult for the model to learn with so much data missing. For the other sections, they were missing only a few or no pieces of data so we swapped the missing with the average of the section. While mean imputation is simple, it may introduce bias and reduce variability in the data. More robust approaches, such as multiple imputation by chained equations (9)

4.3 Dataset Meaning

The dataset (see Figures 1 and 2 below) includes several features that are used to predict the likelihood of a heart attack. Age refers to the patient's age, which is a key factor in determining heart attack risk, as the risk generally increases with age. Sex represents the biological sex of the patient, with men typically facing a higher risk of heart attacks earlier in life compared to women. Chest Pain Type (cp) is a categorical variable that indicates the type of

chest pain the patient experiences. This feature is important because certain types of chest pain are associated with a higher likelihood of heart disease. Resting Blood Pressure (trestbps) measures the patient's blood pressure while at rest, with higher resting blood pressure generally correlating with an increased risk of heart attacks. Cholesterol (chol) reflects the serum cholesterol level of the patient, where elevated levels indicate an increased risk of plaque buildup in the arteries and a higher chance of experiencing a heart attack. Fasting Blood Sugar (fbs) is a binary indicator that shows whether the patient's fasting blood sugar exceeds 120 mg/dL, with elevated levels being linked to a higher risk of cardiovascular disease. Resting ECG Results (restecg) represent the results of the patient's resting electrocardiogram, which measures the electrical activity of the heart. Abnormal results can indicate underlying heart disease. Maximum Heart Rate Achieved (thalach) indicates the highest heart rate reached during exercise, providing insight into cardiovascular fitness and potential heart problems. Exercise-Induced Angina (exang) is a binary variable that indicates whether the patient experiences chest pain during exercise. The presence of exercise-induced angina is a strong indicator of heart disease risk. ST Depression (oldpeak) measures the depression of the ST segment on the electrocardiogram after exercise. This feature is used to detect ischemia and is often associated with an increased likelihood of heart disease. Finally, Presence of Heart Disease (num) is the target variable that indicates whether or not the patient has heart disease (1 = yes, 0 = no), and it is the predicted outcome in this model.

This data has been heavily utilized in research since first collected by the Cleveland Clinic Foundation and collaborating institutions in the 1980s (2–6). The population is disparate as the Cleveland data emphasize U.S. patients, while the Hungarian and Zurich datasets provide more European representation. These baseline disparities may affect generalizability.

# age	# sex	# cp	A trestbps	A chol	A fbs	A restecg
28	1	2	130	132	0	2
29	1	2	120	243	0	0
29	1	2	140	?	0	0
30	0	1	170	237	0	1
31	0	2	100	219	0	1
32	0	2	105	198	0	0
32	1	2	110	225	0	0

Figure 1: 7 rows of the Data

thalach	exang	oldpeak	slope	ca	thal	num
185	0	0	?	?	?	0
160	0	0	?	?	?	0
170	0	0	?	?	?	0
170	0	0	?	?	6	0
150	0	0	?	?	?	0
165	0	0	?	?	?	0
184	0	0	?	?	?	0

Figure 1: 7 rows of the Dataset continued

5. Linear Regression

Linear Regression is one of the most important and fundamental tools in data analysis and predictive models. It lets us see the relationship between the variables and the predicted value by drawing a best fit line. In this project, it is used to predict the likelihood of someone having a heart attack. Here it plots whether someone has a heart attack with one or more independent variables such as age, blood pressure, cholesterol level, heart rate, or smoking history. It would then analyze the data and find patterns. For example, it learned that older ages, and higher cholesterol would have a higher chance of experiencing a heart attack. This approach not only allowed the model to make accurate predictions, but also offered insights into which health indicators had the strongest influence.

To build this linear regression model, we first cleaned out the data set getting rid of any missing pieces of data swapping them with the average. Afterwards, we created histograms to get a general understanding of what each feature's data looked like. Figure 3 is an example histogram created for the feature age. The X value here is the age of the individuals while the Y value is how many individuals are within that age range. For example, we can see that there are over 60 people from ages 50-55.

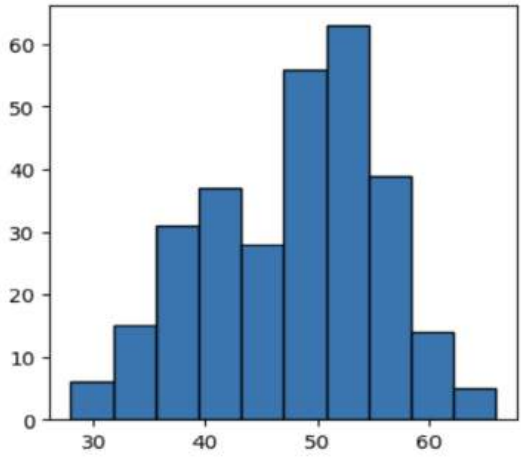


Figure 2: Histogram of Age

The next step was to begin to train the model by splitting the dataset into training and testing sets. This would split the data into two sets, a training set and a testing set. The model was split into a ratio of 80% training, and 20% testing. The training set is used to train the model as stated in the name. This is where the model learns the relationships between features (like age, sex, and cholesterol) and the target outcome of whether someone has a heart attack. Linear regression was used to create and train the model. The testing set is used to test the model with data that the model has not seen to check how well the model can predict on new unseen data. With this, we were able to find the accuracy of the model.

6. Results

This linear regression model achieved an accuracy of 83% which is strong considering the fact that 3 sections were removed due to having over 50% of missing data. This high accuracy demonstrated that the model was able to effectively learn patterns from the data and make accurate predictions from the testset. We expected around this amount of accuracy. However, we were really surprised how quickly this model took to learn this. This model was able to go through over 300 data points and find patterns in just a few seconds. This highlights one of the key strengths of linear regression: its simplicity and speed, especially when working with structured numerical data.

However, this model was not easily interpretable as we were not able to take out any insights on which of the features were the most important. In addition, all the model was able to do was generate an answer as it was unable to give an explanation on why and how this prediction was made. This makes it hard to further improve the accuracy of the model.

The performance of this model was further evaluated using a confusion matrix, which gave us a deeper understanding of its predictive abilities. Out of 59 total test cases, the model correctly identified 33 true negatives (patients who did not experience a heart attack) and 16 true positives (patients who did experience a heart attack). However, it also made 5 false positive errors that predicted a heart attack when there was none, and 5 false negative errors, failing to identify actual heart attacks. This led to an overall accuracy of approximately 83%, matching earlier performance metrics. While the model showed strong ability in distinguishing between the two classes, the presence of false negatives is significant because in a medical context, failing to predict a real heart attack could have serious consequences. However, most people are completely unaware that they may be at risk of experiencing a heart attack, making early prediction tools like this model extremely valuable. By providing individuals with insight into their personal risk factors, this model could help raise awareness and encourage preventative action before a life-threatening event occurs. These results highlight that although the model is reliable, further refinements would be needed to prioritize sensitivity and minimize the risk of missing actual cases of heart disease.

Similar studies using the UCI Heart Disease dataset report accuracies ranging from 77% to 85% depending on the algorithm used (Kavitha & Anuradha, 2016; Perumal et al., 2021), suggesting that our model's performance is consistent with prior research.

7. Conclusion

This project explored the use of linear regression to create a model to predict the likelihood of someone having a heart attack. Despite challenges including missing data scattered everywhere leading to dropping 3 columns, we were still able to create a model with 83% accuracy. This demonstrated that even with reduced data, a simple and efficient machine learning algorithm like linear regression can still be effective in detecting meaningful patterns and making reliable predictions. The speed of training was also impressive—the model processed and learned from over 300 patient data points in under five seconds, reinforcing the value of linear regression as a fast and accessible tool for preliminary analysis in health-related fields.

However, one of the biggest setbacks was the interpretability as it would be hard to understand the result. The key limitation was the lack of insight into why certain predictions were made or which features most heavily influenced the outcome.

The fact that heart attacks are the number one cause of death makes me understand just how important and meaningful this project is. This project is not just about creating a model, but using AI and data analysis to save the lives of millions affected by this issue every year.

Overall, this project has continued our fascination in using machine learning for healthcare and shown the potential it holds to contribute to early diagnosis and preventative care. With better data and more advanced modeling techniques, there is a great potential to create tools that not only predict outcomes but also help doctors and patients understand why they're at risk and what can be done about it. **While you've read this paper, at least 15 people have died from a heart attack somewhere in the world.** This sobering reality highlights just how critical it is to continue researching, developing, and improving tools that can help with early detection and prevention. While this project is just a small step, it's part of a much larger effort to turn data into action—and to save lives with every prediction we make more accurately.

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Design Thinking for Kids
How Kids Can Solve Everyday Problems Using Design Thinking By Tiana Yadav

Abstract

We kids are naturally curious and imaginative, that's how we are at our age. We notice things that adults sometimes miss, or don't think too much about. Design thinking is a simple and fun way to make solutions to everyday problems.

To come to a solution, we must first understand what the problem is, and that starts with caring about how others feel. We understand the problem, because maybe we dealt with it too, or still are dealing with it. Then we get to think of different ideas to solve the problem. Next, we test our possible solutions, and lastly, we improve it. We do the last two steps as many times as it takes until we have successfully solved the problem.

I learned this process while making Wipeband to solve the problem of runny noses and dirty sleeves for children. Wipeband is a wristband with refillable tissues that helps kids wipe their noses easily. As part of my journey inventing Wipeband, I realized that design thinking helps in solving problems in many areas, from school projects to community challenges. In this article, I'm going to share how design thinking works, and how you can use it, because it's not just for adults and scientists — it's for anyone who wants to make a difference.

Introduction – Why Kids Make Great Problem Solvers

As a kid, I've noticed a lot of things, things most adults tend to miss, things that wouldn't even cross their minds because of their busy schedule. Kids make the best problem solvers because they notice everything, every little detail, and are not afraid to question the known way of doing things.

There are no boundaries to their imagination, nothing they can't think of, because they have not been conditioned to a certain way of thinking. They don't look at things through a realistic lens because they don't have one. Design thinking is a way for kids to use their imagination to solve real-world problems in a structured way. I used design thinking to invent Wipeband, a small product to solve big problems, like children with runny nose and dirty sleeves. There are five steps to the design thinking process. It starts with empathy, understanding

what others need, and then moves through brainstorming, thinking of all the different solutions, testing, and improving. You can do the last two steps as many times as it takes to solve the problem. In this article I will be talking about the five steps of design thinking, how I used it in my invention, Wipeband. Design thinking is not just used by adults and scientists, but by anyone who wants to make a difference.

Step 1: Empathize – Seeing the World Through Others' Eyes

To empathize is to understand others' problems, their situation, and support them. I practiced empathy through Wipeband when I noticed how kids would unintentionally wipe their noses on their jacket sleeves or hands when they had runny noses. By touching other surfaces and people with the same dirty hands, I could see that they are spreading germs; causing more people to fall sick. I remembered that I used to do the same at that age, so I thought maybe I could do something about it, and I did. You can show empathy too, by understanding people, identifying what bothers them, what's not working, and how they would fix that. All great inventions, iPhones, pillows, everything, started with caring. They understood other people's problems and gave them a solution.

Step 2: Define – Turning Feelings into a Clear Problem

When I thought about why the kids are wiping their nose with hands or jacket sleeves instead of using tissues, I could see that it is because there are no tissues in easy reach, especially when they are on a playground or with friends. Wiping their noses on sleeves is what they did instinctively. That was how I defined the problem: tissues are not easily accessible or easily available for these kids. It needs to be available while on the go, maybe in the pocket, or stuck on a sleeve. It must be somewhere where it could be used on the go.

Step 3: Ideate – Letting Your Imagination Run Wild

Once I thought about that problem, it was fun to start imagining what could be a solution to solve the problem. No idea could be too silly or unrealistic. For example, my initial idea was that you take a tissue and just glue it onto the sleeve or stitch a handkerchief on the sleeve. Then I thought about having a watch strap that carries tissue in it instead of a watch. You can write your ideas down or draw them on a piece of paper. You can do whatever it takes for you to remember those ideas, because no idea is a bad idea. I had a rule when I was making it, and that rule was quantity first, quality later. I would write all ideas that I could think of in my idea journal. One of those ideas turned out to be wipeband.

Step 4: Prototype – Making It Real

The next step in design thinking is to build solutions and test them out. It is also known as building a prototype. A prototype is a first version that you make to see if it can work. Kids can make prototypes that start with a drawing of the solution and then progress towards building it using simple household items such as cardboard, tape, clay, old toys etc. Remember that it

doesn’t need to be perfect, because in this stage you are just testing ideas to improve them. My first prototype was a sketch I made that showed a child wearing a jacket with tissue attached on the sleeve. I thought there should be a hundred tissues stuck to a sleeve so you don’t need to keep replacing it. I then tried making prototypes by using an old jacket. I tried sticking tissues on its sleeves with glue stick, next I tried sewing a large handkerchief on the jacket sleeve. But I realized that it made the jacket look ugly and it didn’t work as well. Then I thought of having a watch strap which could carry a pack of tissues instead of a watch as a possible solution.

I kept trying various ideas and building different prototypes as part of this journey. I found a lot of joy in building and experimenting, as I got to try out my ideas and see what works and what doesn't. It was like playing and learning at the same time.

Step 5: Test and Improve – Failing Forward

An important part of design thinking is to test and improve. As I built different prototypes, I would test it out to see what works and what didn’t. It helps you understand what can be done to make your solution work better. Feedback from friends and family is always a good thing; as they can point out what does or doesn’t work. You can use their feedback to help you design your next prototype better. Remember, mistakes are part of the design journey, so don’t be afraid of them. My initial versions of Wipeband didn’t work either. They were messy, ugly and not practical. I started making changes to improve the solution. With each newer version I could see it getting slightly better and one step closer to a practical solution. Testing and continuous improvement helped me in reaching my goal

How Design Thinking Helps in Everyday Life

I applied design thinking for producing a new innovative product of Wipeband. However, Design thinking isn’t just for inventors, it can help with all sorts of things. For example, working together on a school project making sure everyone does the part they are best at, so the project has the best outcome, planning an event like a fundraiser, helping the community by volunteering.

Here’s a real-life example that design thinking helps with. Let’s say you have a messy desk, and your mom always asks you to clean it up. You can empathize and see how your messy desk makes the entire room look ugly. Then you start identifying the problem—what is causing the desk to be constantly messy? After that you can brainstorm, list all the ideas to keep it clean and organized. Maybe clean it after every time you use it, or better still try creating an organizer with different boxes or containers for all the items you use daily on your desk. An efficient organizer works well because now you have an assigned place to keep all your things. Design thinking instills creativity, clarity and confidence.

Why Kids Should Start Early

When kids learn design thinking early, they grow into people who don’t just complain; they create solutions. It builds persistence, teamwork, and confidence. I’ve learned that creativity isn’t about having perfect art skills. It’s about noticing, caring, and doing something about it.

Even adults use design thinking to invent new products — but kids can use it, too, at school, at home, and in the community. Now imagine what could happen if every kid learned how to think this way — we'd have cleaner classrooms, safer playgrounds, and maybe even more fun toys !

Conclusion – The Future Belongs to Creative Thinkers

Design thinking changed how I look at the world. Now when I see a problem, instead of feeling frustrated, I feel curious. I wonder how I could fix it, and that makes everyday life more exciting. Every invention starts with one simple question: "What if?". So, to every kid out there, don't wait until you're an adult to start solving problems. Observe, ask questions, imagine, build, test, and repeat. You might just invent something amazing that helps people and makes you proud.

Design thinking isn't about being perfect — it's about being sensitive enough to empathize with challenges in our world and brave enough to try. "You don't have to be an adult to change the world — you just have to start looking at the world with empathy. I believe the warmth of empathy, combined with the sparkle of curiosity and creativity, has the power to make this world a better place."

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Utilizing Number Theory for Clock Drift Detection and Correction in Digital Systems

By Sara Shamail[1], Heather Perlow[2]

KEYWORDS Number Theory, Clock, Drift, Algorithm, Time

SUMMARY / ABSTRACT

Clock drift is the gradual deviation of a clock from true time. It poses a fundamental challenge to maintaining synchronization in digital systems. I present a novel algorithm for detecting and correcting drift by leveraging core principles of number theory, including modular arithmetic, congruences, and the Chinese Remainder Theorem. This approach enables clocks to self-correct and maintain temporal accuracy without continuous external synchronization, even under degrading conditions. In non-irregular drift simulations, my method achieved a 4.99% improvement over the Network Time Protocol (NTP), the current state-of-the-art standard for clock synchronization.

INTRODUCTION

Clock drift is the phenomenon where a clock becomes imprecise and deviates from the expected time, leading to synchronization errors [10]. This phenomenon poses a significant issue in various systems that require precise and accurate numbers, such as communication networks, recording technology, GPS, and any computer-related processes. Although it is more common to notice a time drift between physical analog clocks, clock drift can also affect digital recording devices through external factors, such as environmental conditions, and internal inaccuracies in the timekeeping mechanism, called the oscillator. The oscillator regulates a clock's timing by moving at a regular frequency, which allows the clock to count seconds, minutes, and hours in a consistent pattern. [10]

Modern methods used to limit time drift include software-based synchronization, such as NTP and PTP, and hardware-based synchronization, including crystal oscillators (i.e., temperature-compensated and oven-controlled) and atomic clocks. The most common method for correcting time drift is NTP and period resynchronization, where systems are connected to a reference server to become synchronised with the correct time [15]. NTP, however, requires constant connectivity, and it is vulnerable to network disruptions and security risks. This problem is especially enhanced in more remote areas where constant connectivity is harder to achieve,

immense jitter persists, and internet access is highly limited [7]. Essentially, these factors result in the draining of a device's resources and energy, making it tedious or nearly impossible to use continuously. Besides NTP, another state-of-the-art approach to resist clock drift is using atomic clocks, which can be incorporated in a device's hardware for very accurate time keeping. However, the cost of atomic clocks makes them impractical for everyday use. They are mainly utilized in satellites, space exploration research, and in instances where the necessary cost to

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make and implement an atomic clock (tens of millions of dollars) can be met. Overall, there are utilized in satellites, space exploration research, and in instances where the necessary cost to make and implement an atomic clock (tens of millions of dollars) can be met. Overall, there are very few solutions are currently used that effectively reduce clock drift while also being manageable regarding both resources and accuracy.

Number theory is a branch of mathematics concerned with the properties and relationships of integers. It provides a powerful theoretical framework for solving problems involving periodicity and equivalence, which are concepts that naturally align with timekeeping systems. Within number theory, modular arithmetic and congruences describe how numbers behave under division by fixed moduli, enabling the representation of time as repeating cycles. These mathematical tools are widely used in computer science, cryptography, and digital signal processing, where reliability and precision are critical. For example, modular arithmetic underlies many synchronization and error-correction protocols in distributed systems, allowing for accurate computation despite delays or data inconsistencies. The Chinese Remainder Theorem (CRT), complementary to congruences and modular arithmetic, extends these concepts by providing a method to reconstruct a single, consistent solution from multiple modular systems. [15] In essence, the CRT determines a unique number that satisfies several congruences with coprime moduli, making it desirable for combining separate cyclical measurements into a unified whole system. This property allows CRT to be useful in addressing clock drift, which involves discrepancies between repeating cycles of time.

Building upon the number theory foundation, this research introduces a CRT-based algorithm designed to lessen the limitations of current synchronization methods. Unlike modern approaches that rely on continuous or periodic synchronization, the CRT-based method (which will be referred to as CRTM) requires only one initial synchronization with a reference clock. Afterward, it uses internal computations based on modular arithmetic and congruences to detect and correct drift autonomously. This algorithm can function as a stand-alone time correction model or as a complementary layer to enhance existing synchronization frameworks such as NTP.

The algorithm operates in three primary phases: synchronization, detection, and correction as illustrated in Figure 1. The first phase consists of the drifted clock undergoing an initial synchronization with another, accurate clock or the true time, so both devices have the same original time.

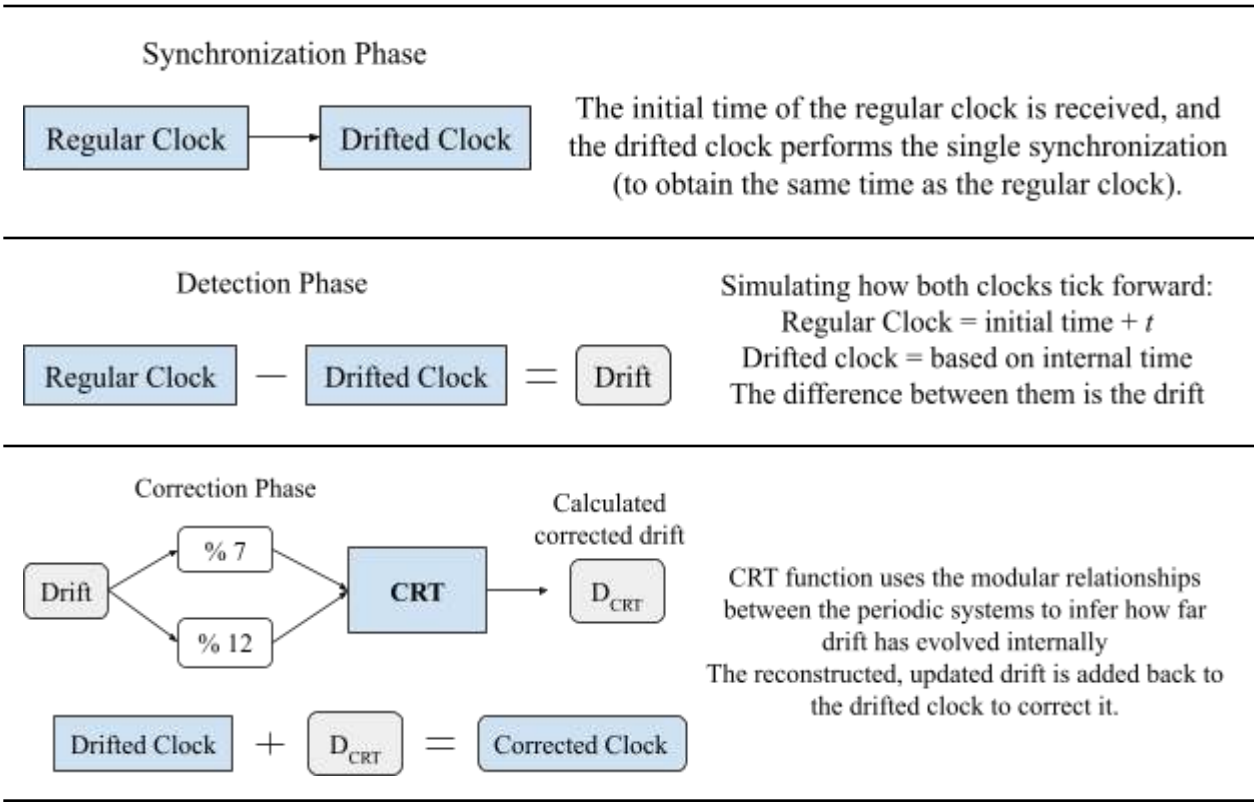


Figure 1: The three phases of the CRT-based algorithm.

During detection, the baseline drift between the drifted clock and the true time is calculated, and the behaviors of the inaccurate clock and the true time are observed over time. Without needing additional synchronizations, the algorithm keeps track of what the accurate time is as regular time *t* elapses, and the difference in drift is found as time also elapses.

The correction phase mathematically restores the accurate time using simulated 7-hour and 12-hour modular systems. By computing the remainders of the drifted clock's time under both moduli and applying the Chinese Remainder Theorem, the algorithm derives a single unified solution in the residue class representing the corrected drift. This value is added back to the incorrect clock to correct it. This approach eliminates the need for constant connectivity and external signals, conserving resources while maintaining accuracy over extended periods.

We tested my algorithm by simulating diverse drift conditions, comparing its performance against state-of-the-art synchronization methods, such as NTP, under various amounts of drift. The results demonstrated that my CRT-based algorithm maintained higher stability and accuracy in most scenarios, outperforming existing methods by an average of 4.99% under non-irregular conditions without relying on an external connection. The CRTM can be applied to modern systems, being used complementary with current methods including NTP. This paper presents the development, implementation, and evaluation of this algorithm, detailing

its mathematical foundation, experimental validation, and potential applications in improving the long-term precision of timekeeping systems.

RESULTS

My CRT-based algorithm (CRTM) was tested through two experiments: first, a perfect-world system to demonstrate if this number theory-based method could improve a clock's time drift; and second, a simulation of real-world systems. The simulation was necessary to determine the algorithm’s functionality in situations where drift occurs in various ways. These conditions included constant drift, sinusoidal drift, random noise, sudden glitches, wrap-around effects near the 12-hour boundary, and irregular sampling. The design shows CRTM’s adaptability and accuracy when compared to a baseline method similar to the Network Time Protocol (NTP) approach, which represents the current method utilized for drift correction today.

My first experiment aims to show the validity of my approach under ideal circumstances. For this first experiment, a simulated environment was created in Python where a regular clock and a drifted clock operated concurrently over 60 seconds. The regular clock increased linearly, while the drifted clock incremented at a slightly slower rate due to a set simulated drift rate of 0.05 seconds per second. These values were chosen to mimic a linear drift where minor discrepancies accumulate over time in digital clocks. The simulation tracked three sets of time values over the duration: the regular clock, the drifted clock, and the corrected clock. The recorded data was examined by comparing the three clocks' performance over time. To visualize the results, the time values were plotted on a graph, with seconds on the x-axis and clock times (mod 12) on the y-axis (see Figure 2). This modular representation allowed for a clear view of time disparities and the success of the correction procedure. The regular clock served as the "ground truth", while the drifted clock displayed the accumulation of time error, and the corrected clock revealed how the algorithm efficiently counteracted the drift, restoring the erroneous clock to normal through the red and green lines on the graph.

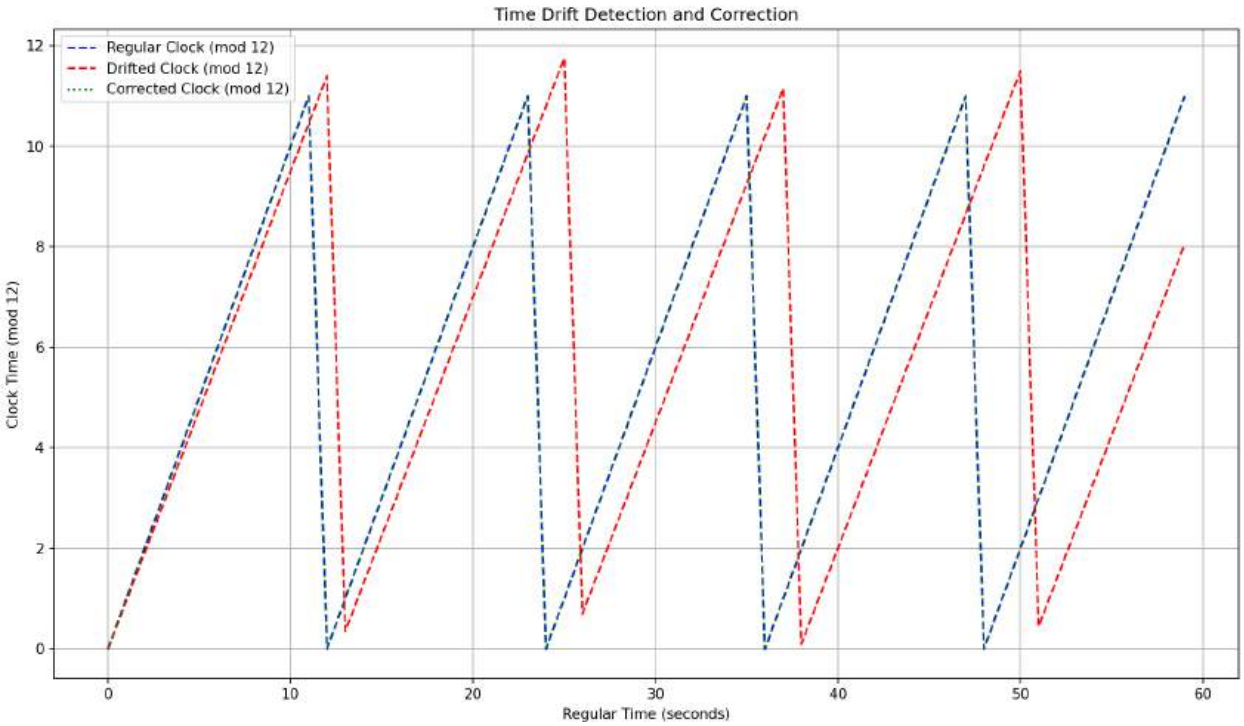


Figure 2: Experiment 1 Results

After these results were observed, the code was altered to include a comparison of how this method performs in relation to the commonly used NTP method. In the second experiment, 50 Monte Carlo trials were conducted, with a varied amount of included noise to convey real-world obstacles. In each trial, a regular clock (baseline "true time") was compared with a drifted clock whose behavior was defined by one of the drift models. The CRTM was then applied to correct the drift, and its results were compared against corrections made using an NTP-style approach. Accuracy was quantified using the mean absolute error (MAE) of the corrected clock relative to the true reference clock, measured in hours modulo 12. Boxplots were generated to visualize the distribution of MAEs across all trials, and the median error for each method and scenario was labeled on the plots (Figure 2). The algorithm was designed so that 50 new trials would run at every execution of the program; the specific values outputted would be slightly different, however, the overall trend remains the same. While the first experiment showed the validity of my algorithm, the second experiment aims to show how my CRT-based algorithm performs under less-than-ideal circumstances.

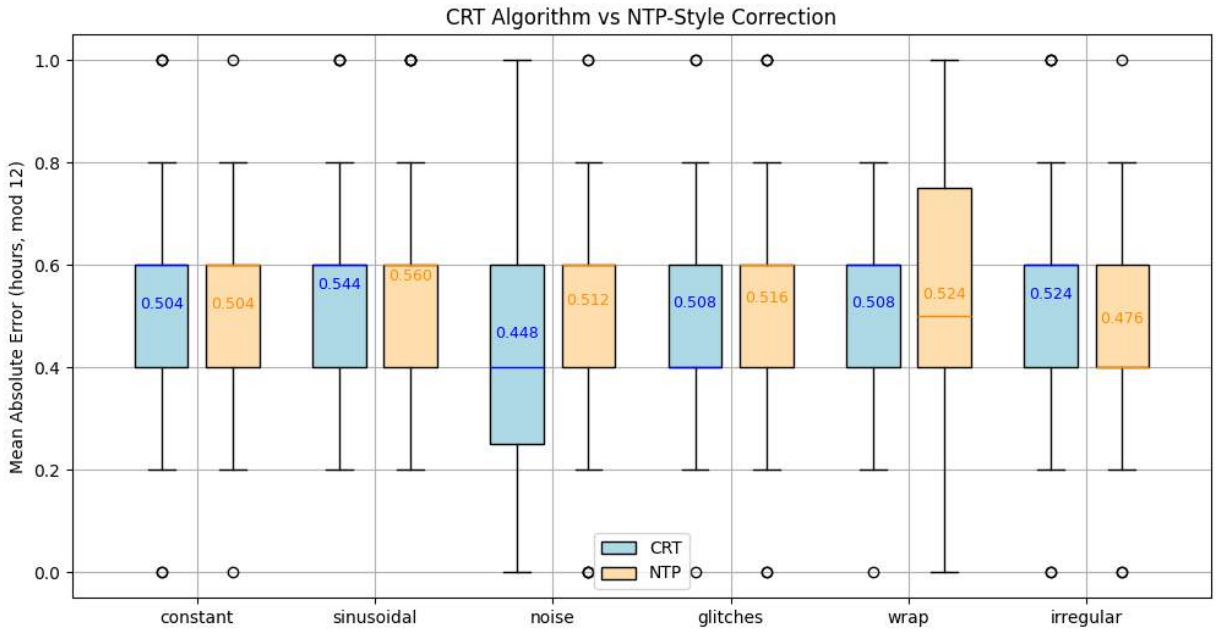


Figure 3: Experiment 2: Mean absolute error (hours, mod 12) for CRTM and NTP correction methods across six drift scenarios. Boxplots summarize 50 Monte Carlo trials per scenario. Median values are displayed on each boxplot.

DISCUSSION

The experimental results confirmed that the CRT-based algorithm is capable of consistently detecting and correcting drift across a wide range of conditions. In the first experiment, CRTM functioned as intended, reverting the drifted clock to the reference time as highlighted by Figure 2. However, the apparent 100% accuracy in that idealized test was largely due to the controlled setup and pre-defined input values, which are not representative of real-world environments where noise and uncertainty exist. To better simulate realistic conditions, noise was introduced so both CRTM and NTP could analyze, determine, and correct more variable data.

In the second experiment, the CRT-based method (CRTM) produced stable corrections across most drift conditions, as displayed in Figure 3. For example, under constant drift, CRTM achieved a median error of 0.504 hours, which is identical to NTP's 0.504 hours. In non-linear drift, such as random noise, CRTM's median error dropped to 0.448 hours, and NTP's went to 0.512 hours. Similarly, in the sinusoidal condition, CRTM's 0.544-hour median error can be compared with NTP's 0.560 hours. Also in the glitch scenario, NTP recorded a 0.516-hour median error, while CRTM maintained 0.508 hours. These results show that the modular arithmetic approach was especially robust in conditions where drift did not follow a predictable, linear pattern. A significant observation was CRTM's ability to maintain accuracy across extended intervals without compounding error. Even as the simulation length increased, CRT's error distributions remained narrow, indicating scalability for long-term use. Additionally, CRTM

produced fewer outliers in its results, while NTP occasionally generated higher-error corrections when drift patterns became irregular.

When drift was introduced at constant, sinusoidal, noisy, glitch-like, and wrapping rates, the algorithm adapted and maintained accuracy by recalculating congruences within the chosen modular systems. Compared to the NTP algorithm, the CRT-based algorithm performed better in cases of sinusoidal drift, glitches, wrap, and especially noise drift, as demonstrated by Figure 3. At constant drift, CRTM and NTP had the same performance, with an expected 0%. Under random noise, CRTM outperformed NTP by 12.5%, and under sinusoidal, glitch, and wrap conditions, CRTM was 2.86%, 1.55%, and 3.05% better, respectively. However, in the irregular drift condition, the CRTM algorithm performed 10.08% worse compared to NTP, understandably due to the algorithm's reliance on predicting the drift from an initial synchronization, without access to the rapidly and unpredictably changing time that NTP has. CRTM does not assume that drift evolves smoothly over time; it simply recomputes congruences based on the periodic cycles of the modular systems. This means that even when the drift increased steadily or jumped suddenly, the corrected time was recalculated exactly within the modulus, which ultimately prevented errors from compounding to a greater extent. In contrast, NTP relies on interpolation and constant resynchronization, which works well if the drift progresses predictably but struggles to correct quickly when noise or sudden shifts are present.

Under irregular drift, however, CRTM's reliance on modular congruences became a limitation. When drift values fluctuated unpredictably, the remainders used in the CRT occasionally misaligned with the modular cycles, producing less stable corrections. NTP's interpolation approach, which smooths the errors statistically, handled these irregular fluctuations more effectively by averaging out the randomness over time. Thus, CRTM performs well when drift patterns have structure, even if noisy or glitch-like, while interpolation-based methods perform better when the drift is highly irregular. These results indicate that the CRT-based method could serve as a complementary approach in systems where external synchronization is unreliable or unavailable, such as embedded devices, offline systems, or energy-constrained environments.

The study also revealed practical challenges that influenced the outcomes. First, the algorithm relies on coprime moduli for CRTM to function correctly. Initially, attempts to pair commonly used systems, such as 12-hour and 24-hour clocks, failed because the numbers are not coprime, which prevented finding a unique solution. By incorporating a 7-hour modulus alongside the standard 12-hour system, the algorithm achieved a workable solution space (mod 84) that remained computationally manageable. While this adjustment made the system mathematically functional, it also raises questions about how such moduli would be implemented in real-world hardware, where non-standard systems may be less practical. The CRT-based algorithm's correction accuracy is bounded by the chosen moduli, meaning that the size and manageability of the solution space (e.g., modulo 84) determine its resolution. In theory, increasing the number of moduli could improve precision, but would also increase computational complexity and the risk of inefficiency in real-time applications. Additionally, the simulated

nature of this drift presented limitations. Although drift rates were designed to model environmental effects like oscillator inaccuracies, temperature fluctuations, and system noise, the absence of a physical clock limited the ability to test hardware-specific influences. In future research, applying the algorithm to real hardware would allow for testing against non-simulated drift sources and provide a better evaluation of its efficiency.

Another important observation is the redundancy in improving accuracy. By combining two modular systems, CRTM effectively created a backup structure in which one system validated the other. This redundancy ensured that corrections were not simply the product of one system's possible error, but of a cross-validated solution that fit both modular conditions simultaneously. This differs from NTP, which continuously resynchronizes to an outside reference rather than leveraging redundancy within the system itself. The CRT-based approach, therefore, has the potential to enhance fault tolerance in long-term operation, especially in systems where frequent external checks are infeasible.

The significance of these findings lies in their implications for practical timekeeping. As modern systems, from IoT devices to distributed sensor networks, continue to grow in scale and decentralization, dependence on constant synchronization through NTP or GPS becomes more impractical. A purely mathematical correction method that can function independently and is resource-light offers a valuable alternative. This work demonstrates that modular arithmetic and CRT can serve as a foundation for such an approach and can serve as a very useful bridge between number theory and modern digital applications.

CONCLUSION

The objective of this project was to design and test an algorithm to detect and correct time drift in clocks using mathematical principles of Number Theory, specifically the Chinese Remainder Theorem (CRT) and modular arithmetic. By using these tools, the algorithm improved the accuracy of clock systems and provided a cost-effective, software-based solution to the problem of time drift.

The CRT-based approach successfully achieved the objective of detecting and correcting clock drift using modular arithmetic. By combining multiple moduli, such as a 12-hour and a 7-hour clock, the algorithm successfully aligned a drifted clock with a reference clock, as illustrated by the simulation results. CRTM proved especially valuable in isolating discrepancies and ensuring precise corrections through its ability to calculate congruences across modular systems. CRTM demonstrated consistent alignment with the reference clock and traditional methods of time synchronizing, especially in noisy, glitch-prone, or wrap-around conditions. While NTP remained competitive in more irregular environments, CRTM's resilience across the other diverse scenarios positions it as a strong candidate for applications where uncertainty and variability are expected, with an average better performance of 4.99% in non-irregular settings as compared to NTP under the same conditions.

Future work involves testing the algorithm on actual hardware to evaluate its performance in real-world conditions. Additionally, expanding the framework to incorporate

larger or more complex modular systems could make it applicable to a broader range of timekeeping challenges. Incorporating real-time data from clocks with physical drift could also validate the algorithm's reliability and address the challenges posed by environmental factors like temperature or system noise.

This study showed that a CRT-based algorithm can successfully detect and correct clock drift using modular arithmetic, with strengths in adaptability and redundancy that distinguish it from traditional synchronization methods like NTP. While limitations exist in real-world testing, the results demonstrate that aspects of number theory, such as the Chinese Remainder Theorem, provide a foundation for advancements in modern technology and applications, for instance, to correct time drift as a complementary or alternative to state-of-the-art methods

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The Hallucination Problem in LLMs: Why Scaling Parameters Isn’t Enough By He Sui

Abstract

Hallucinations in Large Language Models is becoming a growing concern in recent years. We can observe a prominent increase in LLMs usage across various domains, such as chatbots, business assistants, and medical diagnosis. Even though various studies have investigated hallucination in LLMs, there is still the need for further research in this area, as the current understanding of hallucinations in LLMs is limited. Therefore, this paper seeks to address the research questions: Why are Large Language Models (LLMs) susceptible to hallucination, and to what extent is hallucination in relationship with the model parameter? By doing so in an experiment with Gemma-3 models (1B-12B parameters) using SimpleQA benchmark. We also aim to investigate categorization, metric, and mitigation strategies within this domain.

1. Introduction

Large language models show a great deal of promise in a variety of natural language generation and interpretation tasks as well as real-world applications. Reaching onwards from the most popular application of LLMs in content generation and curation, programming code design, and virtual assistants. They open a wide range of application opportunities across numerous scientific fields, and high-stakes domains like law and healthcare.

However, the widespread adoption is undermined by an inherent characteristic of LLMs: hallucinations, when the model generates responses that contain unverifiable content. Their errors range from subtle contradiction to outright falsification, undercutting reliability in high-risk deployment. A clinical LLM could hallucinate out-of-date treatments, and a legal assistant could invent fake precedents. Solving hallucinations requires a systematic categorization of their taxonomy, causality, and mitigation practices.

2. Categories of Hallucination

The most widely accepted distinction in hallucination taxonomy is the division between intrinsic and extrinsic hallucinations.

According to Ahadian, intrinsic hallucination refers to internal inconsistencies within the generated text, wherein the model contradicts itself (Ahadian and Guan). In other words, generated texts that contradict the source query (Bang et al.). Alternatively, extrinsic hallucinations involve outputs that cannot be verified using the provided source context or external knowledge bases. This makes the outcome unverifiable and possibly deceptive because the generated text is neither directly contradicted by nor supported by the information that is now available (Huang et al.).

Recently, some researchers have proposed the building of a new taxonomy upon the foundations of intrinsic/extrinsic classification. Lei Huang's team introduces factuality hallucination and faithfulness hallucination. Huang defines factual contradiction as situations wherein the LLM's output contains facts that can be grounded in real-world information, but present contradictions. Factual fabrication refers to instances where the LLM's output contains facts that are unprovable against confirmed knowledge in the real world.

Similarly, another survey by Yue Zhang creates another categorization of hallucination outputs, separated into three sections: (i) input-conflicting where LLMs generate content that deviates from the source input provided by users; (ii)context-conflicting, where LLMs generate content that conflicts with previously generated information by itself; (iii)fact-conflicting, where LLMs generate content that is not faithful to established world knowledge (Zhang et al.).

However, some critics disagree with such categorization. Yejin Bang disapproves of these categories and highlights that both Zhang and Huang failed to capture inconsistencies with the training data of the model. Bang claims "that an answer that is consistent with the training data of the model but is factually wrong because e.g. the world has changed in the meantime, should not be considered a hallucination" (Bang et al.).

3. Root Causes of Hallucination

Recognizably, LLMs hallucinate for a variety of reasons, some of which are complex and not fully understood. This section focuses on the root causes of hallucination in large language models, divided into these key points: (i) data related causes (ii) model architecture & training (iii) inference & deployment factors (iiii) emerging perspectives.

3.1 Data Related Causes

The process of creating a new family of LLMs often starts with the pre-training phrase, and similarly across many different LLMS publicly available online sources stand out as a key fraction. Machine learning algorithms are crucially dependent on these data to find inter-dependencies and patterns to “learn” and acquire their general capabilities and factual knowledge.

However, the sheer quantity of data over the internet makes it an almost impossible task to evaluate data word by word. Furthermore, the precise way data is distributed and utilized within an LLM often remains opaque – a "black box" – and determining the optimal amount of data needed for various tasks is still an area of uncertainty (Hadi et al.). The reliance on massive amounts of data would be a double-edged sword for the LLMs, because they have an intrinsic tendency to memorize and copy down training data (Huang et al.).

Consequently, problematic sources within pre-training, such as imitative falsehood and societal biased data, may be amplified by the LLM’s algorithm into hallucinated outputs. Misinformation such as a faulty news report or rumor will inevitably introduce generation of false statements leading to imitative false hood (Hadi et al.). Highlighting this, Yue Zhang notes that LLMs sometimes misinterpret spurious correlations, such as positionally close or highly co-occurring associations, as factual knowledge (Zhang et al.). Since training data often reflects societal biases, stereotypes, and prejudices, models can generate biased or discriminatory outputs, even if it's not explicitly instructed to do so.

The critical impact of data related to hallucination is further highlighted by an investigation from Nick McKenna, who demonstrates that LLMs are prone to two biases originating from pretraining. LLMs tend to memorize the exact sentences from their training data and statistical patterns of usage learned at the level of corpora (McKenna et al.). Training data lacking pertinent information therefore leads to hallucinations, because the LLMs might resort to fabricated responses based on its memorized, yet inadequate, knowledge. This highlights what is known as a “knowledge boundary”, which encompasses limitations such as the need for Up-to-date knowledge and issues related to copyright knowledge.

3.2 Model Architecture & Training

The transformer architecture is the fundamental building block of all Language Models with Transformers the reason the transformer architecture successfully outperforms other architecture like Recurrent Neural networks is due to its unique “attention mechanism” concept, which critically lets the model focus on different parts of the input sequence when making each

output token (CryptoGPTo). Research from Michael Hahn discusses the limitations of self-attention in complex conditions, contributing to hallucinations. Specifically, the author shows that self-attention's inability to model hierarchical structures and periodic regular languages can lead to hallucinations (Hahn).

Fine training refers to the process of applying certain techniques to a pre-trained model whose weight has already been updated through prior pre-training. Fine training aims to align the model to desired behaviors, in spite of that models inevitably will encounter new information, possibly extending beyond the knowledge it acquired during pre-training. Zorik Gekhman studied the impact of integrating new factual knowledge through fine-tuning with the following findings: (1) Acquiring new knowledge via supervised fine-tuning is correlated with hallucinations. (2) LLMs struggle to integrate new knowledge through fine-tuning and mostly learn to use their pre-existing knowledge (Gekhman et al.).

3.3 Inference & Deployment Factors

Hallucinations could also arise from inference factors, chiefly the ability of a LLM to comprehend and encode input text into meaningful representations. Encoder is a seriously complex computational heavy structure that involves multiple layers of varying features. Being vital to LLMs, encoders allow the model to discern fine-grained differences in meaning, and clears the way to perform a range of tasks (Ghafforov).

With that in mind, a faulty encoder will wrongly understand relationships between section data, and could result in erroneous generation that diverges from the input. However, while encoder is still used in many LLMs, its traditional structure of encoder-decoder has been dispensed and replaced with decoder-only models like in GPT-3 and LLaMA. Similarly, the design of the decoding strategy itself can contribute to hallucinations, such as top-k sampling, and is positively correlated with increased hallucination (Dziri et al.).

4. Hallucination Evaluation & Detection

Although very similar hallucination detection is mainly directed at identifying if a hallucination exists at an instance level (one specific output). On the other hand, hallucination evaluation includes a system level scope and is more about the characteristics or system performance regarding hallucinations.

4.1 Statistical Metrics

Statistical metrics are focused on leveraging lexical features to calculate information overlap and contradictions between generated and reference texts. Dhingra’s research works on these metrics, proposing PARENT (Precision And Recall of Entailed n-grams from the Table). Generated text is matched with the source table and target text using PARENT n-gram lexical entailment. The accuracy of the table-to-text task is reflected in the F1-score, which combines the entailment's precision and recall. Dhingra further shows that previous metrics such as ROUGE and BLEU are too reliant on the target text (refers to desired or reference output text),

becoming problematic as the target text might not contain all the information from the source (Dhingra et al.).

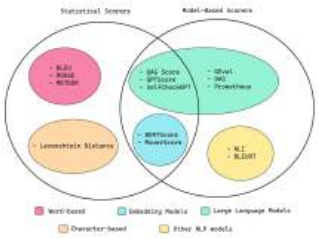


Fig 1: Types of Metric Scorers (LLM Evaluation Metrics)

First, let's define the terms based on the detection task:

True Positive (TP): The detector correctly identifies a hallucination as a hallucination.

True Negative (TN): The detector correctly identifies a non-hallucination (factual statement) as a non-hallucination.

False Positive (FP) / Type I Error: The detector incorrectly identifies a factual statement as a hallucination. (This is bad because you might discard correct information). *

False Negative (FN) / Type II Error: The detector incorrectly identifies a hallucination as a factual statement. (This is bad because you let an error slip through).

Metric	*Formula*	*Interpretation*	*Use Case*
Accuracy	$\frac{TP+TN}{TP+TN+FP+FN}$	Overall correctness of the detector	Balanced datasets; general performance
Precision	$\frac{TP}{TP+FP}$	Percentage of flagged hallucinations that are actual hallucinations	When false positives are costly (e.g., medical diagnostics)
Recall(sensitivity)	$\frac{TP}{TP+FN}$	Percentage of actual hallucinations correctly detected	When false negatives are risky (e.g., legal advice)
F1-Score	$2 \cdot \frac{Precision \cdot Recall}{Precision+Recall}$	Harmonic mean of precision and recall	Balancing FP/FN trade-offs (default for PARENT [13])
Specificity	$\frac{TN}{TN+FP}$	Percentage of factual statements correctly identified	Avoiding over flagging (e.g., customer service chatbots)

False Positive Rate	$\frac{FP}{FN+TP}$	Percentage of factual statements wrongly flagged as hallucinations	Evaluating detector safety
False Negative Rate	$\frac{FN}{FN+TP}$	Percentage of hallucinations missed by the detector	Assessing coverage gaps
AUC-ROC	Area under ROC curve	Model's ability to distinguish classes across thresholds	Model's ability to distinguish classes among thresholds
AUC-PR	Area under PR curve	Precision-recall balance, especially for imbalanced data	Precision-recall balance, especially for imbalanced data

Fig 2: Metrics used to evaluate the performance of hallucination detection systems

In addition to PARENT, BLEU, and ROUGE there are several more statistical methods including METEOR (Metric for Evaluation of Translation with Explicit Ordering) and Levenshtein Distance, which next I will quickly go through.

METEOR: An automatic metric for machine translation evaluation that is based on a generalized concept of unigram matching between the machine-produced translation and human-produced reference translations (Banerjee and Lavie).

Levenshtein Distance: A string metric for calculating the difference between two sequences. The smallest number of single-character modifications (insertions, deletions, or substitutions) needed to transform one word into another is known as the Levenshtein distance between two words (Levenshtein).

4.2 Model-based Metrics

Model-based metrics utilizes neural models, relying on NLP models, which are found to be more accurate in handling more complex and semantic variations. However, it is also prone to errors that may propagate and negatively impact the precise measurement of hallucination.

This method includes what can be called as "LLM as a judge", in other words using another LLM to evaluate LLM (system) outputs. These LLM judges utilize LLM's innate reasoning abilities to evaluate other LLM generations. Not only is this cost effective compared to human based approaches, it is also a scalable detection method.

```
evaluation_prompt = """You are an expert judge. Your task is to rate how relevant the
following response is based on the provided input. Rate on a scale from 1 to 5, where:

1 = Completely irrelevant
2 = Mostly irrelevant
3 = Somewhat relevant but with noticeable issues
4 = Mostly relevant with minor issues
5 = Fully correct and accurate

Input:
{input}

LLM Response:
{output}

Please return only the numeric score (1 to 5) and no explanation.

Score:"""
```

Fig 3: Simple Scoring for “Output Relevance"

4.2.1 BERTScore

BERTScore first introduced in a research paper titled "BERTScore: Evaluating Text Generation with BERT", it is based on a pre-trained BERT contextual embedding to evaluate the semantic similarity between pieces of text (Devlin et al.). Importantly, BERT is a transformer-based machine learning model for nature language processing (NLP) introduced in 2018. At its time, it showed powerful ability to understand the meaning of words in its context and could also be easily fine-tuned for different tasks, this enabled BERTScore to capture the nuances of word meanings in different contexts.

The following steps are needed to calculate BERTScore:

1. Token Representation: Mainly using the BERT model, the input text is tokenized into a sequence of word pieces to be then computed again with a Transformer encoder.

2. Similarity Measure: Making use of the vector representation, the cosine similarity of a reference token and candidate token is computed.

3.BERTScore: Every word in the reference sentence is used to find the most similar word in the candidate sentence, the average of the similarity score is the recall score. Oppositely, each word in the candidate sentence finds the most similar word in the reference sentence and is averaged to compute a precision score Finally, the precision and recall are calculated to assess and combined into a single F1 score which is the BERTScore.

$$R_{\text{BERT}} = \frac{1}{|x|} \sum_{x_i \in \boldsymbol{x}} \max_{\hat{x}_j \in \hat{\boldsymbol{x}}} \mathbf{x}_i^\top \hat{\mathbf{x}}_j \quad , \quad P_{\text{BERT}} = \frac{1}{|\hat{x}|} \sum_{\hat{x}_j \in \hat{\boldsymbol{x}}} \max_{x_i \in x} \mathbf{x}_i^\top \hat{\mathbf{x}}_j \quad , \quad F_{\text{BERT}} = 2 \frac{P_{\text{BERT}} \cdot R_{\text{BERT}}}{P_{\text{BERT}} + R_{\text{BERT}}} \quad .$$

Fig 4: Illustration of BERTScore calculation steps: token representation, similarity matching, and F1 score computation

This metric has been shown to correlate better with human judgment on tasks like summarization than BLEU or ROUGE, since it captures meaning, not just exact wording (Zhang et al.).

4.2.2 HalluCounter

This is a reference-free hallucination detection method (RFHD) that utilizes both response-response, query-response consistency and alignment patterns. HalluCounter can perform hallucination detection while obviating the need for an external knowledge base (KBs) or a correct reference text. This is particularly useful for closed-source LLMs where internal states like generation probabilities are inaccessible.

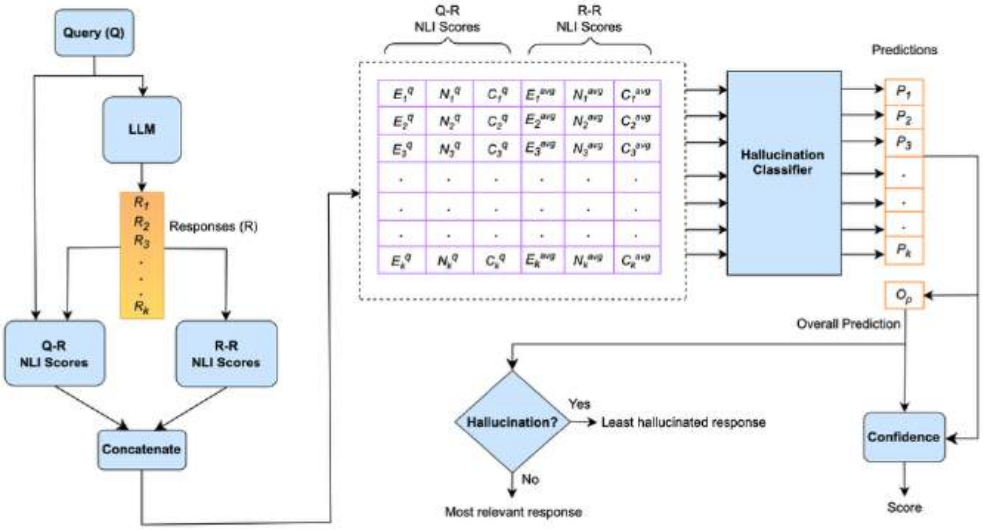


Fig 5: Hallucounter's Pipeline with Three Main Stages (Urlana et al.)

1. Extracting Natural Language Inference (NLI) Features:
    a) This stage generates multiple LLM responses to a query and then employs an NLI model to produce entailment, neutrality, and contradiction scores. These scores measure the relevance of each response to the original query and the consistency among the generated responses.
2. Hallucination Detection Classifier
    a) The NLI features are then fed into a classifier, a BERT-based model. This classifier's role is to predict whether each individual LLM-generated response is a hallucination or not.
3. Optimal Response Generation and Confidence Score Calculation (aggregation):
    a) Finally, this stage aggregates the individual response classifications into an overall prediction for the query using a majority vote. Based on this overall prediction, it selects an optimal response (prioritizing low contradiction if hallucinated, high entailment if not) and calculates a confidence score for its decision (Urlana et al.).

4.2.3 Luna

The researchers at Luna addressed hallucination with Luna, a lightweight RAG hallucination detection model that generalizes across multiple industry-specific domains and scales well for real-time deployment. Luna used a 440M parameter DeBERTa-large encoder and fine-tuned on real-world RAG data.

How Luna detects hallucinations: The core idea is NLI and Token-Level Support, Luna frames detection as an entailment problem, like a Nature Language Inference. Comparing and determining if the LLM response is supported by the RAG retrieved content. In addition, Luna at

a granular level can provide predication at a token level which specific token in the response is supported by the context (Belyi et al.).

4.2.4 G-EVAL

This framework uses LLMs, specifically GPT 4 and GPT 3.5 as the backbone of its evaluation. Proposing advantages such as higher correlation with human judgments and continuous scores that better reflect the difference in quality. G-EVAL, a prompt-based evaluator, is divided into three main components:

1. Prompt: Defines the evaluation task and the desired evaluation criteria, in other words the specific aspects to be evaluated.

2. Auto Chain-of-Thought: Chain-of-thought is the sequence of intermediate reasoning steps LLM takes to arrive at the final answer. Using this, instead of manually designing detailed step-by-step instructions for every evaluation criterion, G-EVAL uses the LLM itself to generate these steps.

3.Scoring: After calling upon the scoring function, the LLM is provided with the complete prompt, automatically generated Cot, input content, target text. Then, G-EVAL directly performs the detection task by a form-filling paradigm (Liu et al.).

4.3 Human Hallucination Evaluation

Given the limitations of current automatic hallucination detection methods, human evaluation remains an essential approach (Sun). This typically involves two main strategies: (1) scoring, where human annotators assess the degree of hallucination on a graded scale, and (2) comparison**,** where annotators evaluate outputs against baseline references or ground-truth texts.

Comparison evaluations are simple and easy, which involves human annotators assessing whether generated text contains hallucinations compared to a trusted source. The annotators will need to mark each single claim as either faithful (supported), hallucinated (unsupported), or partially faithful.

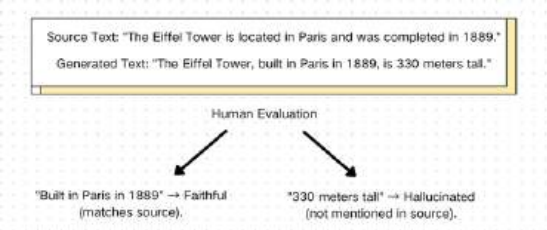


Fig 6: Comparison Evaluation

5. Hallucination Mitigation Approaches

Having established the root causes of hallucinations in Large Language Models, this section now turns to the corresponding mitigation strategies. The approaches discussed are organized to directly address the origins of the problem, focusing on two primary categories:

data-related and training-related hallucinations. For each, we detail specific techniques designed to enhance the factual accuracy and reliability of LLM outputs.

5.1 Mitigating Data Related Hallucinations

Data-related hallucinations can stem from low-quality, biased, or outdated pre-training data, leading LLMs to reproduce misinformation or fabricate responses. Mitigation strategies include rigorous data filtering/curation, dynamic model editing (e.g., ROME, MEMIT), and Retrieval-Augmented Generation (RAG) to supplement knowledge with verified external sources.

5.1.1 Data Filtering and Curation

An intuitive approach to reduce the presence of misinformation and bias is to use human labor to carefully select high quality sources one-by-one, validating the data during the process (Huang et al.). However, this approach becomes problematic when dealing with massive quantities of data, as manual curation is inevitably inefficient for such large-scale tasks. Therefore, to construct information rich pretraining corpora, early approaches usually rely on heuristic filtering using hand-crafted rules (Raffel et al.).

Nevertheless, these heuristic approaches cannot identify complex content noise and lead to suboptimal LLM performance (Wang et al.). Leading to the development of model-based data filtering, which gradually emerged as an optimal strategy for its ability to select high quality content, such approaches like AutoPureData demonstrate the effectiveness of model-based filtering (Vadlapati).

Wang's team outlined two main challenges with model-based approaches, stating that they: (1) resource heavy validation requires costly training, and (2) reliance on manually selected seed data that introduces human subjectivity (Wang et al.). To counter the high cost and inefficiency of data validation, Wang et al. introduce an 'Efficient Verification Strategy' namely "Ultra-Fine web." This method uses a nearly-trained LLM, and then incorporates candidate corpora into the final training steps to rapidly assess data quality and its impact on LLM performance with significantly reduced computational expenditure.

5.1.2 Model Editing

The objective of model editing is to efficiently alter the behavior of LLMs within a specific domain without negatively impacting performance across other inputs. There are two main paradigms for model editing, integrating an auxiliary network with the original model without changing it (Preserve LLMs' Parameters), or adjusting the model parameters that contribute to the undesirable output (Modify LLMs' Parameters) (Yao et al.).

a. Preserve LLMs' Parameters

1. Memory Based Models: This methodology utilizes local model editors to update the behavior of base (pre-trained) models, allowing for the injection of updated knowledge or the correction of undesirable behaviors. Examples include SERAC and ROME,

specifically SERAC avoids directly altering the base model's weight (Mitchell et al.; Meng et al.). Instead, it uses an external memory to store edits and two auxiliary components, scope classifier and counterfactual model.

2. Additional Parameters: The added parameters are trained on updated or corrected knowledge, allowing localized adjustments without disrupting the base model's general capabilities. Meanwhile, the original model parameters remain static, frozen in place. T-Patcher is an example of such an approach, adding *task-specific patches* (small neural networks) to intermediate layers of the transformer, effectively fixing factual errors (Huang et al.).

b. Modify LLMs' Parameters

1. Locate-then edit: This method mainly consists of two core stages. First, it identifies the specific layers or parameters responsible for storing knowledge. Afterwards, it modifies them to correct hallucination behavior. For example, ROME locates the edits-related layer by destroying and subsequently restoring the activations and then updates the parameters of the FFN in a direct manner to edit knowledge.
2. Meta-Learning: This approach uses an external hyper-network to learn the necessary parameter updates for modifying a mode's behavior. However, showcasing key limitations in efficiency, due to its requirement of additional training overhead plus memory resources. In addition, contains the risk of unintended knowledge degradation when modifying parameters (Hahn et al.).

5.1.3 Retrieval-Augmented Generation (RAG)

Retrieval-augmented generation is a technique for enhancing the accuracy and reliability of generative AI models with information fetched from specific and relevant data sources (Merritt). This capability significantly enhances transparency and lessens the probability of hallucination in AI-generated responses. This technique offers three key benefits: (i) Query Clarification (ii) Hallucination Reduction, minimizes the risk of models generating confident but factually wrong answers (iii) Implementation Efficiency.

There are three main stages of RAG orderly; they follow the steps of retrieval, augmentation, and generation. The retrieval phrase of RAG works by first converting the user input into a search query. This query is embedded into a vector and compared against a vector database (e.g. FAISS). Afterwards, the system will fetch the most relevant information based on semantic similarity. In the augmentation phase the content retrieved is added to the user's prompt as context. Finally, during the generation phase the LLM will generate a response conditioned on both the query and the retrieved context.

```
# 1. Retrieve
docs = vector_db.search(query_embedding, top_k=3)
# 2. Augment
augmented_prompt = f"Context: {docs}\nQuestion: {query}"
# 3. Generate
response = llm.generate(augmented_prompt)
```

Fig 7: Example implement of RAG

In terms of drawback, RAG approaches are crucially vulnerable to irrelevant, abnormal retrievals. Which will degrade output quality and increase the computational waste. Furthermore, the interaction between the retrieval and generation is often weak, leading to incomplete answers for multi-hop queries and redundant retrieval.

5.2 Mitigating Training-Related Hallucinations

Training-related hallucination in Large Language Models can stem from the transformer architecture and the deficiencies during the process of ore-training and fine-tuning. This following section provides a comprehensive overview of mitigation strategies organized to address these problems.

5.2.1 Addressing Pre-training Deficiencies

Mitigation approaches focus on architectural improvements and refinements to pretraining objectives. Recent advances in architectural focus on bidirectional context modeling**,** attention stabilization, and parallel inference frameworks to improve factual consistency. On the other hand, research on pe-training objectives can roughly be divided into factuality-enhanced training, In-Context Pretraining, and Corruption-reconstruction objectives.

Bidirectional context modeling: Unlike traditional unidirectional autoregressive models, bidirectional context models are an innovative solution towards hallucinations (Devlin et al.; Li et al.).

Attention Stabilization: The attention mechanism is fundamental to transformer-based LLMs like GPT, but meanwhile it also significantly contributes to hallucinations in some cases. Several strategies have been invented to promote higher attention, such as Zeqiu Wu team's inductive attention approach (Wu et al.).

Factuality-enhanced training: This method aims at training LLMs with factually rich plain-text corpora, primarily to enhance the factuality of the LLMs through exposure of data. The key component of factuality-enhanced training is TopicPrefix, which involves prepending a topic prefix to sentences in the factual corpus. Ideally, separating each sentence as a standalone fact; this will aid the "fragmentation" of information, an occurrence when wrong association of entities appear in independent documents with similar context. The introduction of TopicPrefix and sentence completion loss has been shown to significantly improve the factuality of LLMs, seen to reduce the named-entity factual error rate from 33.3% to 14.5% (Lee et al.).

5.2.2 Mitigating Misalignment During STF and RLHF

While supervised fine-tuning (SFT) and reinforcement learning from human feedback (RLHF) are powerful tools for reducing hallucinations in large language models (LLMs), improper implementation of these techniques can actually become a significant source of misalignment and subsequent hallucinations. This paradoxical situation arises because the fine-tuning process involves two critical phases that must be carefully managed: (1) the collection and annotation of high-quality instruction-following datasets, and (2) the actual fine-tuning of base LLMs using maximum likelihood estimation (MLE) (Wang et al.; Lin et al.).

Supervised Fine-tuning: One approach to reduce hallucination during the supervised fine-tuning stage is curating the training data. Experimental results by Stephanie Lin suggest that LLMs fine-tuned on such curated instruction data demonstrate higher levels of truthfulness and factuality compared to LLMs fine-tuned on uncurated data.

Reinforcement Learning from Human Feedback (RLHF) : When supervised fine-tuned reach their limits RLHF appears as an approach that can further strengthen LLMs. The process consists of two main steps, **Reward Model Training**: A specialized reward model (RM) is developed to approximate human preference judgments. This model learns to assign calibrated reward scores to LLM-generated responses based on quality assessments. **Policy Optimization**: The supervised fine-tuned (SFT) model undergoes iterative refinement using reinforcement learning algorithms. The reward model's output guides this optimization process, with proximal policy optimization (PPO) being the most commonly employed algorithm for stable policy updates (Zhang et al.). Although this method is useful in guiding LLMs in their knowledge understanding, the approach poses challenges in exhibiting over-conservatism in RL-tuned LLMs.

5.2.3 Mitigating Inference-Related Hallucinations

Inference-time mitigation strategies currently offer a complementary and flexible approach to de-hallucination. These methods address hallucinations during text generation, leveraging real-time adjustments without modifying the underlying model parameters. This section explores four key paradigms: (1) decoding strategies that steer generation toward factual consistency, (2) uncertainty estimation to identify and filter unreliable claims, and (3) auxiliary techniques like prompt engineering and human-in-the-loop verification. These inference-time miti/gation are effective in the sense that they have great adaptability to new domains or knowledge updates, but also face challenges such as balancing computational overhead with accuracy and handling black-box model constraints.

Decoding Strategies

Decoding strategies are crucial in determining how we choose output tokens from the probability distribution generated by models. Shehazaad Dhuliawala from Meta AI studied and developed Chain-of-Verification (CoVe) method, following the line of research of encouraging language models to first generate internal thoughts or reasoning chains before responding. Their approach is to first generate a list of questions when given the initial draft response, then

systematically answering those questions for an improvised response. Generating separate verification questions helps get more accurate facts, improving the overall response compared to just using the original long answer. To prevent the model from repeating its own mistakes, they further improved this by separating the verification steps and carefully managing what context the model sees, leading to even better performance. Each of these steps is performed accessing the same base LLM, capable of being prompted with general instruction in either a few-shot or zero-shot fashion. They showed that CoVe significantly decreased the generation of factually incorrect information; furthermore, improved precision in longform generation (e.g. 28% from the few-shot baseline), with CoVe effectively providing a guideline for a model's self-correction. However, it is limited on directedly stated factual inaccuracies and cannot address other forms of hallucinations. Its complexity of implementations, especially with the factored variants and factor + revise steps combined with multiple steps also makes it computational expensive (Dhuliawala et al.).



Figure 1: Chain-of-Verification (CoVe) method. Given a user query, a large language model generates a baseline response that may contain inaccuracies, e.g. factual hallucinations. We show a query here which failed for ChatGPT (see section 9 for more details). To improve this, CoVe first generates a plan of a set of verification questions to ask, and then executes that plan by answering them and hence checking for agreement. We find that individual verification questions are typically answered with higher accuracy than the original accuracy of the facts in the original longform generation. Finally, the revised response takes into account the verifications. The factored version of CoVe answers verification questions such that they cannot condition on the original response, avoiding repetition and improving performance.

Fig 8: CoVe Method

Uncertainty Estimate

This approach discusses that the inherent uncertainty in Large Language Models outputs themselves can be a useful indicator for mitigating hallucination also during the inference process. The core idea is that, once the LLM's confidence in its generated output is accurately estimated to be highly uncertain, we can predict these responses to be more likely hallucinated. The user or automated systems then can filter out this likely fabricated response and attempt to rectify them. Yue Zhang's paper mainly outlines three primary approaches to estimate the uncertainty in LLMs: logit-based estimation, verbalize-based estimation, and consistency-based estimation.

1. Logit-based Estimation:

a) This method relies on accessing the internal state of the LLMs, specifically the logits (raw scores). In addition, also accessing the probabilities assigned to each potential token during generation. Next, the uncertainty is calculated at a token level (e.g. lower probability for the chosen token indicated higher uncertainty). Neeraj Vershney exclaimed this logit-based method to detect "false concepts" in LLM outputs, once detected the hallucinations are mitigated using auxiliary retrieval-augmented LLMs (Varshney et al.).

2. Verbalize-based Estimation:
    a) The second approach relies on prompting the LLM to express its own uncertainty verbally. Therefore, the effectiveness of this method strongly depends on the LLM's instruction-following capabilities, and its own ability to introspect its confidence. An example prompt requesting the LLM to express their confidence may be "Please answer this question… and provide your confidence score (from 0 to 100)." In addition, research suggested the use of chain-of-thought prompts to potentially enhance the reliability of this method (Xiong et al.). Nevertheless, a significant issue is that LLMs often will exhibit overconfidence when asked to present their confidence level, this fundamentally problem crucially makes this method limited.
3. Consistency-based Estimation:
    a) Consistency-based estimation proceeds on the basis that if an LLM is hallucinating or in doubt when responding to a question, then it would behave the same for similar questions. Approaches include sampling several responses (e.g., with temperature > 0) then measuring their consistency, with greater inconsistency indicating greater chance of hallucination. Numerous works have applied the method for hallucination detection. For instance, SELFCHECKGPT was a pioneering model that employed consistency-based uncertainty estimation in a zero-resource, black-box setting, evaluating consistency of responses using many metrics. However, an accurate measurement for all the different responses' consistency remains a troubling issue for all (Manakul et al.).

Prompt engineering and other innovative strategies:

Prompt Engineering: Existing research has found that hallucination can vary based on the prompts given by the users. For instance, a user may receive different answers from a LLM with different prompts. Consequently, engineering more effective prompts could be a workable method to mitigate hallucination.

Example Prompt: If you don't know, or don't fully understand the answer to a question, do not share the false information

Human-in-the-loop

The intervention of a human user is seen to clarify intent and guide the LLM towards more accurate and relevant information. This strategy notes that hallucinations that may arise from a misalignment between (retrieved) knowledge and the user's actual question or intent. It addresses such issues by involving a human user in the process to refine queries or clarify the relationship between LLMs query and available knowledge. The MixAlign framework of such kind is reportedly to not only reduce hallucination but also to enhance the overall quality of outputs (Zhang et al.).

Multi-agent Interactions

This strategy's core idea is that instead of relying on a single model's output, multiple agents will independently generate responses and then collaborate—often through debate or discussion—to reach a consensus. Best case scenario, this will filter out individual hallucinations and improve overall factuality. Wanyu Du's benchmark for factual accuracy in LM-generated biographies, showed that multiple LLMs significantly reduced hallucinations compared to single-agent outputs (Du et al.). Similarly, Zhenhailong Wang introduced a cost-effective approach for mitigation. Their method employs a single LLM self-collaborating with multiple personas (e.g., domain-specific "experts"), iteratively refining outputs while minimizing computational burdens (Wang et al.).

6. Experiment

6.1 Experiment Design

This experiment aims to evaluate the relationship between LLM parameter count and hallucination rates. Proposing the hypothesis that a large model perimeter will exhibit a lower rate of hallucination in terms of factual knowledge, while keeping constant the model architecture and training protocols. Aiming with two major research questions: (i) To what extent is the hallucination rate affected by the model size (1B to 12B parameters) (ii) What patterns emerge in hallucination types (e.g., factual errors vs. fabrications) across scales.

6.2 Models Selected

For this experiment we selected three separate Gemma-3 models from Google, which are multimodal models with pretrained and instruction-tuned variants. Gemma-3 models can handle 128,000 token context windows and can reply in JSON formats. In addition, Gemma-3 is computationally highly efficient, effectively making this model suitable for local installation with personal computers (Gemma 3). Gemma-3 models are available in three different four sizes: 1B, 4B, 12B, and 27B (billion) parameters. Unfittingly, the 27B model was hard to implement locally and had to be abandoned for the overall efficiency of the experiment.

6.3 Benchmark Dataset

SimpleQA focuses on evaluating the ability of language models to answer short factual questions, which contains 4,326 short, fact-seeking questions. SimpleQA features a diverse

variety of questions created by AI trainers and validated again with other trainers. The questions in this dataset are designed with specific criteria: they require unique answers, are definitive regardless of the time period, and present a significant challenge. Visible in the figure, SimpleQA features a diverse range of topics, with Science & Technology leading the largest fractions (n=858). As for diversity in sources, wikipedia.com is by far the biggest source (one of the sources for 3.5k of 4.3k questions), followed by fandom.com (410 questions), ac.uk (154 questions), and imdb.com (121 questions) (Wei et al.).

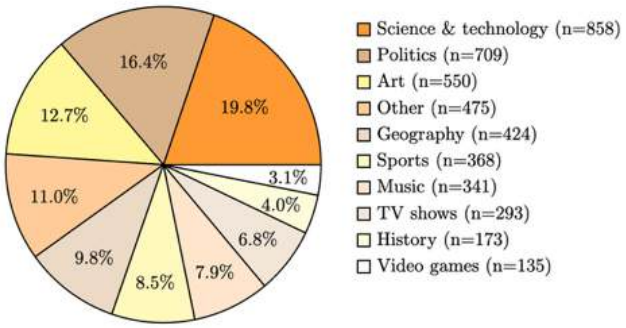


Fig 9: Topic Distribution of SimpleQA

6.4 Procedure

During this experiment, identical prompts were used as inputs for each model, with the questions extracted from the SimpleQA benchmark using Python coding and formatted accordingly. The API from the locally deployed models in LM Studio was utilized to generate outputs, with the answers saved to a JSON file. To evaluate the quality of these generated answers, the Python script evaluate_hallucinations.py was employed. This script assesses the model's tendency to hallucinate by comparing its answers against the known correct answers from the SimpleQA benchmark (https://github.com/Cheezecats/Hallucination-Evaulation). It calculates a hallucination rate based on whether the ground truth answer is present in the model's response, providing a quantitative measure of the model's reliability. The script saves the raw responses to a JSON file and prints the hallucination rate and number of correct answers. It is important to acknowledge that our hallucination detection method is rather basic, relying on a simple string match, and may not catch more nuanced or paraphrased correct answers. However, ideally this would not propose any significant differences to our evaluation because the SimpleQA benchmark is specifically designed in such a way that there is only one answer, without doubt. Therefore, it is likely that any paraphrased answer will not meet those requirements and would be considered hallucinations. In addition, for the spite of experimental accuracy all models were run on the same hardware to eliminate API variability, and we ran each trial at least three times to check for any major errors that might happen.

Component	Specification
Hardware	NVIDIA RTX 4080 (16GB VRAM), 64GB RAM
API	LM Studio (local inference, OpenAI-compatible endpoint at http://127.0.0.1:1234
Generation Config	Temperature=0.7, Top-p=0.9, Max tokens=30000
Evaluation Metric	Hallucination rate = (Incorrect Answers) / (Total Answers) × 100

6.5 Results

Table 9: Performance of Gemma Models

Model	Parameters	Hallucination Rate	Correct Answers	Incorrect Answers
Gemma-1b	1	97.11	125	4201
Gemma-4b	4	95.19	208	4118
Gemma-12b	12	93.85	266	4060

We found that by a slight margin, larger models(without RAG) showed lower hallucination rate. For example Gemma-12b had a hallucination rate of 93.85% compared to the 1b model's 97.11% hallucination rate. A manual inspection of 50 of the models' incorrect responses revealed that 62% of hallucinations involved plausible but incorrect facts (e.g., "Leipzig 1877 honored Paul Morphy" vs. correct "Adolf Anderssen"). The rest of 38% percent are completely fabricated and are not backed out by any events.

Noticeably, the absolute improvements were modest, suggesting model size alone doesn't resolve hallucination. The 12B model reduced hallucinations by only 3.26 percentage points compared to the 1B variant, despite a 12x parameter increase. Arguably, LLM don't benefit significantly on factual context simply by scaling along; instead these LLMs will need architectural improvements or training data curation for hallucination mitigation.

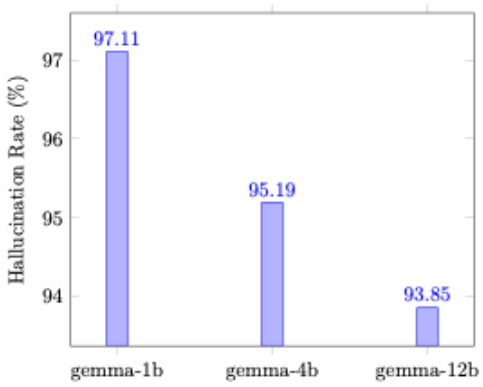


Fig 10: Hallucination Rates Recorded

6.6 Limitations

Admittedly, this current research has several limitations. There is limited resource to perform more evaluations, the current 4,326 QA from SimpleQA is not sufficient in vivifying the generalizability of such LLMs with other domains. Its limitation only to the field of English

language also does not represent constant performance perhaps for other languages. In addition, due to the consideration of simplicity the current binary classification does not capture the degree of error severity. Adding on, a fixed model setting such as the temperature (0.7) might also be problematic because it may not reflect the optimal deployment settings in real life situations. The relatively small amounts of experiment repeats could also propose a problem as LLM do not perform the same all the time and differences in responses are unavoidable.

7. Discussion + Future Work

7.1 Discussion

Our research provides valuable practical implications for real life deployment. First, we outlined that current Gemma variants require verification mechanisms (e.g. RAG) to improve performance on factual tasks. Secondly, the unworthy tradeoff between model size, computational requirements, and hallucination rate raises concerns against upsizing in resource-constrained scenarios.

Furthermore, the consistent high hallucination rate (>93% across all models) underscore the unreliability of unsupervised LLMs for critical applications like medical diagnostics or legal advice. Outlining that smaller, specialized fact checking models are a necessity to accurately validate the outputs of a larger less specific model.

7.2 Future Work

The limitations and insights uncovered in this study point to two major critical avenues for future research.

1. Hybrid Structures:
    a) Extending outwards, we can focus on increasing model parameters of hybrid LLMs, such as those with retrieval-augmented generation. By testing the differences between these models, we can observe the effect when responses are anchored with verified sources.
2. Evaluation Paradigm Shifts
    a) Instead of a binary classification of response, in our future research we can work towards introducing tiers of correctness (partially correct, mostly correct) to capture a wider range of nuances. In addition, work towards evaluating both reasoning and factual ability, gaining a bigger overview of a model's ability. One possible direction is to train the and command the models themselves to output a confidence score and degree of uncertainty.

Meanwhile, the ethical considerations of such research should also be seriously considered. RAG extracting sources from the internet should not come at the cost of introducing bias, even if it is a "trusted" source. It is also equally important to focus on the disturbing contradiction between performance vs. transparency. Larger models better represent a black box;

on the other hand, they also produce more nuanced responses, these two aspects will require a certain level of balance.

8. Conclusion

In recent years, LLMs have gained significance across every domain for their astonishing understanding and generations capabilities, creating revolution in healthcare, law, and education. However, hallucinations, responses where the model either misunderstood the user's prompt or fabricated against grounded real-world facts; this is a critical challenge we currently face in fully impeding LLMs in practical applications. Therefore, this article addresses such a problem offering a comprehensive review and an experiment diving into real world scenarios. The survey examines key aspects of LLMs, offering a well structured perspective on the current state of LLM research and the underlying problems awaiting to be solved.

We first examined the categorization of hallucinations; while also acknowledging differences in current understanding, we paid close attention to the separation of intrinsic vs. extrinsic hallucination. Afterwards, our article provides a general overview of the different approaches and metrics of hallucination evaluation. Specifically, divided into three sections, statistical based, model based, and human based evaluations. Thirdly, our review of mitigation strategies provides a precise rundown of the current state of LLMs. Also bringing forth many examples of limitations and challenges faced by current methods, highlighting the continuous need for methodology improvements.

In the end we conducted an experiment demonstrating the current limitations of LLMs, exploring the correlation between model parameter size and hallucination. Though basic and limited in certain details, our investigation still provides insights into mitigating hallucinations. The results suggest that hybrid architectures, especially when combined with retrieval-augmented generation, hold promise for improving factual accuracy in question-answering scenarios.

In the end, it is important to remember that amidst the complex landscape of large language models and hallucinations artificial intelligence should always serve for the good of human kind. To see the current challenges of hallucination as also an ethical imperative, as well as a technical one.

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Tuberculosis: Beyond Mutational Resistance By Zachary Lai By Zachary Lai

Abstract

Tuberculosis (TB), caused by Mycobacterium tuberculosis (Mtb), remains one of the world's leading infectious diseases, with millions of new cases and deaths each year. Antibiotic resistance poses a significant challenge to treatment, often resulting from mutations in genes such as katG, inhA, and rpoB. However, recent evidence suggests that resistance is not only a bacterial mutational problem but also shaped by host and environmental factors. This literature review examined studies published in the last 25 years that connect the rise of TB antibiotic resistance with the following associated disease factors: the gut microbiome, comorbidities, diet, and environmental conditions. Findings suggest that gut dysbiosis can compromise immune defenses through the gut-lung axis, with short-chain fatty acids (SCFAs) playing a pivotal role in regulating lung immunity. Chronic conditions like diabetes and human immunodeficiency virus (HIV) weaken the microbiome and immunity, making TB treatment less effective, while environmental factors such as overcrowding, poor sanitation, and misuse of antibiotics increase the spread of resistant strains. Effective control strategies should extend beyond antibiotics, incorporating nutritional support, microbiome health, and public health interventions to enhance treatment outcomes and mitigate the spread of antibiotic-resistant TB.

Introduction

TB is still a serious global health problem, with high morbidity and mortality compared to other infectious bacteria, despite the availability of antibiotic treatments for TB. This is because Mtb, the bacterium that causes TB, has a high prevalence of antibiotic resistance. As such, TB is more challenging to cure, requires longer and more toxic treatment regimens, and leads to over a million deaths each year, making TB, especially drug-resistant forms, one of the top infectious killers worldwide. Regimens for resistant strains are considered toxic because second-line TB drugs can cause severe side effects, including liver damage, kidney failure, hearing loss, and gastrointestinal intolerance, which not only reduce adherence but in some cases contribute directly to patient deaths (Companion Handbook to the WHO Guidelines for the Programmatic Management of Drug-Resistant Tuberculosis; Dobler). In 2023, there were approximately 10.8 million new TB cases worldwide. This makes TB the second most common infectious disease (Mudoola; Yang et al.), with the rise in cases influenced by a combination of factors, including antibiotic resistance, gaps in treatment access, and host and environmental conditions that complicate disease control. TB is one of the most deadly infectious diseases in the world, killing 1.25 million people yearly.

In the past, TB was treated with a single antibiotic, streptomycin. However, over time, doctors learned that using multiple antibiotics, such as the 4-drug regimen of isoniazid (INH), rifampicin (RIF), pyrazinamide (PZA), and ethambutol (EMB) simultaneously, works better and slows the development of resistance. (Companion Handbook to the WHO Guidelines for the Programmatic Management of Drug-Resistant Tuberculosis; Mitchison). Resistance can be

primary, where a person is infected with a resistant strain, or acquired, where the bacteria have become resistant due to inadequate treatment (Allué-Guardia et al.).

Most antibiotic resistance in Mtb comes from genetic mutations. For example, mutations in the katG gene can cause INH resistance, and mutations in the rpoB gene can cause RIF resistance (Rostamian et al.; Seifert et al.). However, these genetic mutations do not explain why some Mtb strains develop resistance while others exposed to similar treatment do not. This is why understanding the mechanisms of resistance is essential: without knowing how Mtb evades treatment, physicians cannot design effective therapies or improve current drugs.

Recent studies suggest that the gut microbiome, the community of bacteria living in the digestive system, may play a role in the immune response to Mtb infection (Alvarado-Peña et al.). The gut microbiome can influence how the immune system responds to TB infection and how effective antibiotics are, meaning the gut microbiome may contribute to whether resistance develops or treatment succeeds (Wipperman et al.). The gut-lung axis refers to the concept that the gut and lungs can influence each other through the immune system and chemical signals. For example, if the gut microbiome is imbalanced (e.g., changes in the diversity of the gut microbial community, proteins, or pH), a condition known as dysbiosis, the lungs' immune defenses can be weakened (Dang and Marsland). An example of dysbiosis is a change in the levels of short-chain fatty acids (SCFAs). As some gut bacteria produce SCFAs that help regulate immune cells in the lungs (Dang and Marsland; Koh et al.), these SCFAs support the proper function of a host of immune cells, including macrophages, T-cells, and B-cells. Thus, these SCFAs help immune cells become activated when needed to fight infection while also preventing excessive inflammation that can damage lung tissue. If SCFA levels are disproportionate, the downstream effect may lead to immune dysregulation. In other words, if there is a change, such as a decrease in gut bacteria producing SCFAs, the immune response may be negatively affected, leading to a worse outcome in patients infected with TB. Thus, a healthy gut biome contributes positively to the immune response to infections.

Other factors, including diet, chronic diseases like diabetes and HIV, medications that affect the immune system, and environmental conditions like poor sanitation or excessive antibiotic use, can also alter the gut microbiome. This review highlights that resistance to TB is associated with multiple factors, in addition to bacterial mutations. As such, this review contrasts with prior discussions that highlight one factor at a time, like mutations or the gut microbiome, and instead holistically examines multiple factors (e.g., chronic diseases, diet, medications, and environment) that contribute to TB resistance. Such an integrated understanding could lead to more effective treatments and improved outcomes for patients with TB.

Mtb mutations conferring antibiotic resistance

A well-studied mechanism of resistance in TB lies in genetic mutations. These mutations reduce the effectiveness of antibiotics, allowing Mtb to survive even under drug treatment (Table 1). One of the most common mutations leading to INH resistance involves an S315T mutation in the KatG protein. The katG gene encodes an enzyme (catalase-peroxidase) that activates the drug

INH by converting it into its active form inside the bacterium. When the S315T mutation is present, the enzyme no longer functions properly, so INH cannot be converted into its active form, and the drug loses its ability to kill the bacteria (Seifert et al.; Vilchèze and Jacobs). Another common mutation occurs in the promoter of the inhA gene, causing the bacteria to produce excessive amounts of the InhA enzyme (enoyl-acyl carrier protein reductase). The excessive amount of InhA enzyme outcompetes INH for its intended binder, rendering INH ineffective (Seifert et al.).

Regarding RIF resistance, the most common mutations involve the rpoB gene in a section known as the rifampicin-resistance-determining region (Rostamian et al.; Zaw et al.). This gene encodes the β-subunit of RNA polymerase, the enzyme to which rifampicin normally binds to block bacterial transcription. Mutations in this region alter the binding site, preventing RIF from attaching properly. As a result, the bacteria's RNA polymerase continues to function, allowing the bacteria to survive and multiply despite the presence of the drug.

Other antibiotics, such as fluoroquinolones and aminoglycosides, are resistant when mutations occur in the gyrA/gyrB and rrs/eis genes (Zaw et al.). The gyrA and gyrB genes encode subunits of DNA gyrase, an enzyme essential for bacterial DNA replication; mutations in these genes prevent fluoroquinolones from binding effectively to DNA gyrase. The rrs and eis genes are involved in protein synthesis and enzymatic drug modification, and mutations in these regions reduce the ability of aminoglycosides to bind to bacterial ribosomes, leading to resistance (Zaw et al.).

In addition to direct mutations in Mtb genes that confer resistance and enable survival, Mtb can also survive treatment by entering a low-activity state called dormancy, where antibiotics are less effective (Gengenbacher and Kaufmann). In this dormant state, the bacteria slow down or stop many of their normal processes, such as cell division and metabolism. Since most TB antibiotics are designed to target actively growing and dividing bacteria, they would have little effect on dormant cells, allowing populations of Mtb to "hide" and evade antibiotic killing. Thus, Mtb in this state can reside within the host for long periods, which can lead to treatment failure, relapse, or the emergence of resistant strains. Dormancy can last for months to years, far beyond the standard antibiotic treatment period (Gengenbacher and Kaufmann). Together, these examples highlight that genetic mutations and dormancy are central drivers of resistance, but they are only part of the overall picture. To fully understand resistance, one must also consider host and environment-related factors, such as diet, which influence the microbiome and immunity.

Table 1. Major Mycobacterium tuberculosis gene mutations, the proteins they affect, and the corresponding molecular mechanisms that generate antibiotic resistance and produce resistant strains.

Gene/Mutation	**Protein Encoded**	**Mechanism of Resistance**	**Resulting Effect**
katG (S315T)	Catalase-peroxidase (activates INH) (Seifert et al.; Vilchèze and Jacobs)	Enzyme cannot activate isoniazid (INH) into its active form (Seifert et al.)	Isoniazid resistance (Seifert et al.)

inhA (promoter mutation)	Enoyl-acyl carrier protein reductase (InhA) (Seifert et al.)	Overproduction of InhA enzyme prevents INH from binding (Seifert et al.)	Isoniazid resistance (Seifert et al.)
rpoB (mutations in rifampicin-resistance-determining region)	β-subunit of RNA polymerase (Rostamian et al.; Zaw et al.)	Structural change prevents rifampicin from binding RNA polymerase (Rostamian et al.; Zaw et al.)	Rifampicin resistance (Rostamian et al.)
gyrA/gyrB (mutations)	DNA gyrase (subunits A and B) (Zaw et al.)	Fluoroquinolones cannot bind effectively to DNA gyrase (Zaw et al.)	Fluoroquinolone resistance (Zaw et al.)
rrs/eis (mutations)	16S rRNA (rrs) / Aminoglycoside acetyltransferase (Eis) (Zaw et al.)	Reduced binding of aminoglycosides to ribosome / enzymatic drug modification (Zaw et al.)	Aminoglycoside resistance (Zaw et al.)

Dietary factors in Mtb antibiotic resistance

Host-related factors, such as underlying health conditions or diet, can contribute to the development of antibiotic resistance (Kumar Nathella and Babu). For example, consuming a high-fat diet can reduce the diversity of gut bacteria and increase the abundance of species associated with inflammation, such as certain strains of Escherichia coli, Enterococcus faecalis, and Bacteroides. These bacteria can produce endotoxins, such as lipopolysaccharides (LPS), which trigger chronic, low-grade inflammation in the gut and throughout the body (Makki et al.). This shift in gut composition makes the immune system less effective at controlling infections, which may give TB more time to adapt and survive under antibiotic pressure. Moreover, eating very little fiber reduces both the levels and metabolic activity of SCFA-producing gut bacteria, which lowers the amount of SCFAs available to support immune function (Makki et al.). This is a widespread issue, as fewer than 10% of Americans consume the recommended daily amount of dietary fiber, highlighting the prevalence of fiber deficiency in the general population (Makki et al.). These SCFAs not only help control inflammation but also influence the activity of immune cells in the lungs. Without sufficient SCFAs, the immune system may not respond strongly enough to infection, meaning that immune cells, such as macrophages and T-cells, may fail to fully activate and kill TB bacteria (Dang and Marsland), resulting in only partial control of the infection. One study that evaluated the microbiome of TB patients showed that those with reduced levels of SCFA-producing gut bacteria had diminished immune response to infection, which made post-TB antibiotic treatment less effective (Wipperman et al.), leading to an increase in persistent and resistant TB (Makki et al.). Diet is therefore not only a source of calories and basic nutrients; it also alters the gut microbiome and immune system in ways that directly shape how the body responds to antibiotics and infection. Studies show that these shifts in immune function can occur within days of dietary change, as fiber intake quickly modifies gut microbial composition and SCFA production (Makki et al.).

Impact of health and medicine on Mtb antibiotic resistance

An increase in TB resistance has been observed in individuals with comorbidities that compromise immune function. This review highlights HIV and diabetes, two of the most common TB-associated comorbidities worldwide, that impair the immune system (Morgan et al.; Kumar Nathella and Babu). Diabetes alters immune cell function, which can cause dysbiosis, leading to slower TB recovery (Kumar Nathella and Babu). Such dysbiosis, an unhealthy gut microbiome, often indicates a reduced diversity of beneficial bacteria, fewer SCFA-producing microbes, and an overgrowth of pro-inflammatory species, such as Escherichia coli or Enterococcus, which collectively weaken immune regulation and increase inflammation. High blood sugar levels can alter the balance of gut bacteria by favoring sugar-metabolizing species that promote inflammation, while reducing beneficial SCFA-producing microbes. The pro-inflammatory state not only worsens gut health but also compromises immune regulation, making it more difficult for the body to control TB infection. Studies show that high blood sugar levels in diabetic patients impair the ability of macrophages to fight diseases in general, and this effect is particularly significant in the case of TB, since macrophages are the primary cells responsible for controlling the bacteria (Kumar Nathella and Babu). At the same time, diabetes often comes with chronic low-grade inflammation and gut imbalance, which may reduce how well TB treatments work. Studies show that diabetic TB patients often have slower recovery and higher treatment failure rates than non-diabetic patients. This is because diabetes weakens macrophage and T-cell function and disrupts the gut microbiome, making it harder for the immune system to support antibiotic therapy (Kumar Nathella and Babu).

Moreover, a concomitant HIV infection weakens the immune system and damages the gut lining, making patients more likely to get drug-resistant TB. Because HIV lowers CD4 T-cell counts, people living with HIV struggle to mount strong immune responses. Their gut microbiota also becomes disrupted, leading to increased inflammation and a reduced ability to control TB This disruption occurs because HIV damages the gut lining and immune barriers, allowing harmful bacteria to thrive, while also reducing the stability of beneficial microbes.

Both diabetes and HIV are strongly associated with higher TB incidence and worse treatment outcomes, further exemplifying that compromising immunity makes it easier for resistant strains of TB to emerge and spread (Kumar Nathella and Babu; Morgan et al.). Thus, the existence of comorbidities in patients who develop TB adds to the difficulty of treatment, especially when antibiotic resistance is common.

For patients with other coexisting medical conditions, concomitant medications can also impact the gut and immune system; therefore, understanding these medications and their effects on the body's response to TB infection and therapy is crucial. Common examples include proton-pump inhibitors, widely prescribed for acid-related conditions, and immunosuppressive drugs, such as corticosteroids or biologics, used in the management of autoimmune diseases (Dobler; Freedberg et al.); these medications can have adverse effects on the gut and immune system. For example, although they reduce stomach acid for individuals with gastroesophageal reflux or peptic ulcers, proton-pump inhibitors (PPIs) may also allow harmful bacteria to survive

more easily in the gut. With the natural acidity of the stomach reduced, the gastric environment no longer acts as a strong barrier against pathogens. This means PPIs may indirectly encourage the growth of bacteria such as Streptococcus, Enterococcus, and Escherichia coli, which disrupt gut balance and immune regulation (Freedberg et al.).

Additionally, drugs that suppress the immune system, such as corticosteroids or biologics used to treat autoimmune conditions, reduce the body's ability to contain TB infections. In individuals already exposed to TB, immunosuppressants can cause latent TB to reactivate. When combined with antibiotics, these immunosuppressants may create conditions that favor the survival of resistant strains (Dobler). Medicines designed for other illnesses, therefore, can lead to consequences that affect how TB is controlled. This highlights that, similar to diet and comorbidities, medications not directly aimed at TB can still shape outcomes and must be considered in the complete picture of TB management.

Environmental drivers of Mtb antibiotic resistance

Environmental conditions play a major role in the spread of antibiotic-resistant TB. Poor sanitation exposes people to bacteria carrying resistance genes, while contaminated water, food, and surfaces enable these microbes to spread (Houben and Dodd; Van Boeckel et al.). Overcrowded housing further accelerates TB transmission, especially when resistant strains circulate. These issues are most severe in densely populated urban areas and institutions such as prisons and refugee camps. Supporting this, a Brazilian study found that household crowding strongly links socioeconomic inequality to higher TB incidence, highlighting crowding as a key driver of TB spread (Pelissari and Diaz-Quijano).

In prison settings, the risk is even greater, with TB incidence in prisons up to 23 times higher than in the general population, according to a systematic review (Baussano et al.). One study reported that in Brazil, the TB incidence among prisoners rose dramatically during incarceration, increasing from about 111 to over 1,300 cases for every 100,000 people each year, reflecting how prison conditions strongly amplify transmission (Mabud et al.). When antibiotics are overused or taken without proper medical guidance, bacteria in the gut can accumulate resistance genes that may indirectly influence TB treatment outcomes (Van Boeckel et al.). This overuse of antibiotics is often driven by easy over-the-counter access, lack of regulation, and self-medication practices, particularly in low and middle-income countries. In a global study, researchers estimated that general antibiotic consumption increased by 36% between 2000 and 2010, with the most significant rises observed in countries such as India, China, and South Africa (Van Boeckel et al.). These regions also report widespread non-prescription sales of antibiotics, especially among poorer populations who rely on pharmacies or informal vendors rather than formal healthcare systems. As a result, TB resistance is more common in these settings, since inappropriate or incomplete antibiotic use increases the survival of resistant strains.

Studies from high-burden countries such as these show higher rates of multidrug-resistant TB, reflecting how easy access to unregulated antibiotics directly contributes to the problem. By documenting these patterns, the study highlights that antibiotic misuse is not evenly distributed

worldwide but is concentrated in resource-limited settings where healthcare access and regulation are weaker. This is important to highlight because these structural conditions directly influence how quickly resistant TB strains emerge and spread, showing that resistance is not only a biological issue but also a consequence of social and environmental systems. This makes resistance not only a medical issue but also a social and public health problem shaped by the conditions in which people live.

How the gut-lung axis causes antibiotic resistance

Changes in the gut microbiome ultimately affect the gut-lung axis, a pathway that links digestive health to lung immunity, influencing how effectively the body controls TB infection. As discussed, SCFAs made by gut bacteria affect how immune cells in the lungs work, especially alveolar macrophages, which help fight TB (Dang and Marsland; Koh et al.). Patients infected with TB who have fewer SCFA-producing gut bacteria often have weaker immune control over the infection (Wipperman et al.), suggesting that those patients with disrupted gut microbiota may not respond as well to antibiotics, since their immune systems cannot work together with TB treatment drugs to eliminate the bacteria in the lungs, the primary site of TB infection.

The gut also serves as a reservoir for antibiotic-resistant genes, which can be passed between bacteria, potentially making TB treatment more challenging (Li et al.). When these resistance genes move between harmless gut microbes and potential pathogens, they create new opportunities for resistant strains of TB to emerge. More recent studies further expand this idea by demonstrating that the gut-lung axis not only influences local immune activity in the lungs but also affects systemic inflammation and disease progression. For example, in a study examining TB patients with gut dysbiosis, researchers found that impaired microbiome health weakened mucosal immunity and altered the course of treatment (Alvarado-Peña et al.). This weakens the body's ability to stop Mtb from spreading, making the infection harder to treat. The study found that patients with fewer beneficial gut bacteria had more inflammation and weaker immune responses and produced fewer SCFAs. As a result, these patients recovered more slowly from TB and had a higher chance of relapse. When the gut's balance of good and bad bacteria is disrupted, the immune system, which protects the body's first line of defense, such as the intestines and lungs, does not work as well.

Similarly, a study analyzing lung immunity demonstrated that SCFAs produced by gut microbes regulate innate lung defenses and help prevent excessive tissue damage (Kotlyarov). Together, these findings suggest that the gut-lung axis is a system in which gut health can influence both the effectiveness of antibiotics and the severity of lung disease in patients with TB. This highlights that the gut is not only a supportive system for immunity but can also play a crucial role in the spread of disease from the lungs to other organs.

Discussion

Understanding an individual's physiologic condition and response, as well as the environments where TB becomes more challenging to control with antibiotics, is crucial in

combating multidrug-resistant TB. The gut microbiome, gut-lung axis, chronic diseases, and environmental conditions impact TB treatment results. Because both diabetes and HIV affect the immune system and disrupt the microbiome, the presence of these conditions lowers fatty acids and encourages inflammation, creating an environment for TB to thrive; thus, supportive therapies such as supplemental therapy that boost the immune response or stabilize the gut may reduce the risk of resistant TB in such patients. Research exploring the adjustment of existing treatment regimens for diabetes and HIV may affect TB outcomes in these patients as well. Moreover, when designing TB treatment plans, concomitant medications that affect the microbiome (e.g., PPIs and immunosuppressants) need to be considered and potentially adjusted during the TB treatment period.

This becomes clear in sub-Saharan Africa, where high HIV prevalence is linked to significantly worse TB outcomes (Wondmeneh and Mekonnen), supporting this link between co-infection and harder-to-treat cases. Likewise, in countries with rising rates of diabetes, such as India and China (Gudegowda et al.), challenges in TB control are increasing, correlating with the observation that concomitant chronic illnesses, particularly those affecting the immune system, amplify the risk of resistance.

While these connections are consistent across multiple studies, the relationship is not always straightforward. For instance, not all TB patients with diabetes develop drug resistance, suggesting that other co-factors, such as genetics, adherence to therapy, or nutrition, influence outcomes. These exceptions are essential evidence that resistance is multi-layered and cannot be explained by any single factor.

Because diet impacts the gut microbiome and the immune system, nutrition should be studied and considered in parallel to antibiotic treatment. A diet high in fiber supports bacteria that produce SCFAs, which could strengthen lung defense by helping macrophages and T-cells combat TB infection. In contrast, diets high in processed sugars and fats promote inflammatory microbes that weaken immune responses and may make antibiotics less effective. Future research could investigate whether incorporating more fiber-rich foods into TB therapy improves recovery times or reduces the risk of relapse. Although people with diabetes, HIV, or malnutrition may benefit most from these interventions, better nutrition could support improved outcomes for all TB patients (Bhargava et al.). Several studies evaluating nutritional support during TB treatment have had mixed results, but have noted that providing oral supplements likely improves weight gain, which may impact treatment outcomes. A field trial in India, which provided TB patients with regular food supplementation alongside standard therapy, is evaluating whether providing nutrition and supplementation will yield higher treatment completion and cure rates, as well as lower rates of failure and relapse (Bhargava et al.; Carwile et al.; Grobler et al.).

Conclusion

In addition to novel antibiotic development, TB treatment paradigms that consider the interplay between bacterial evolution, human health, and environmental factors may be more effective and lead to a reduction in antibiotic resistance by promoting initiatives that improve gut

health through diet or probiotics, personalizing treatment for each individual based on their comorbidities, and enhancing sanitation and infection control in high-risk areas. Limiting unnecessary antibiotic use will also be important in areas where data show misuse and overuse. Alongside TB medical therapy, addressing inequities across the globe with additional resources allocated to more education about concomitant illnesses, proper antibiotic stewardship, and diet modification will enhance TB outcomes and make treatment more cost-effective.

Dietary intervention has direct relevance in high-burden countries where malnutrition is common. In Southeast Asia and parts of Africa, undernourished TB patients often struggle to recover, and studies have shown that poor nutrition is linked to higher relapse and mortality rates (Feleke et al.). These real-world patterns align with the evidence from the literature, which suggests that diet and gut health can have a direct impact on the effectiveness of treatment. Maximizing good nutrition as part of TB care could significantly improve outcomes, particularly in resource-limited settings. Although research directly testing diet-TB relationships is limited, existing evidence suggests a meaningful opportunity for global intervention. If future studies confirm these benefits, nutrition could become a low-cost, practical addition to TB treatment, expanding care beyond medical therapy to include basic public health measures such as nutrition guidance.

Regarding nutritional supplementation, probiotics may aid TB treatment by enhancing SCFA production in the gut and directly inhibiting the growth of TB bacteria. Certain probiotic strains, such as Lactobacillus plantarum and Lactobacillus rhamnosus, can reduce TB growth by improving macrophage activity, making these probiotics a potential supplement to antibiotics (Memariani et al.). Thus, the addition of supplements should be considered when creating a coordinated care plan for patients with TB. Future studies evaluating which probiotics have the most influence on TB treatment are needed to define further how to incorporate these adjunctive therapies into TB treatment algorithms.

Given TB's innate ability to develop resistance, combining drug therapy with strategies that strengthen immunity, improve nutrition, and reduce environmental risks offers a "multi-hit" approach that could be more sustainable than relying only on producing new antibiotics, which TB would eventually be able to resist. Understanding bacterial mutations and recognizing that resistance can emerge from the interaction of bacteria, the host, and their interaction with their environment broadens the scope of possible solutions. Human health factors, including diet, chronic diseases, medications, the gut microbiome, and living conditions, coexist in many patients infected with TB, complicating treatment. Such factors warrant closer examination because addressing them will help promote more effective treatment regimens for TB. Integrating better nutrition, comorbidity management, and public health improvements alongside antibiotics could reduce resistance and improve patient outcomes. The significance of this research lies in demonstrating that TB control will depend on combining biological, medical, and social strategies, providing a pathway to make treatments more effective and limit the global impact of TB resistance.

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The Psychological Edge: Exploring the Benefits of Fencing for Teens By Su Xie

Abstract

Fencing is often referred to as "physical chess" because it combines physical agility with mental strategy. Although the physical benefits are well known, its psychological impact on high school students is rather unexplored. The aim of research is to describe the benefits of fencing for teens, particularly in relation to cognitive development, stress reduction, and emotional management. Through a review of recent scientific research, online discussions, and analysis of fencing programs, this study shows fencing as a unique sport that promotes both mental well-being and personal growth. It can be mentioned that the sport is a valuable tool for teenagers to improve strategic thinking, boost confidence, and develop skills to manage hyperactivity and stress, which are useful beyond the piste.

Introduction

Fencing, a sport that traces its origins to medieval combat, has turned into an exciting modern athletic activity that emphasizes precision, agility, and tactics (Encyclopaedia Britannica, n.d.). The sport is divided into three main disciplines: foil, épée, and sabre, each with its own set of rules (Table 1). Fencing has drawn a wide range of participants, particularly young adults (u/FencingFanatic, 2023; See Figure 1). It is not only a test of physical fitness and skill, but also a mental challenge. It demands quick thinking, focus, and strategic planning as well as strength and coordination. Such a combination of physical and mental work makes fencing an ideal sport for teenagers.

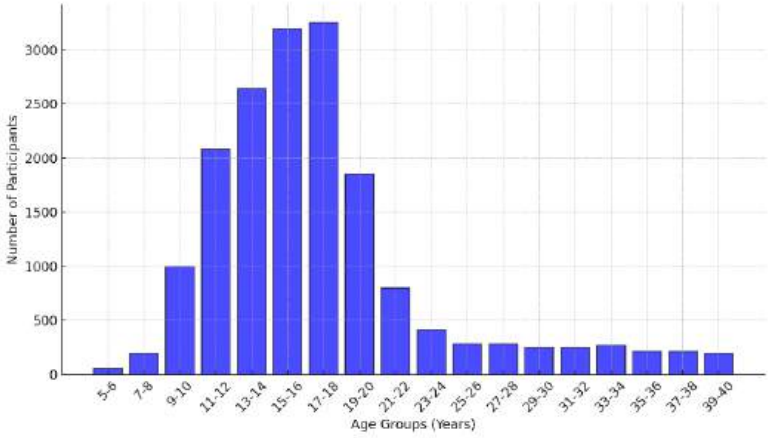


Fig 1. US Fencing Demographics by Age Groups (modified after u/FencingFanatic, 2023). The sport attracts participants from a wide range of age groups, with a strong focus on young adults.

The rising interest of teens in fencing is an indicator of a greater appreciation for the various advantages that it can bring. Teenagers in high school often face both academic pressures and social problems. These may lead to significant mental health concerns. Fencing is demonstrated to be a holistic path to development and wellness (Martín-Rodríguez et al., 2024). The aerobic aspect of the physical activity itself helps decrease stress and boost mood. At the

same time, the cognitive demands of strategic decision-making activate the brain. They encourage concentration and critical thinking. Together, these effects have been shown to ease anxiety and depression and to provide participants with both short-term relief and long-term emotional balance.

Table 1. Comparison of Foil, Épée, and Sabre in Fencing (Including Psychological Aspects)

Aspect	Foil	Épée	Sabre
Target Area	Torso only (including back and shoulders)	Entire body	Upper body (torso, arms, and head)
Weapon Characteristics	Light and flexible, with a smaller blade	Heavier and stiffer blade	Light with a flat blade for cutting actions
Scoring Method	Touches scored with the tip of the blade	Touches scored with the tip of the blade	Touches scored with both the edge and tip of the blade
Right-of-Way Rules	Yes (priority rules apply for awarding points)	No (simultaneous touches allowed)	Yes (priority rules apply for awarding points)
Pace of Match	Moderate to fast-paced	Slower, more deliberate and strategic	Fast-paced and aggressive
Tactical Approach	Precision and timing are key	Patience and careful defense	Speed and aggressive attacks
Mental Focus	Requires anticipating opponent's moves and timing	High level of focus to avoid simultaneous touches	Split-second decision-making and adaptability
Psychological Challenges	The right-of-way rule requires mental clarity and composure to handle disputes, fostering focus on strategic anticipation.	The large target area and no-priority system increase the psychological pressure, demanding exceptional patience and stress resilience.	The fast pace requires heightened concentration and emotional control to avoid overreacting or making hasty decisions.

Fencing helps young athletes to build a number of essential life skills that go beyond the limits of the sport. One of them is critical thinking (Martín-Rodríguez et al., 2024). During a match, fencers need to analyze opponents' tactics, anticipate further moves, and make a quick decision in order to obtain the most effective counter-strategy. These split-second decisions require logical reasoning and creative problem-solving. Clearly, these skills can easily be transferred to other academic challenges, such as solving complex problems in mathematics or science. Besides, the ability to evaluate situations critically and to apply strategies effectively has its full potential in personal and social contexts, which serves as another important layer of value to life development.

Second, the emphasis on memory and pattern recognition in fencing helps reinforce learning and retention (Tsolakis, 2010). In a match, a fencer would want to look at previous bouts and see what worked and what did not work. For example, they might remember how a particular opponent tends to favor a specific attack, such as a lunge to the right. Recognizing these repeated tactics allows them to anticipate and counter effectively. Over time, this process

enhances their ability to recognize patterns quickly and adapt strategies on the spot. All these skills are also very useful in real life. In schools, students need to memorize information for exams. In the business or engineering profession, people need to remember and recognize patterns in order to analyze tendencies and come up with solutions to problems. Therefore, the cognitive demands in fencing are especially important for developing the "mental agility" needed to excel in both academic and professional settings.

Fencing also enhances focus and concentration (Aydin et al, 2024). The sport requires total attention to an opponent’s movements. To do it, the person needs to shut one's self off from all the surrounding distractions, which include external noise, internal self-doubt, and overthinking. Such practice of sustained attention sharpens mental engagement, a skill useful for the classroom. It allows students to absorb information more effectively and commit themselves to their studies. In addition, the mental discipline of fencing fosters mindfulness, which is a real asset for learning and remembering in educational settings. Many fencers report that the focus developed on the strip helps them study for long periods of time and tackle academic challenges with tenacity and persistence. This proves the role of fencing as a tool for the holistic development of personality and intellect.

Last, fencing's structured focus on rules, techniques, and repetitive practice gradually builds a sense of responsibility and perseverance in the athletes. At the same time, the dynamic nature of the sport pushes fencers to work their way through high-pressure situations, sharpening their ability to adapt and respond accordingly. This dual focus not only enhances performance on the piste but also equips athletes with the confidence and composure to face setbacks and challenges in everyday life (Athanas, 2007). Moreover, the individualistic nature of the sport also thrusts the burden of victory and defeat upon the fencer's shoulder. It instills self-reliance, and a strong personal accountability aspect therein. Unlike in other team sports where success is a resultant of the entire group's efforts, fencing places this responsibility upon an individual for one's actions and their mistakes, urging continuous improvement in turn. Consequently, the discipline, flexibility, and accountability fostered by fencing shape a fencer into a well-rounded and resilient individual.

While fencing offers numerous advantages, the perception of this sport as either elitist or overly complicated may hinder some teenagers from attempting it (Chirashnya, 2017). Such misconceptions stem from stereotypical connotations associated with its history and privilege, coupled with technical challenges one goes through while learning its intricacies. Such perceptions can create a barrier for young athletes who otherwise would enjoy substantial benefits from it. Addressing these misconceptions is essential for making fencing more inclusive and appealing to a broader audience.

One effective approach to changing these perceptions is through targeted outreach initiatives. Social media campaigns of relatable stories of determination and growth in the sport can inspire other teens to consider fencing as a viable and rewarding activity. Besides, mentorship programs where experienced fencers guide and support beginners will create an enabling environment that helps skill development and personal confidence. This will build a

strong sense of community, but also emphasize the psychological advantage of the sport. It means that with a chance to portray fencing in an approachable, vibrant, and entertaining format, current obstacles to participation could be overcome for many teenagers. Increasing awareness of the sport's benefits, particularly its psychological advantages, can play a significant role in achieving this goal. This paper explores these psychological aspects, with a particular focus on how fencing can help teenagers navigate the challenges of adolescence while promoting resilience and overall well-being.

Building Physical and Psychological Strength Through Fencing

Fencing is an ideal activity for teenagers in search of complex personal development. On the physical side, fencing develops in an individual the foundational attributes: speed, strength, and agility (Roi & Bianchedi, 2008). These attributes are improved in systematic training aimed at building endurance, explosive power, and precision. Strength-enhancing exercises, such as weightlifting, push-ups, and resistance band drills, allow fencers to achieve more considerable muscle power and stability-key components in performing fast lunges and strong counterattacks. Agility training, such as ladder exercises and shuttle runs on cones, refines reaction times and footwork, thus enabling fencers to react with precision on the piste. It in turn develops coordination and adaptability, whereby a fencer learns to respond timely to changes in the positions of his/her adversary or adversaries. In addition, flexibility exercises round these activities by decreasing injury risks and making one mobile for diverse, unpredictable moves at combat. Indeed, recent studies confirm this practice. For example, it is shown that young fencers who added yoga to their training regime demonstrated significant improvements in physical and psychological performance (Pandya, 2023). Specifically, the inclusion of yogic asanas such as Dhanurasana and Tadasana was linked to measurable gains in muscular strength, as shown by post-test improvements. It highlights yoga's role as a comprehensive tool for enhancing flexibility and mindfulness, which are key contributors to improved results.

On the other hand, fencing training inherently fosters psychological strength through the engagement of both one's mind and body. The mental tools developed through systematic training allow fencers to perform well under pressure. They enable fencers to adapt to changing situations, and also help them overcome challenges both during fencing matches and in everyday life (Gujarathi & Dongare, 2024). Fencing requires unwavering focus, as each bout demands split-second decisions and precise reactions. With regular training, the ability to concentrate sharpens in an athlete through training under pressure, training of not letting distraction occur. If a fencer can stay present and focused during the bout, then he or she can study his opponents' movements and take advantage of this effectively. Training in fencing not only builds emotional control but also teaches how to manage frustration. It helps fencers channel nervous energy into productive actions and maintain composure. Repeated practice strengthens emotional resilience, allowing fencers to stay calm and confident even in high-pressure competitions.

Fencing training sessions can also include drills and simulated bouts that are set to meet the sportive kind of fencing, flexible in tactics and decisions (Gujarathi & Dongare, 2024). This

will strengthen a fencer's strategic thinking ability and further enable problem-solving in situations under pressure. Besides, fencing training frequently puts athletes into situations that test their mental toughness. It means that through recovery from a failed attack, being in front of a more skillful opponent, or withstanding the physical demands of prolonged practice, fencers also learn to overcome adversity. Each of these various challenges at training builds resilience, teaching the athletes how to cope with a setback and look at difficulties as possibilities for their own growth. The ability to persist and maintain a positive outlook becomes a cornerstone in their psychological strength.

Physical and mental demands in fencing contribute to mental endurance. Most of the training consists of very long and exhaustive sessions that need great concentration and effort. Thus, fencers are constantly improving their ability to sustain sharpness and performance for a long period of time. It is important to develop this mental stamina in order to stay focused and precise during those matches, which usually are long and test the physical and cognitive endurance of the competitors. With the advanced training, the fencers develop confidence in their abilities. It is through mastery of techniques and successful execution in practice that one develops a sense of self-assurance that will carry over into competitions. Training also fosters self-reflection, whereby athletes review their performances to identify areas of improvement and establish goals for future development. Such continuous self-evaluation and adjustment help fencers establish a growth mindset and make them capable of embracing challenges and striving for excellence.

Psychological Training in Adolescent Fencing

Psychological training is considered one of the important factors in successful adolescent fencers, along with physical and technical preparation (Han & Wang, 2024). The training has two levels of meaning: it broadly refers to the systematic process of influencing mental and emotional states with the purpose of improving the general state of psychological well-being, while narrowly, it involves specialized techniques tailored to help individuals control their mental states and behaviors in competitive or challenging environments. Particularly for adolescents, psychological training is essential for achieving the best performance, developing resilience, and fostering a comprehensive understanding of the sport.

There are several approaches to psychological training (Gujarathi & Dongare, 2024; Han & Wang, 2024; See Table 2). Relaxation training, a foundation in psychological preparation, is considered an essential requirement for any form of sports that are as highly demanding and pressure-requiring for precision. This technique uses verbal cues or self-instruction to quiet the mind and body, slowing breathing and decreasing muscle tension. In relaxation training, physiological recovery is enhanced and mental focus improved by the activation of the parasympathetic nervous system. In the case of young fencers, these techniques prevent performance anxiety and reduce the physical effects of stress linked to competition. Progressive muscle relaxation, deep breathing exercises, and mindfulness have been reported to enhance

focus and composure, thus enabling athletes to perform technical skills more successfully. It also develops resilience to surprise stressors that may occur during competition.

Imagery training, also known as visualization, involves the creation of mental images of specific actions, strategies, or outcomes one wants to achieve. It enhances the relationship between the brain and motor skills, enabling the athlete to perform specific difficult moves with more precision. In fencing, imagery training enables the adolescent athlete to rehearse mentally various offensive and defensive moves, thereby developing the predictive capability of the opponents' next move. Through visualization of successful bouts and particular technical performances, confidence is enhanced along with reinforcing muscle memory. Other uses for visualization include goal setting: the fencer can rehearse mentally various high-pressure competitive situations and change strategies in real-time.

Self-control training is aimed at managing emotions and keeping one's cool during stressful situations. Adolescent fencers often face intense competition, requiring them to manage frustration, anger, and anxiety effectively. Self-control training teaches them how to harness these emotions toward the most constructive channeling that will ensure that the best decisions are made and performances are realized. This includes self-talk, cognitive reframing, and other emotional regulation techniques. For example, fencers learn not to get distracted while losing a point or when competitors are really challenging. With self-control, the athletes learn how to stay focused on their strengths and how to adjust their strategy without getting distracted by emotions.

Table 2. Psychological Training Methods and Their Impact on Adolescent Fencers

Aspect of Psychological Training	Description	Benefits for Adolescent Fencers	Examples
Relaxation Training	Uses verbal cues, deep breathing, and progressive muscle relaxation to reduce stress, improve focus, and enhance physiological recovery.	Prevents performance anxiety, reduces stress, and develops resilience to surprise stressors.	Progressive muscle relaxation before a match; deep breathing to calm nerves during competition.
Imagery Training	Involves creating mental images of actions or strategies to improve precision, predict opponent moves, and build confidence.	Improves motor skills, muscle memory, and confidence through mental rehearsal.	Visualizing successful parries or attacks; mentally rehearsing counter-strategies for specific opponents.
Self-Control Training	Teaches emotional regulation techniques such as self-talk and cognitive reframing to manage emotions during competition.	Helps manage frustration, anger, and anxiety, ensuring better decision-making under pressure.	Using self-talk to stay focused after losing a point; reframing frustration into determination.
Attention Training	Focuses on enhancing attention and concentration through exercises like reaction training, situational awareness, and mindfulness meditation.	Enhances ability to track opponent movements, respond effectively, and maintain performance during long matches.	Practicing mindfulness meditation to improve focus; engaging in reaction drills to enhance tracking of opponent movements.

As mentioned earlier, concentration is a critical skill in fencing. Attention training is aimed at enhancing the ability of the athlete to focus on the task at hand and to filter out irrelevant stimuli. In this respect, reaction training, situational awareness tasks, and mindfulness meditation are examples of attention-enhancing exercises in fencing. These practices enhance a fencer's ability to track their opponent's movements, respond to feints, and exploit openings effectively. Sustained attention helps athletes to maintain performance across even very long matches.

Overall, the integration of these approaches into fencing programs provides a holistic perspective on the development of athletes so that adolescents could fully express their potential in this sport. Further research and practical work should be directed at individualization of these techniques, which will promote further development of psychological support in competitive fencing.

Psychological Benefits of Fencing Competition

Sport competition is a powerful motivator to developing personal growth and mental stability in teenagers (Brown et al., 2017; Ramdinmawii 2024), especially in such a sport as fencing. In competitive conditions, adolescents are able to develop in themselves a sense of self-efficacy and teach themselves to set objectives and achieve them in a challenging atmosphere (Eime et al., 2013). By pushing their limits, they build a growth mindset that can carry over into other areas of life. Through both victories and defeats, young fencers can gain important insights into their abilities, and are thus enabled to build confidence and self-esteem.

Other psychological benefits of competition include the growth of resilience and coping skills (Ramdinmawii 2024). Competitive fencing teaches young athletes to handle pressure. Be it dealing with stress before a match or responding to an unexpected loss, teens learn emotional handling and adapt one to challenging situations. This resilience is something that's not only critical to success in fencing but one that gives them life skills quite applicable to the academic setting and future careers where competition and performance are integral.

Moreover, competitive fencing will bring out better focus and discipline (Di Martino et al., 2024). Mastery of such complicated techniques and strategies means developing concentration and a good work ethic. These cognitive skills are transferable, benefiting their academic performance and overall mental agility. The habit of regular training and competition teaches young fencers to structure their time and tasks in such a way that the effects can last well into later life, concerning organizational skills and efficiency in many other areas of their lives.

Competition in fencing helps teens develop social skills and build lifelong friendships. Social interactions are especially important during adolescence. At this stage, peer relationships play a big role in emotional growth. In team tournaments and fencing clinics, teens are placed in environments where they must work together. They learn to communicate, cooperate, and support each other. These experiences can develop long-lasting friendships and networks. Training and competing together create a sense of belonging. This sense of community helps them feel supported and valued, which is important for good mental health.

Finally, competition in fencing is able to boast a number of mental health benefits, such as fighting against anxiety and depression (Martín-Rodríguez et al., 2024). The physical activities within this sport are able to release endorphins, improving mood and reducing stress. Besides, the structure of competition offers routine and predictability, which can be comforting for teenagers in an effort to make their way through the turmoil of adolescence. It nurtures mental well-being, hence serving as a strong tool for building resilience and emotional health in the young.

Misjudgment in Fencing and Psychological Challenges

Misjudgment in fencing by referees, opponents, or the athletes themselves can have a strong psychological impact on high school athletes. Fencing is a sport so dependent on split-second decisions and subjective interpretations of right-of-way rules that it carries within itself the inherent risk of contested calls and perceived unfairness (Roi & Bianchedi, 2008). The disputed match between Sun Yiwen and Miho Yoshimura during the 2024 Paris Olympics underlined the challenges of misjudgment in fencing. While high-resolution cameras and better scoring rules can reduce these issues, it is still difficult to ensure fair results for all players every time. Such situations can significantly affect a young athlete's mental state, causing frustration, self-doubt, and stress.

One pervasive cause of psychological stress for the fencer is the referees' subjectivity (Heil et al., 2007). In fencing, referees are constantly required to interpret the complexity of the action-applying blades and timing-to determine who holds right-of-way. This requires quick judgment and can lead to decisions that are seen as inconsistent or one-sided. For young athletes, feeling unfairly treated or victimized by these calls can be particularly upsetting. They may begin to question the fairness of the sport and feel frustrated by what they consider as biased decisions. Over time, this stress can decrease their confidence, making them fear future misjudgments. The fear may distract them during matches, reducing their focus and harming their performance. Therefore, ensuring fairness and clear communication from referees is essential to supporting young athletes in these situations.

Another issue is self-perceived misjudgment. This is due to the feeling that one has made a poor decision or failed to execute a planned action. For a high school fencer who has not reached full emotional maturity, such a belief may feel like a personal failure. As a result, the fencer could develop negative self-talk and become unmotivated or avoid being adventurous in further bouts. This avoidance of challenges is likely to limit their growth and development, preventing them from reaching the full potential.

Social dynamics of fencing can also intensify the psychological impact of misjudgment. Many high school athletes compete publicly in front of their peers, coaches, and family members. These circumstances raise the stakes for performance. For example, a perceived mistake or bad call in such a public setting can result in embarrassment or shame, adding to the emotional weight of the misjudgment. The experiences, if repeated, can lead to a fear of failure,

making athletes hesitant to take risks or fully commit during matches. It can further hinder their confidence and limit their ability to grow and excel in the sport.

Although the psychological challenges caused by misjudgment can be significant, with the right strategies and support, high school fencers can effectively confront them and build the mental resilience needed for success. In particular, coaches play a critical role in this process (Vasyl & Marian, 2022). A coach could relieve the impact of misjudgment by creating an atmosphere of support. They can encourage athletes to view setbacks as opportunities for growth and learning, rather than as failures. By guiding them to focus on factors within their control, coaches can help athletes regain confidence and composure. Techniques such as mindfulness, visualization, and self-reflection can further equip fencers to manage the stress of misjudgment, allowing them to stay positive and maintain their focus during challenging moments. Therefore, with the right strategies and support, high school fencers can overcome these challenges and build the mental strength needed to perform successfully.

Biological Mechanisms Linking Physical Activity to Mental Well-Being

The connection between physical activity and mental well-being has a strong biological basis. Regular physical activity triggers chemical changes in the brain that influence mental well-being. It can improve mood and help reduce feelings of stress. These changes play a significant role in maintaining emotional stability. The most important mechanisms involve the release of endorphins, a group of so-called "feel-good" hormones (Abdulrasool et al., 2020). Endorphins activate receptors in the brain that cut down the intensity of pain sensation and at the same time induce feelings of happiness and relaxation. This is that natural phenomenon which causes an individual to exhibit what is usually termed as a “runner's high” after intense exercise, a state of euphoria.

Besides endorphins, physical activity also promotes the release of serotonin and dopamine, two crucial neurotransmitters responsible for maintaining mood and emotional balance (Abdulrasool et al., 2020; Jing et al., 2024). Serotonin reduces symptoms of depression and anxiety by promoting feelings of well-being and stabilizing emotions, while dopamine is related to feelings of pleasure, motivation, and reward. The increase in neurotransmitters via exercise shares similarities with certain antidepressant and anti-anxiety medications, placing physical activity as a strong complement in the management of mental health disorders.

Regular physical exercise also decreases levels of cortisol (De Nys et al., 2022), which is generally recognized as the human body's main stress hormone. Elevated cortisol levels commonly become the aftermath of chronic stress and often accompany anxiety and depression. By bringing cortisol levels down, physical activity acts against the physiological changes caused by stress, thus protecting and soothing a person's psychological constitution.

Moreover, physical activity contributes to brain health by influencing neuroplasticity, or the brain's ability to adapt, reorganize itself, and form new neural connections (Li et al., 2024). This is most significant within the hippocampus, a section of the brain linked to memory, learning, and emotional regulation. Exercise provokes the secretion of brain-derived

neurotrophic factor, a protein that helps in the growth and survival of neurons. In addition to improvements in memory and cognitive functioning, elevated levels of brain-derived neurotrophic factor (BDNF) are protective against neurodegenerative and age-related decline, along with neuropsychiatric diseases such as Alzheimer's disease (Bathina & Das, 2015). For athletes who take part in strategic sports, such as fencing, a recent study showed that they have heightened activity in the prefrontal cortex-the area of the brain involved in decision-making and planning (Heiland et al., 2021). The result suggests that for teenagers, this cognitive sharpening can mean improved academic performance and enhanced problem-solving abilities outside of sport.

Another important benefit of physical activity is improved blood flow to the brain (Liu et al., 2023). Aerobic exercise, in particular, increases oxygen and nutrient delivery to the brain, enhancing its overall function and efficiency. This heightened circulation supports energy metabolism and waste removal, ensuring optimal brain performance. Moreover, angiogenesis or the formation of new blood vessels due to exercise further improves the vascular network within the brain, contributing to long-term mental health benefits.

Fencing for Managing Hyperactivity

Being an open-skill sport, fencing is ideal for hyperactive individuals because it is highly physically demanding. The sport involves constant movement, sudden changes in direction, and bursts of energy. These activities help release accumulated energy that might otherwise appear as restlessness or impulsiveness. By channeling energy constructively, fencing helps reduce symptoms of hyperactivity and improves concentration. Indeed, studies have shown that experienced fencers perform better on inhibitory control (Chan et al., 2011). This is reflected in higher neural efficiency, reduced processing variability, and less cognitive effort during self-regulatory tasks. Such improvements in executive functions, including decision-making and emotional regulation, are particularly beneficial for managing challenges associated with disorders like ADHD and anxiety.

One study (Reche, 2016) explored the use of fencing as an effective treatment for ADHD. The structured, systematic, yet exciting nature of the sport helps address core issues of ADHD, such as attention problems, impulsivity, and emotional dysregulation. The study highlighted that fencing enhances sustained attention by requiring participants to intensely focus on their opponents' movements and strategies while planning their own. This mental engagement trains individuals to maintain focus over extended periods, a skill that can positively impact academic and personal success.

Quick decision-making and the elaboration of a strategy also strengthen inhibitory control through fencing, a vital area of weakness in ADHD cases (Seiffer et al., 2022). Over time, participants learn to pause and assess their responses thoughtfully, rather than acting impulsively. It is evident that this skill transfers well to everyday situations, providing significant advantages in managing ADHD symptoms.

Research by Farrag and Abd El-Rahman (2015) examined the effects of basic fencing skills training on hyperactive children, focusing on physical, behavioral, and biochemical changes. In a four-month training program, children were trained in systematic fencing activities such as footwork, coordination drills, and weapon handling. The study reported a significant reduction in hyperactivity levels, as measured by the Abbreviated Conners' Teacher Rating Scale (ACTRS). They had gone down to 16.40 from 21.56, reflecting improvement in attention with diminished impulsivity (see Figure 2). Additionally, stress-related catecholamines, hormones linked to physiological tension and hyperactivity, decreased from 8.925 mg/d to 8.05 mg/d, reflecting fencing's calming effects on participants.

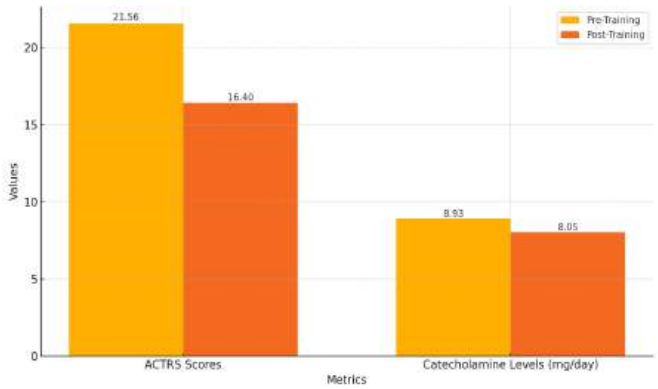


Fig 2. Reduction in Hyperactivity Symptoms Through Fencing: Changes in ACTRS Scores and Catecholamine Levels. (Data are from Farrag and Abd El-Rahman's study)

These findings highlight fencing's ability to balance tension states and improve psychological well-being. Beyond physical benefits, the sport promoted discipline, self-control, and moral character. Children learned to channel their energy constructively, develop non-violent behaviors, and improve their emotional and social functioning. This underscores the value of integrating fencing into school and community programs, particularly for children with ADHD and related conditions. Such initiatives provide an inclusive, effective approach to addressing hyperactivity while fostering personal growth and development.

Stress Reduction through Fencing

Fencing offers a unique outlet for managing stress by combining physical activity with mental engagement, creating a dual mechanism for relief (See Figure 3 for the flow diagram). The physical demand of fencing involves continuous movement, including lunges and quick footwork. It stimulates the release of endorphins that reduce stress and promote feelings of happiness as discussed previously. This biochemical response, by inducing relaxation and improving overall mood, counteracts the physiological effects of stress. It is also clear that activities like fencing, which entail sudden bursts of anaerobic exertion, help lower cortisol levels and stabilize mood.

In addition, the mental intensity of fencing plays a significant role in stress reduction (İlhan 2021). Fencing is different from most other sports due to its strategic nature. For example, during bouts, athletes need to remain wholly present to anticipate what the opponent will do and coordinate with the action to take with the implementation of a strategy. This mindfulness, combined with the shift in focus away from external irritants, is developed through the mental effort needed to stay fully engaged in the match. As a result, it not only helps reduce stress but also promotes a sense of mental clarity and balance. This idea is echoed by a contributor to a Reddit discussion, who noted, “When I'm fencing, I can't think about anything else—just me and my opponent. It's the ultimate stress reliever” (Reddit, n.d.).

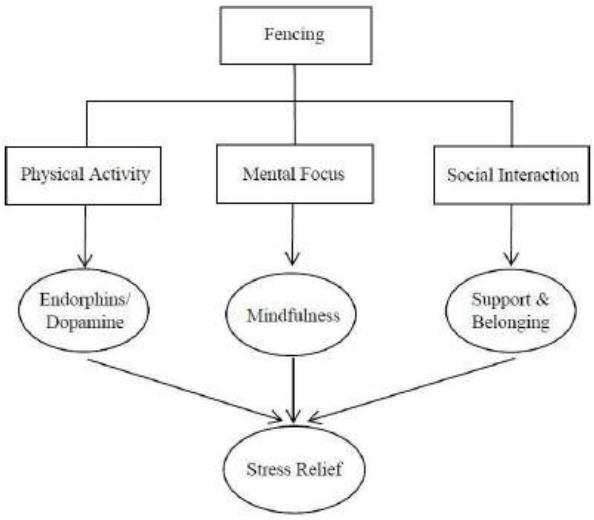


Fig 3. Flow Diagram: Fencing for Stress Management

Besides, fencing often places athletes in high-pressure situations, like competitive tournaments or difficult matches. These experiences help participants manage their emotions constructively and thus build emotional resilience. The structured environment of operation, which is based on discipline and respect, gives a framework for processing and dealing with stress. The Academy of Fencing Masters says, "Fencing teaches you to respond, not react—a skill that helps in managing stress both on and off the strip." Because athletes repeatedly meet and overcome such challenges, they develop their adaptability and composure. Besides, social contacts also enrich the stress-relieving effects. During training and competitions, it is easy for an athlete to establish close relationships with colleagues and coaches, thus developing a sense of friendship and being supported. According to some research, regular activity within a group sport improves mood and decreases states of loneliness, reinforcing the emotional benefits of the sport.

Fencing's repetitive drills and disciplined training approach also provide the athletes with effective coping mechanisms. The focus required during a bout mirrors the concentration needed for complex tasks or tight deadlines, teaching fencers how to remain calm and composed under pressure. These skills will translate seamlessly into other aspects of life and help the young athletes cope better with stress in academic and personal contexts. Another inherent feature of

the sport that fosters emotional resilience is unpredictability. Athletes should be able to change with the circumstances-for instance, reassessing strategy at mid-bout-or deal with disappointment if one loses a point. These experiences also parallel real-life challenges and thus equip students with tools for navigating adversity. A recent study underlined that sports like fencing, in which individual performances are enacted within a rule-governed framework, offer ideal conditions for developing self-efficacy and emotional control (Martín-Rodríguez et al., 2024). Young fencers often say that keeping their emotions in check on the piste carries over into keeping their emotions in check in life.

Case Studies: High School Fencers in Action

With the above benefits in mind, I researched online forums and high school fencing programs to gain more understanding of the impact of fencing. The analysis of message boards and an in-depth look at fencing programs reveal further the deeply transformative impact of the sport. It's evident that mental flexibility, discipline, and self-confidence have been fundamental themes. These qualities demonstrate the outstanding advantages of fencing in promoting well-rounded development and transformations in students' lives.

The Vermont Fencing Alliance emphasizes how fencing builds self-confidence and emotional control (Vermont Fencing Alliance, n.d.). It helps their young athletes grow both competitively and socially. The Academy of Fencing Masters highlights that fencing teaches discipline, respect, and adherence to rules (Academy of Fencing Masters, n.d.). These values also extend beyond the sport itself, which have been carried over into important areas of life like academics, work, and relationships. Fencing enhances focus and decision-making skills, according to the New Jersey Fencing Alliance (New Jersey Fencing Alliance, n.d.). Many families involved in the program have reported improvements in academic performance and time management as a result. The above examples clearly illustrate the sport's profound impact on personal and social development.

Improvement in fencing techniques also influences better study habits and management of time. For instance, students learn how to set priorities, as one does while setting up and conducting strategies in a match, and they could start making study schedules or sticking closer to deadlines. These approaches help in disciplining the students to stay organized and reduce procrastination. All these skills are bound to give way to gradual improvement in their performance and boost confidence in performing school work, among other life challenges.

One parent of the California Fencing Academy shared, "She went from an awkward, shy kid to a confident, self-assured child with high self-esteem" (California Fencing Academy, n.d.). They noted how fencing kept her grounded and gave her an outlet through the challenging teenage years. Similarly, a Reddit contributor discussed a personal experience of starting fencing at age 15 (Reddit, n.d.). He had to fight all odds to get into any sport at a somewhat older age than most kids. Despite this, the nature of the fencing community, being warm and welcoming, made the transition both smooth and enriching. For him, fencing evolved from a physical activity into a lifelong passion. Reflecting on the experience, he said, "The strategic nature of fencing

taught me to think critically under pressure and adapt quickly," a skill that has proven invaluable in both academic and professional settings.

Another significant influence, as mentioned by contributors on online message boards, was the social aspect of fencing. They noted that local clubs and tournaments brought together individuals from diverse backgrounds, all united by their shared passion for the sport. As one contributor expressed, "There is nothing to compare with the camaraderie in the fencing community," suggesting how the sport promotes connections and teamwork. Additionally, the rigors of the sport inculcate values of hard work as well as responsibility. "On the strip, you're responsible for your actions, and that mindset has helped me in my career and personal life," he concluded, encouraging others to pursue the sport regardless of their age or background.

Programs like Fencing in the Schools further illustrate how the sport may be transformative in nature (Fencing in the Schools, n.d.). Through workshops, afterschool programs, and partnerships, these initiatives reach out into schools with different socioeconomic populations of students. They provide equipment free of charge along with training and mentorship opportunities, which helps remove barriers that prevent people from participating. Besides promoting physical fitness, these programs also teach important life skills like persistence, teamwork, and adaptability. The structured training teaches students the importance of consistent effort. At the same time, the supportive environment helps them build friendships and social connections.

On a broader level, high school fencing programs like the above help strengthen school communities through mutual respect, collaboration, and inclusivity. Participants in these programs are usually better off in terms of self-esteem and resilience. Many students transfer the confidence they gain from competing in matches to other areas of life. For instance, a student who once avoided public speaking began volunteering to present projects in class after learning to manage pressure during fencing competitions. Another student embraced leadership roles in group activities, inspired by the strategic thinking and quick decision-making developed through fencing. These examples highlight the far-reaching impact of fencing programs on personal growth and life skills.

Conclusion

In conclusion, fencing offers much more than just physical exercise to high school students. It can enhance their mental health, and support their growth and development in all areas of life. The sport combines strategy, discipline, as well as physical activity. It provides young athletes with a mental edge that undergirds stress management, emotional resilience, and cognitive growth. As schools and communities look for ways to address the increasing mental health challenges, fencing stands out as one particularly promising solution. Real-life examples confirm its value in helping high school students build resilience, develop critical thinking, and gain confidence. By offering both immediate and long-term benefits, fencing helps students navigate the complexities of adolescence and prepare for future success.

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Forecasting TSLA: An Investigation Into AL Model Accuracy and the Impact of Weighted Ensemble Learning By Kevin Mathew

Abstract

Predicting stock prices is an extremely challenging task due to various factors involved, such as the volatility of the market, complex interactions among financial indicators, and the influence of external factors such as politics and the news. This study investigates the use of artificial intelligence (AI) models such as Neural Networks, Random Forests, Decision Trees, Linear Regression, and KNNearest Neighbors, to forecast Tesla stock prices using past data imported from Yahoo Finance. The research aims to determine which models, individually or in combination, provide the most accurate and reliable predictions. My hypothesis is that combining multiple models through a weighted average set will outperform individual models by leveraging their individual strengths. Historical stock data, including daily opening, closing, high, and low prices, were split into training and testing sets to evaluate predictive performance using Mean Squared Error (MSE). Results indicate that these predictions generally reduce errors compared to single-model predictions, with Neural Networks and Linear Regression showing particularly strong performance. A simulation of a simple trading strategy based on model predictions demonstrates how accurate forecasts can translate into potential financial gains. These findings suggest that AI-based approaches can effectively capture patterns in stock market data and support informed investment decisions. The research paper highlights the importance of parameter tuning, regularization, and careful data handling to prevent overfitting and improve model generalization, providing a foundation for further research in AI-driven financial forecasting.

Introduction

The stock market is a system made up of exchanges, brokerages, and over-the-counter platforms where investors buy and sell shares of publicly traded companies. Shares, or stocks, represent fractional ownership in a company. When people refer to “the stock market,” they often think of specific exchanges like the New York Stock Exchange, but it actually includes all regulated places where stocks are traded. This network is protected by laws that prevent fraud and unfair trading practices, ensuring trust and stability in the system.

The main purpose of the stock market is to provide an organized and regulated environment where companies can raise money by offering shares to the public, and investors can easily buy and sell those shares. This system supports economic growth by allowing businesses to finance operations and expansion while giving individuals and institutions opportunities to invest and earn returns. Without the stock market, companies would struggle to secure funding, and investors would lack a reliable, transparent way to trade and value shares.

The origins of the modern stock market can be traced to 1602, when the Dutch East India Company (VOC) became the first organization to issue publicly tradable shares, allowing investors to buy and sell ownership in the company. This led to the creation of the Amsterdam Stock Exchange, widely regarded as the world's first formal stock exchange and the birthplace of concepts such as joint-stock ownership, limited liability, and secondary trading. Over time, this model spread across Europe and later to the United States, where the New York Stock Exchange was founded in 1792 after 24 brokers signed the Buttonwood Agreement on Wall Street. These developments marked the beginning of organized capital markets, enabling companies to raise large amounts of funding and laying the foundation for the global financial systems that exist today.

Understanding the history of stock markets helps provide context for how modern trading operates. Today, investors closely monitor key metrics such as opening and closing prices, which reflect the dynamics of buying and selling throughout a trading session. The opening price marks the first transaction of the day, shaped by pre-market orders and news that influence investors. sentiment, while the closing price represents the final trade and serves as a benchmark for the stock's daily performance.

Artificial Intelligence (AI) is redefining how investors make decisions. Once seen as futuristic, AI has now become one of the most powerful tools in finance, capable of analyzing thousands of data points, predicting price trends, and identifying opportunities in seconds. Traditional stock analysis once depended on human judgment and experience. Now, AI can process vast amounts of financial and sentiment data faster, more accurately, and without emotional bias. AI stock analysis uses artificial intelligence algorithms to study financial data, price movements, and news sentiment to support investment decisions. AI combines several technologies, such as machine learning, natural language processing (NLP), and deep learning, to interpret and predict market trends.

Materials and Methods

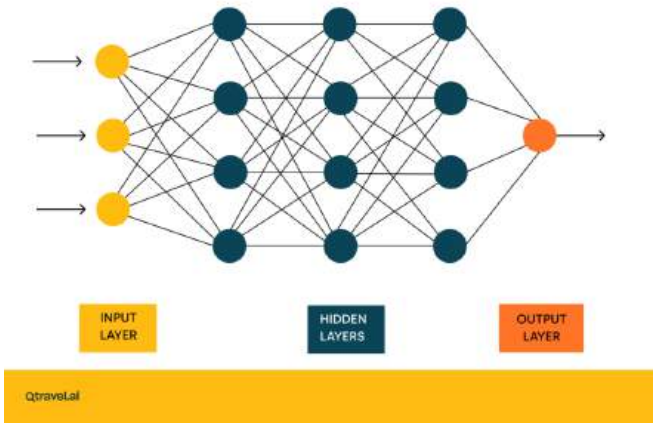
The dataset used in this analysis consists of historical stock price data for Tesla Inc. obtained from Yahoo Finance, a widely used and reliable platform for financial market information. It includes daily records of Tesla's stock performance, featuring variables such as the date, opening price, highest and lowest prices of the day, closing price, and trading volume. This dataset is commonly used for financial trend analysis, forecasting, volatility studies, and technical analysis due to its accuracy, accessibility, and comprehensive coverage of market activity over time.

We split the dataset into training and testing sets to measure how well the model works on unseen data. The training set is used to teach the model the underlying patterns and relationships, while the testing set is used to evaluate its accuracy and performance on new information. This prevents errors and ensures the model can make reliable predictions in real-world scenarios. Here are the models used:

Neural Network/MLP Regressor

A neural network is an artificial intelligence model inspired by the structure of the human brain, consisting of interconnected nodes (neurons) arranged in layers that learn patterns in data through a process called training. It works by adjusting the weights of these connections based on errors during prediction, allowing the model to capture complex, non-linear relationships. Neural networks are highly flexible and perform well on tasks like image recognition, time-series forecasting, and classification, especially when large amounts of data are available. In an MLP Regressor, a model with very large parameters may still appear to perform well if it achieves a low MSE, but this does not mean it is free from overfitting; the model simply prefers the configuration that produces the smallest error, even if it requires excessively large weights. For example, if Option 1 uses large parameters and yields an MSE of 2 and Option 2 uses smaller parameters with an MSE of 2.1, the model will always choose Option 1 because it focuses solely on minimizing the error. To prevent the model from relying on unnecessarily large weights, a penalty must be introduced; this is the purpose of L2 regularization, which adds a cost for large parameter values. The penalty is controlled by a factor (alpha), where a small alpha makes the penalty negligible, and a large alpha makes the penalty strong. The optimization objective becomes optimization = MSE + a*sum of weights; a = alpha/the factor.

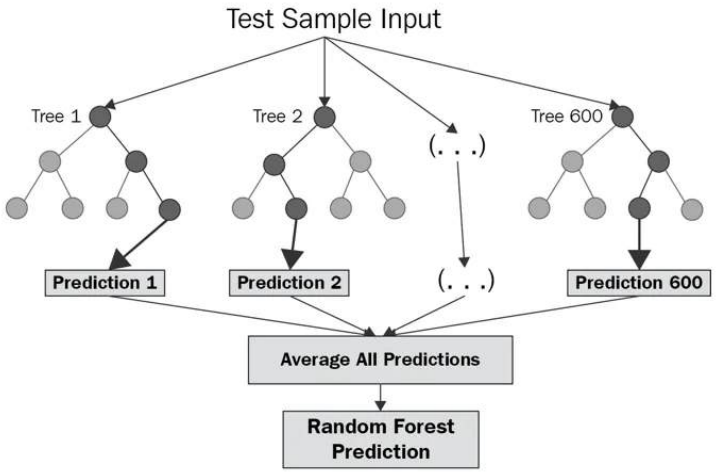
Alpha (default = 0.0001) determines the strength of this L2 term, which is divided by the sample size before being added to the loss. This encourages the model to balance accuracy with model complexity, reducing overfitting by discouraging excessively large weights.



Random Forest

A random forest is an ensemble learning model that builds many individual decision trees and combines their outputs to make more accurate and stable predictions. Each tree is trained on a random subset of the data and features, which reduces overfitting and increases robustness. By averaging the predictions of multiple trees (for regression), random forests provide high accuracy, handle complex data relationships, and work well even when the data contains noise. Random forests don't overfit easily because they combine many decision trees, each trained on a

different random subset of the data. This introduces diversity among the trees, so while individual trees might overfit their subset, the averaging process (for regression) cancels out individual errors and noise. Essentially, the model captures general patterns instead of memorising specific training examples, which makes it much more robust and less prone to overfitting than a single decision tree.



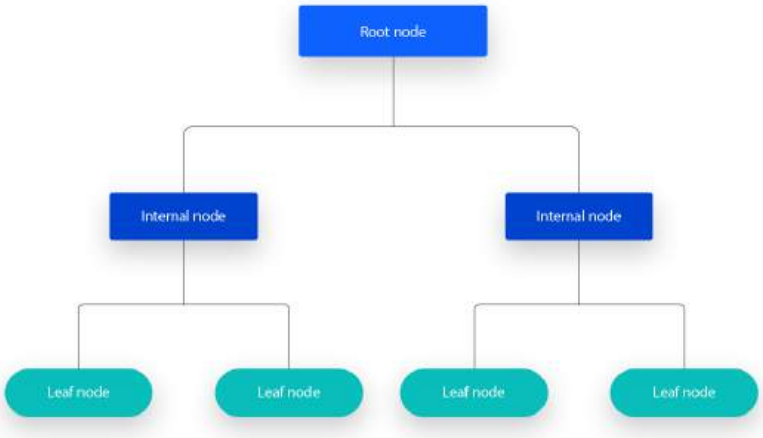
In a Random Forest**,** many decision trees are built on different bootstrapped samples of the training data, and their predictions are averaged for regression tasks. The min_samples_leaf parameter applies to each individual tree in the forest. By setting a minimum number of samples required at a leaf, it controls how deep each tree can grow and how specific or 'general' each tree's predictions are. Trees with very small leaves can overfit to noise in their specific bootstrap sample, but because a random forest averages predictions across many trees, the model is more stable. Still, setting min_samples_leaf too low can allow each tree to overfit individually, increasing variance, whereas a higher value smooths each tree's predictions, improving generalization across the forest. In short, min_samples_leaf in Random Forest acts as a regularizer for all the trees.

Decision Tree

A decision tree is a simple, interpretable model that makes predictions by splitting the data into branches based on various feature values, forming a tree-like structure of decision-based rules. It works by choosing the most informative features at each step to divide the dataset into smaller, more homogeneous groups. Decision trees are easy to understand and visualize, but they can overfit if not properly controlled, making them better suited for smaller datasets or when model transparency is important.

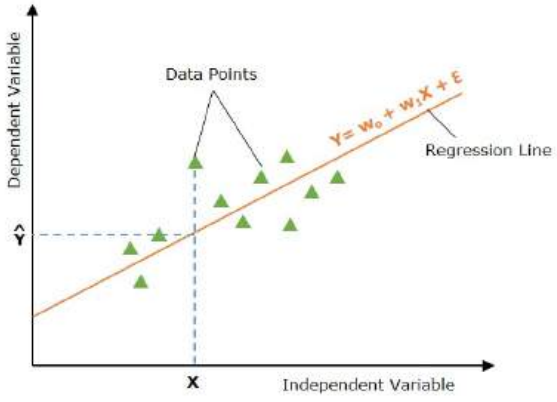
In a Decision Tree Regressor, optimization refers to the process the algorithm uses to choose the best split at each node by minimizing a loss function, usually the Mean Squared Error, so that the resulting tree makes the most accurate predictions possible on the training data. However, if a tree is allowed to split freely, it can grow too deep and place each individual

training instance on its own leaf, which leads to overfitting. To prevent this, the parameter min_samples_leaf is used: it specifies the minimum number of training samples that must be present in a leaf node. A split is only accepted if both resulting branches contain at least this many samples. By increasing min_samples_leaf, the tree is forced to create larger, smoother leaves instead of tiny ones that memorize noise, making the model more general and less prone to overfitting. The training samples referenced here are simply the data points used to train the model.



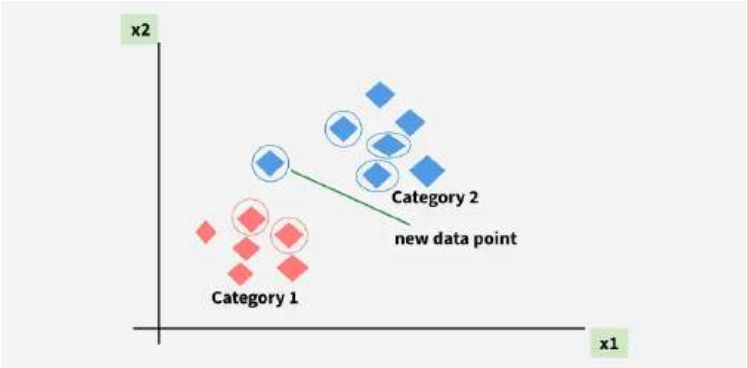
Linear Regression Model

A linear network, or linear regression model, predicts an output by learning a straight-line relationship between input features and the target variable. It assumes that changes in the input lead to proportional changes in the output, making it simple, fast, and interpretable. While it performs well when the relationship is truly linear, it struggles with complex or non-linear patterns and may require preprocessing or transformation of data for better accuracy.



K-Nearest Neighbours (KNN)

K-Nearest Neighbors is a non-parametric, instance-based model that makes predictions by comparing a new data point to the 'k' most similar points in the training dataset. Instead of learning explicit patterns during training, KNN relies on distance measures—such as Euclidean distance—to determine similarity. It is easy to understand and works well for small datasets, but it can become slow with large datasets and is sensitive to feature scaling and noisy data. In KNeighborsRegressor, the n_neighbors parameter (k) controls how many nearest points are considered when making a prediction. A small k makes the model highly sensitive to individual data points, which can cause overfitting, while a larger k averages over more neighbors, smoothing predictions and reducing overfitting. The weights parameter determines how much influence each neighbor has: 'uniform' treats all neighbors equally, while 'distance' gives closer neighbors more weight. Using distance-based weighting can further reduce overfitting by emphasizing nearby, more relevant points, rather than letting distant neighbors disproportionately affect predictions.



In this project, Mean Squared Error (MSE) is used as the main evaluation metric to measure how accurately each model predicts continuous Tesla stock prices. MSE calculates the average of the squared differences between predicted and actual values, meaning larger errors are penalized more heavily. All models—Neural Network, Random Forest, Decision Tree, Linear Regression, and K-Nearest Neighbors—use MSE because it provides a clear, quantitative indication of how far each prediction is from the true stock price. A lower MSE reflects stronger predictive performance, while a higher MSE signals weaker accuracy, making it easy to compare which models are performing best.

Building on this, the project uses a weighted-average approach to combine predictions from all models into a single, more reliable forecast. Since MSE reveals how accurate each model is, models with lower errors are assigned higher weights, giving them more influence in the final prediction. Each model has an associated weight (w1, w2, w3, …) that must lie between 0 and 1, and the sum of all weights must equal 1. As a model's error decreases, its weight increases; if its error grows, its weight decreases. This ensures that the algorithm naturally favors the most accurate models at any given time. By integrating both MSE-based evaluation and

weighted averaging, the system produces predictions that are more stable and reliable than those of any single model alone.

You start with several prediction models, each with an initial weight (e.g., w1=w2=w3=w4=w5=1/5). Each day, you aggregate their predictions (e.g., up or down, or price values) into a combined forecast via a weighted average. After observing the actual outcome, you evaluate which models were correct, then reduce the weights of models that were wrong (e.g., the weight gets divided by 2), while keeping the weights of correct models unchanged (or relatively higher). Finally, you re-normalize the weights so they sum to 1 (i.e., divide by the sum of all updated weights). Over time, models that predict correctly more often gain relatively higher weight, and those that perform poorly gradually contribute less; thus, future ensemble predictions rely more on historically reliable models. This is an instance of the general method known as the Multiplicative Weights Update.

Simulation

This simulation models a simple trading strategy where you start with $5000 in cash and 0 Tesla shares and then buy or sell shares based on predictions made by your Neural Network model. For each day in the 1200-day period, the model looks at the next day's predicted price (Predictions[i+1]) and compares it to the current actual price (Y[i]). If the model predicts the price will go up, and you have enough money to purchase k shares (in this case, 5 shares), you buy those shares at the current day's price. This reduces your cash balance by k * Y[i] and increases the number of shares you own.

In contrast, if the model predicts that tomorrow's price will be lower than today's price and you currently own more than one share, the simulation sells k shares. These shares are sold at the current price (Y[i]), increasing your cash amount while reducing the number of shares you hold. This buy-and-sell process continues daily throughout the 1,200-day window. On the final iteration (i = 1199), all remaining Tesla shares are automatically sold at the last available price, so the simulation ends with only cash. The final printed values show your total ending amount in dollars and the number of shares left (which should be 0). This provides a simplified estimate of how profitable your predictive trading strategy would have been using Neural Network forecasts.

The simulation results highlight how model predictions directly influence trading decisions and profitability. However, strong performance in a controlled test environment does not guarantee that the models will behave consistently in real-world markets. To understand the limitations of these models, it is necessary to discuss overfitting, underfitting, and the model's ability to generalize. These concepts provide the foundation for interpreting why certain models perform well temporarily while others degrade when market conditions shift.

In machine learning, overfitting occurs when a model fits too closely or even exactly to its training data, such that it can't make accurate predictions or conclusions from any data other than the training data. Overfitting defeats the purpose of the machine learning model. An overfit model is analogous to an invention that performs well in the lab but is worthless in the real world.

To avoid overfitting in machine learning, several techniques can be applied. Simplifying the model by reducing the number of parameters or layers prevents it from memorizing noise in the training data. As such, regularization is a method for increasing a model's generalizability, that is, its ability to produce accurate predictions on new datasets. Regularization provides this increased generalizability at the cost of increased training error. In other words, regularization methods typically lead to less accurate predictions on training data but more accurate predictions on test data. Regularisation methods, such as L1 or L2 penalties, constrain the magnitude of model weights. Using more training data helps the model generalize better to unseen examples. Dropout randomly disables neurons during training in neural networks, reducing dependency on specific pathways. Additionally, cross-validation ensures the model's performance is tested on different subsets of data, and early stopping halts training when validation error starts increasing. Together, these methods help the model learn underlying patterns rather than memorize the training set.

Results

Table of Results—Testing Data						
Testing MSE	Apple	Nike	Nvidia	Pfizer Inc.	Goldman Sachs	Starbucks Corporation
Random forest(Min_samples_leaf=1)	154.63	101.81	784.61	4.31	1062.82	13.90
Random forest(Min_samples_leaf=5)	172.66	101.73	764.38	4.57	1308.36	18.58
Decision Tree (Max Depth = 5)	9.86	5.01	50.69	0.28	80.16	1.93
Decision Tree (Max depth=20)	7.68	4.35	67.49	0.15	45.02	2.09
Neural Network(alpha=0.0001)	8.24	3.57	47.04	0.15	57.42	2.39
Neural Network(alpha=1)	8.3	3.34	46.87	0.15	45.02	2.25
Linear regression	3.74	1.86	30.25	0.07	25.86	1.57
KNeighbor(n_neighbors=2)	9.85	4.44	92.13	0.19	62.33	2.9
KNeighbor(n_neighbors=5)	9.55	3.48	76.10	0.2	58.54	2.44

Table of Results—Training Data						
Training MSE	Apple	Nike	Nvidia	Pfizer Inc.	Goldman Sachs	Starbucks Corporation

Table of Results—Training Data						
Random forest(Min_samples_leaf=1)	159.44	73.25	556.96	4.86	1426	13.30
Random forest (min_samples_leaf=5)	192.91	73.17	556.88	4.93	1507.68	14.66
Decision Tree (Max Depth = 5)	7.08	3.68	37.47	0.19	49.19	0.84
Decision Tree (Max depth=20)	0	0	0	0	0	0
Neural Network(alpha=0.0001)	7.07	4.29	38.76	0.17	45.09	1.66
Neural Network(alpha=1`)	7.29	4.3	39.8	0.17	36.51	1.51
Linear regression	3.87	2.68	32.22	0.08	16.85	0.73
KNeighbor(n_neighbors=2)	3.87	2.68	32.22	0.08	16.05	0.73
KNeighbor(n_neighbors=5)	3.87	2.68	32.22	0.08	16.05	0.73

	Nvidia	Apple	Nike
$1000	13354.06	3674.49	1744.79
$10,000	22287.42	15899.74	10744.79
$100,000	112287.42	107335	100744.79

Conclusion

This research paper explored the use of AI models such as Neural Networks, Random Forests, Decision Trees, Linear Regression, and K-Nearest Neighbors to predict Tesla stock prices using historical data. By analyzing key variables such as opening and closing prices and combining the model predictions through a weighted average method, the approach achieved more accurate and stable predictions. Mean Squared Error (MSE) was used to evaluate the performance, and techniques like regularization and careful data splitting helped prevent overfitting and improve generalization to unseen data. The results demonstrate that AI-based models can effectively identify patterns in stock market data and support data-driven investment decisions.

What would you like to do in the future with your paper?

In the future, I would like to make a model that incorporates other factors such as politics, news, and volatility of the stock market, and also make use of a portfolio, extending my dataset beyond Tesla, that gives suggestions based on the price to investigate what would happen. I

would also like to explore real-time predictions to see how well my model performs in live market conditions.

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The code used is :
https://colab.research.google.com/drive/10Nmvv2umrSN-fJqtpbW7S6whV-_3pZZu

The Attitude of the Contemporary Audience Towards the Traditional Music and Non-traditional Music By Yiru Lucy Wang

Introduction

Many argue that traditional Chinese music is an ancient art form. Yet it continues to circulate in new ways influencing contemporary life. At the same time, contemporary artists redefine the art form with modern meaning. From the Ming dynasty (1368-1644), Chinese people have communicated and exchanged culturations with Asian and African countries. Chinese music was later brought to the world through European missionaries during the Qing Dynasty (1622-1722), to be recognized globally. The Qing Dynasty was the golden age for Chinese traditional music, but as Chinese people start to value western forms of music, they gradually play less of the original form of Chinese traditional music (Lin,2023).

Most of these ancient musical forms are no longer directly accessible to the public today. They have been replaced by popular songs largely originating from European style. The Chinese government has made efforts to preserve some ancient music as cultural heritage to protect a disappearing culture. Contemporary artists, however, have transformed traditional music by combining western elements with what is considered 'traditional music' by the people. It continues to rank as one of the most popular categories in music streaming apps. Appearing as'Gufeng Special' or 'Guofeng Special', Chinese contemporary audiences have a positive attitude and even excitement towards reimagined traditional music. Most popular musical forms fall somewhere in the middle between traditional music and western music.

This paper explores the boundary between traditional and non-traditional music, focusing on genres that cross this boundary, such as jazz and Chinese minority ethnic music, as well as the effects of journalism and social media on this process. This paper's conclusions merge insights from interviews with music professionals, as well as social media commentary from Zhihu, like Quora, an app that allows users to pose questions, provide answers, and engage in discussions on a wide range of topics. This method bridges the gap between professional, or elite understandings of musical composition and production with consumer perspectives.

This essay aims at analyzing Chinese perspectives on the boundary between traditional and non-traditional music through the lenses of music-as-technology and music-as-emotionally-evocative-art. This division encompasses both professional producers and general audiences, whose differing perspectives are largely shaped by cultural influences, educational backgrounds, and national affiliations or familiarities. The critical distinction

between these categories places traditional music as a representation of emotional expression, while the evolution of non-traditional music depends on the technical mode of presentation.

Methodology

I began my research with an extensive review of literary materials published in the west to trace how scholars have positioned or interpreted Chinese music in global enthnomusicology. Also, I consulted China National Knowledge Infrastructure (CNKI) which contains the majority of Chinese academic publications, in order to understand how Chinese scholars analyze domestic musical traditions, what angles of inquiry they inspect from, and how they conceive of the less developed idea of ethnomusicology.

I conducted three interviews with Chinese music scholars, each lasting at least 30 minutes, with a mean of about 50 minutes. One interview was with a professor teaching at Zhejiang Conservatory of Music, who majored as composer; another interviewee was the guzheng performer from the Jade Guzheng Ensemble, and a well-known music producer who also manages some music television programs. Contact with these professionals was successful due to personal connections to a music teacher. For all the interviews, I used the same set of questions, phrased differently to account for their specialized knowledge on the topic I was exploring. While they were talking, I incorporated their perspective, and asked follow up questions triggered by their understanding. Among the three, two were conducted face to face, while the last one was finished over the phone. I obtained permission to record and review the interviews again afterwards.

I selected the social media platform, Zhihu, to collect comments and perspectives from general consumers. While some arguments published on other social media sites like TikTok and Weibo are likely to be deleted or controlled for the sensitive information included, Zhihu offers a platform more conducive to building discussion with authentic, unfiltered ideas. I used keyword searches using terms such as,‘Chinese and western music’ or ‘traditional music’ to see how many people were debating the topics on the popular discussion boards. Though users are anonymous and most of the time we don’t know whether they are general audience or professional musicians, I take in the perspectives of all of them and collect the ones that stood out to me, with representative voices or a distinctive point of view.

Chinese Traditional Music

The major appearance of Chinese awareness of western music appears as an early generation of students studying abroad. During the Minguo period(1912-1944), Chinese students who had studied abroad during the Qing dynasty returned home, bringing foreign melodies that began to influence Chinese music. A famous example is Songbie, an example of Xuetangyuege, the music of the study hall. Its melody is adapted from an American hymn tune ‘Dreaming of Home and Mother (Lau, 2025).

In the early twentieth century, during the May Fourth Period, an anti-imperialist, cultural and political movement in China, the Xuetengyuege was just becoming popular. Guangqi Wang,

the music reformer of the May Fourth era, stated that Chinese music should embody the nation's spirit of progress, that it should be recognized by the international community, and it should serve three functions: represent ethnic identity, promote national virtues, and express national sentiments. He proposed three methods to accomplish these aims: collect ancient music, preserve folk music and traditions, and arrange pieces that emphasize ethnicity, morality, and emotion. Another musician at the time, Youmei Xiao, believed the essence of music is not simply in its formal structure, but is deeply rooted in its meaning and purpose. These early musicians revealed their expectations for the development of Chinese traditional music. This projection also signaled the oncoming global expansion of Chinese music (Wang, 2022).

The classification of traditional music, however, has been under debate. In Wang Yaohua's Introduction to Chinese Traditional music in 1990, mainstream scholarship defined traditional music in three categories: folk music (minjian yinyue) circulated among and performed by ordinary villagers; courtly elegant music (gongting yayue) adapted and arranged by palace musicians from folk music; and literati music, dominated by Guqin (One of the oldest Chinese plucked instruments with seven strings, no movable frets, no bridge, and written in jianzipu notation, 2025) tradition and by poetic songs. However, scholars have been debating these classifications. Either they cannot fully cover every specific style or they over-simplify musical styles. Still, scholars commonly understand traditional music to be the work created by Chinese musicians using indigenous techniques to show distinctive national identity. The music modeled on European style introduced after Qing clearly excluded these necessary components (Song & Song, 2025).

Traditional music has not been preserved or governmentally codified and some musical forms of Chinese traditional music are no longer directly accessible. Since before western notation was imported to China, Chinese traditional music is improvisational. While some Chinese traditional music has been preserved as intangible cultural heritage by the government, and others have transformed into new presentations, becoming a unique cultural phenomenon, much musical traditions from the ancient times have been lost.

Traditional music, popularized as folk music in the past, particularly in the form of Xiqu and often translated as Chinese opera, has been lost gradually through the centuries. While it has partially been passed down by westernized forms or pop music blending those traditional elements, official organizations assigned by the government have been protected. Most are stored as historical archives, prepared for the latter generation to review, with recent music shown in videos and more ancient music documented as scores.

Ethnic diversity is an essential feature of Chinese traditional music as it encompasses vernacular music traditions derived from numerous minority groups. While some have already been lost, some tribal music has been performed currently as one of the country's tourism programs. Since the domestic tourism economy has increased these years by propaganda, experiencing tribal music has become one activity tourists.

With traditional music becoming part of tourism campaigns or a program of a political assignment, the disadvantage of such a form is the criticism that it has lost its sincerity. Firstly,

the location of the music being performed is a part of defining the kind of that music. Likewise, performers would ponder using different strategies and expressions while acknowledging the location of performing and the audiences listening. Secondly, the administration would likely produce conformity and increase political flavor but discourages individuality (Zhang, 2016).

Less divisive than the dispute held between the music professionals during the May Fourth era, even most music professionals share optimism for Chinese traditional music influenced by western music culture. In this way, the tradition is actively conserved and would add to the resource base to be used as an element in the future. Second, popularizing these forms could enhance the cultural identity shared by the masses. Minnan music, for example,is a music culture originated from Fujian, China that, with the support of the government perhaps, is popular for its memorable beats despite its unfamiliar language. Most importantly, the fading culture arouses the sense of cultural identity to the public which attracts more people to Minnan culture.

Westernized Chinese traditional music

Today, westernized forms of traditional Chinese music are more common. Audience comparisons between Chinese music and western music are hegemonic, though popular topics. People set mainstream music or culture as the standard, and make judgements on other types of music in terms of this 'biased' baseline (Yang, 2025).

For example, in recent music channels like 'Asia new voice", performances have sparked a dispute over music development in China and other countries. Some said, among contemporary world music, Chinese music could only be an element that adheres to other music styles and itself is not eligible to be an independent genre. Guofeng Rock and Guofeng Rap are all styles of western countries. Those critics even reasoned that the Chinese music system does not even have a harmony system so there could not have such a term as Chinese contemporary music (Xiaohan, 2022).

The music industry is now flooded with commoners, as the cost of producing and publishing a piece of music is low enough that most people are capable of gaining popularity. Consequently, the low barriers to music production made things really tough for professional singers signed to music companies. Musical themes have also gradually evolved to love stories rather than the martial arts. Chinese traditional music has then become the alternative music, and sometimes adds color for popular music. Although Gufeng music popularized, it is basically adding the sound of Xiqu and several Chinese traditional instruments, not creating systematic change. The capable musicians were already old and out.

With the introduction of western music, music in China has undergone a significant change. Higher numbers of Chinese students choose to learn Western musical forms and traditions over traditional Chinese forms. This shift is the result, in part, of a more comprehensive, formal system of musical education. Educators have established these education structures over four hundred years, a stark contrast to China's music education development of

less than a hundred years, and the systematic application of traditional instruments education with a history of about 30 years.

Starting from the Western Zhou Dynasty (1046-771BCE), China began to implement the ritual and music system, which is a means of governance to consolidate the social hierarchy by regulations on the type of the scale of music performance people from different social statuses could enjoy. Thus, it also provides a foundation for the professionalization of music and the development of music theory systems. The court musicians developed the concept of tonality in music theory, and some (Zhihu, 2021) said the twelve-tone equal temperament might have been transmitted to Europe through East-West cultural exchanges. Two thousand years ago, Chinese music theory had already been shaped and people had enough theory basis to create sophisticated works, but those have been lost; many folk songs and the craftsmanship of the instruments like the chime bell have been lost over time.

The Chinese music education system is still in progress. However, noting that western and Chinese education systems are compared by length and logistics, specifically, the harmony theory, people have a divisive perspective on concerning music as art or as technology (Xu, 2014). Moreover, differences in education contribute to the development of distinctive music styles. For example, western classical music might be compared to a long table with all kinds of dishes, representing varied musical forms and traditions. For many Chinese listeners who have not received specialized musical education, nor exposure to diverse musical forms, such a range of "dishes (Nemo, 2020)", or musical forms may be unappealing. This is another underlying reason why music with direct stimuli will have a greater impression overall on the Chinese audience.

As one zither performer stated, people often consider Western instruments like a piano, as elite. They might believe, for example, a piano concerto performed in a luxurious hall with delicate sound evokes the utmost value and sophistication. In contrast, traditional Chinese instruments, such as the erhu, performed on city streets would not be associated with the same prestige. The surrounding of where Chinese or western music is usually played has shaped the overall perception of the characteristics of those two kinds of music.

How difference is understood at professional level

If a difference has to be recognized, it might be the culture of each music. In the ethnomusicology study in China, many music types indeed derive from various aesthetics, different living habits, and the performers' perspectives. While talking of arts, the scientific analysis of the machines or instruments should not be taken into account. Thirdly, Confucianism and Taoism shape the aesthetic of Chinese traditional music. It puts stress on that human emotion naturally betrays; it emphasizes the art of heart. In other words, it's not constructing music with a scientific approach, but through the structure of human emotion needs. Thus, people say music is the words of the heart. For example, in the traditional music of China, more than 90% of the titles are poetic descriptions of nature. Poetic imagery is a central aspect of performing, where the space left for imagination is what distinguishes it from other music (Zhihu, 2020).

There are some critics arguing that Chinese music is inferior to westernized music (Zishu, 2024). However, from the interviews with composer Shi, performer Zhang, and a music producer, all strongly agreed that this comment is largely the result of social media and the deliberate discourse brought out by journalists. As Chinese people are more open and connected to the west, a comparison with western culture would spark a discussion by the audiences, such as the music shows “Asia New Voice" or “singer”. These music programs differentiate themselves from others by setting a singing competition among the Chinese singers and foreign singers. Following the program, discussions (Zhihu, 2024) about whether Chinese music has fallen behind or that Chinese people prioritize idol worship over genuine musical appreciation are ubiquitous. Most debates focus on entertainment gossip or vocal techniques, rather than engaging with the formal music theory system taught in the textbooks. Thus, I argue that this tendency could be attributed to the mentality “curiosity or worship of the foreign things” where Chinese people wander between national pride and a sense of uncertainty towards extraneous cultural influences. Ultimately, we must confront this fundamental question whether we should make this comparison between the two music traditions or how should the comparison be justly made?

A valid comparison between two objects requires a full understanding of both sides, as suggested by Mieczyslaw Kolinski. He states that when ethnomusicologists are analyzing music from another nation, they tend to evaluate that alien culture with the standards of their native music culture. This bias influences how critics assess foreign music (Kolinski, 1957).

Furthermore, each type of music is suited to particular tastes that caters to particular groups within the larger audience. Music itself is inclusive. Classical music and Chinese music are good examples. Classical music is not often seen or known by most Chinese. Some pointed out in the social platform, at most times, what we deemed euphonious or not is indeed simple or complex. In fact, complicated matters are liked by a small portion of people. In this case, one commenter said that people inherently tended to like either the complicated, the classics, or the straightforward, Chinese popular music. Likewise, the former experience corresponds to the taste of a tea, with layered smell, and the latter is like coke, the soda with direct stimuli to our senses (Zhou, 2019).

The value comparison between two categories of music cannot be made in the first place. Music, as art, is abstract. For example, the reason why the Fountain by Marcel Duchamp or John Cage’s Four minutes, thirty-three seconds are famous and great is that they propose new ideas. It turns the core of arts from the concrete to the idea and scenario behind it, which completely overturn the definition of arts. The four minutes, thirty-three seconds proposes that new idea of aleatory music that emphasizes the role of environment sounds and the sound of silences, again extending people’s acknowledgment to the music essence. As a result, it’s inappropriate to suggest superiority or how much the artistic value that one piece contained (Nemo, 2020).

Beyond that, an innate behavior could have led to a different habit of listening to music. Upon my own performing experience and on account of all other performers, Chinese music has its distinguishable character. Firstly, Chinese traditional music does not have a framed beat while

Chinese pop music has a definite beat. According to statistical demonstration, a lot more Chinese music is in four four beats than western music. The zither instrument, for example, is played at varying speeds and with dynamic intensity to convey emotion. A technique like string-rubbing is often played freely, without adhering to a strict beat.

The general public and even professional musicians all tend to listen to popular music. In comparison, the influence of traditional music has decreased notably, and the complexity or the long time required to reach the core of traditional music discourages the young from practicing those forms. On the other hand, the increasing diversity of cultures is diverting people's attention away from their unique and attractive traditional music.

Chinese contemporary audiences generally think positively towards westernized music and believe it is beneficial for societal development, regarding it as a sign of progress rather than conservatism. As time and global circumstances change, music maintains cultural value as long as it possesses ethnic characteristics and national sentiment. In other words, people no longer rigidly define traditional music by its form or instrumentation, believing its traditional cultural value remains preserved. Thus, the general audience is more inclined to classify traditional music in terms of the feeling or art rather than analyzing the scales.

On the other hand, this renovation of the style also benefits and is inevitable to the development of the history of music itself, as according to a Chinese zither performer, many pioneers in the past have already claimed a transcendent achievement so that people from the latter generations should perform the music in a new form. Consequently, guofeng music, which is now very popular, is categorized in the pop music system instead of the continuation of traditional music. In fact, the music that passed down just as its original form is called intangible culture inheritage. Those may not even have the recordings but a few scores discovered.

Another industry professional, who also upholds adapting old traditional pieces with new styles, said that music inherently should be changed and renovated, to serve different generations. When someone uses a new composition for an original piece, it revives the song with a new presentation. This is an important step for transmitting music.

The zither performer said that in zither pieces, piano depends on the zither's melody; it is harmonizing for the zither, rather than taking over the melody or changing the tone of the zither piece. Thus, combining styles in this way would add thickness to the zither solo with a diversified color, and a wetter harmony.

In respect to formality (Shi, 2023) of Chinese traditional music, many are retained in the Chinese popular music that the continuity of Chinese national aesthetic psychology inherited through thousands of years has led to the preservation of traditional composition in contemporary structures. Therefore, the melodic techniques, such as "fish biting tail" (where the end of one phrase and the beginning of the next share the same note), interlocking (a chain-like overlapping of short melodic motifs), ornamentation or reduction, used in the popular music endow the music with a distinctive Chinese national style that are readily accepted and disseminated among the general public. Admittedly, the author also points out that solely adhering to the tradition could limit the momentum or creativity.

How Difference is understood at the general listener level.

While Chinese traditional music and western music have similarity in their origins, Chinese music has greater concentration on self expression and conveyance of personal thoughts and western music has more of an inclination towards narrating myths or religious rituals. The distinction grew over time, forming a varied cultural music. Thus, Chinese traditional music emphasizes the melody while western music focuses on the harmony. Later in its development, western music also places more emphasis on beats and rhythm (Zhihu, 2021).

Other than the perspectives of the professions, I tried to inspect the mind of the audience through consumption of popular music at the time. Why is popular music popular? As we mentioned, popular music is mostly music with simple but memorable beats. Together with the trait that popular music has a narrower range of notes, it is most suitable for the common audiences to sing; I also mentioned that singing is the greatest representative of music accessed by people. In essence, the reason why pop music is popular is that it is easy to understand as it is close to people's daily life and could stir sympathy between many listeners. The piece conveys the true feeling of the author himself, as the listeners feel the same atmosphere and the same sound of their own minds. Consequently, popular music makes art a way of life and makes people's life a work of art.

Notably, most music displayed to the public in China is conveyed by a singer. Nearly all music programs centered around singing skills, like "Super-Vocal", "the Voice of China", "Sing My Song", etc. because singing is more applicable among the public that doesn't require the starting process to learn an instrument. Vocals are therefore the most widespread and popular form of music spreading on social media that represents a great part of musical understanding of the Chinese. It's an art of life that enables people to express their emotions and easily resonate with others.

Curiosity is a characteristic of human minds. Popular music, as a means of entertainment basically to satisfy the commercial interests, must establish on the ground of fitting a representative social mind and adapting the public. Therefore, the music to be accepted should have a part that's familiar to the audiences and a part that's new and exciting to the audience. It also illustrates that pop music in China would not likely be supplanted entirely by the extraneous kind.

As Chinese people are not paying attention to beats from history, now people prefer simple beats to pop music, which occupies a larger market than western music. Therefore, it's not that people are selected to not to listen to classics, but no such sources are explored to them for a fairly long time. For two, language is restricting the kind of music the people of the nation are listening to. There is, for example, a great population speaking a Latin-derived language, but do those music cultures have a large influence over the world? Thus, whether we like their music depends on our understanding of their culture and their language. Language is a crucial aspect to the spirit of music.

Zhuyu has been a popular song recently. It is created in Dorian and composed under the background of A Dream of the Red Mansion. The major style, varied greatly from the traditional Chinese music, and the connection of the Chinese feeling as it has to the Chinese drama contributes to its popularity.

Additional evidence of Chinese audiences liking westernized music is the rise of a category on the music streaming apps, labeled “Gufeng Special” or “Guofeng Special”. Both are contemporary and modern genres of Chinese traditional music. Gufeng music creates the romanticized sounds that feel old which is like a fantasy novel set in a fictionalized ancient world, telling poetries or epic stories from the past; Guofeng music, on the contrary, directly mixes traditional music elements with the modern genres like pop, hip-hop, and Electric Dance Music. It refers to the types of music that convey a Chinese feeling through many Chinese signals or elements. However, this is not a traditional music passed down from thousands of years before; rather, it represents the common combination of Chinese traditional music and western electronic music. This new pop music keeps the iconic idea of conventional culture and satisfies the audience's aesthetic needs. They are more inclined to accept this type of music which in one part keeps the familiar way and in the other part attracts novel transitions.

Any music that could embody the characteristics of the times or the emotion of contemporary Chinese audiences could be defined as our country’s traditional music. The traditional music, in the modern context, is fundamentally concerning spiritual inheritance, enabling it to inherently evolve through the musicians’ creativity and integration with the contemporary developments or interests. This view was upholded and responded to by Tianhua Liu, a pioneer composer and educator in early 20th-century China, and Yinliu Yang, who is considered the founding father of modern musicology in China.

According to a critic, some Chinese are superstitious in western music and idolize it as a textbook to study, but they forget that music is a means of emotional expression. They should notice that all music theories, performing techniques, singing capabilities which they learned, should be served for music itself. Those who attach to the minor and abdicate the main, do not get the idea of music with their whole life studying it.

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Evaluation of Concentrated Solar Power Systems with a Focus on Power Tower Molten Salt System By Gaeun Choi

Abstract

As global energy systems shift toward renewable energy systems, a majority of existing research on Concentrated Solar Power (CSP) has focused on systems without thermal energy storage (TES). However, it is possible that some technical or economic challenges might make it difficult to integrate TES. This study therefore evaluates how CSP tower systems with TES perform across five high-DNI locations in the United States-Brazoria, Bastrop, and Grimes Counties in Texas, Boulder City in Nevada, and Calexico in California-and how their energy output correlates with seasonal changes in Direct Normal Irradiance (DNI) and temperatures. This research was conducted using the System Advisor Model (SAM) to simulate annual and monthly energy generation, capacity factors, and environmental conditions of an hypothetical Power Tower Molten Salt System. The simulation disclosed that DNI is the most significant contributor to the energy output: Boulder City and Calexico outperformed the Texas sites due to stable, year-round irradiance. The findings suggest that in the absence of TES, CSP systems depend more on the consistency and intensity of DNI. This research contributes to the current field by offering practical insights for implementing CSP in environments with limited financial budget and technical challenges. Without the TES, the site selection of CSP becomes extremely important to generate the maximum energy output and that it is still possible to generate a substantial amount of energy.

Key Words Concentrated Solar Power, Direct Normal Irradiance, Power Tower Molten Salt System.

Introduction

Problem Statement

Solar power has emerged as one of the most promising renewable technologies in the transition toward cleaner energy systems due to its abundance and scalability. Among utility-scale solar technologies, Concentrated Solar Power (CSP) stands out for its ability to generate electricity by converting sunlight into thermal energy using mirrors and a central receiver. Unlike photovoltaic (PV) systems that generate electricity directly from sunlight, CSP

systems rely on Direct Normal Irradiance (DNI) and perform effectively in sun-rich environments. [1]

As the demand for renewable energy integration into the grid increases, CSP systems can play a larger role in providing reliable electricity. However, most existing research focuses on CSP systems equipped with Thermal Energy Storage (TES) and overlooks the performance of CSP systems without storage. While storage is considered essential for dispatchability, analyzing the performance of CSP systems without TES is critical to understanding CSP's potential role in regions with variable solar resources or lower initial investment capacity. [1]

Objective

The study aims to provide insight into the following research question: How does the monthly and annual energy generation of CSP systems without thermal energy storage vary across regions with high solar irradiance, and how does this generation correlate with seasonal changes in DNI and temperature?

It is hypothesized that CSP systems without thermal energy storage will demonstrate strong seasonal variation output, with higher generation in months and higher DNI values. Locations with consistently high DNI will exhibit higher annual production and more reliable generation compared to regions with greater seasonal variation in solar irradiance.
The results of this study will provide insight into how CSP systems without thermal energy storage behave in real-world conditions, especially in high-DNI regions of the United States. This insight will be essential for deployment planning in areas without access to storage infrastructure.

Background

Solar Irradiance

Solar Irradiance refers to the power per unit area received from the Sun through electromagnetic radiation, typically measured in watts per square meter ($W/m^{\wedge}2$). Understanding the different components of solar irradiance is essential for designing and optimizing solar energy systems. [2]
DNI is when radiation from the Sun falls on a plane surface at 90 degrees to the beam. On a clear day, up to 95 percent of the energy received at the Earth's surface is DNI, but it is close to zero on a cloudy day. DNI is essential to solar energy technologies that rely on focusing the light from the Sun, such as CSP systems and Concentrating PV Systems. [2]

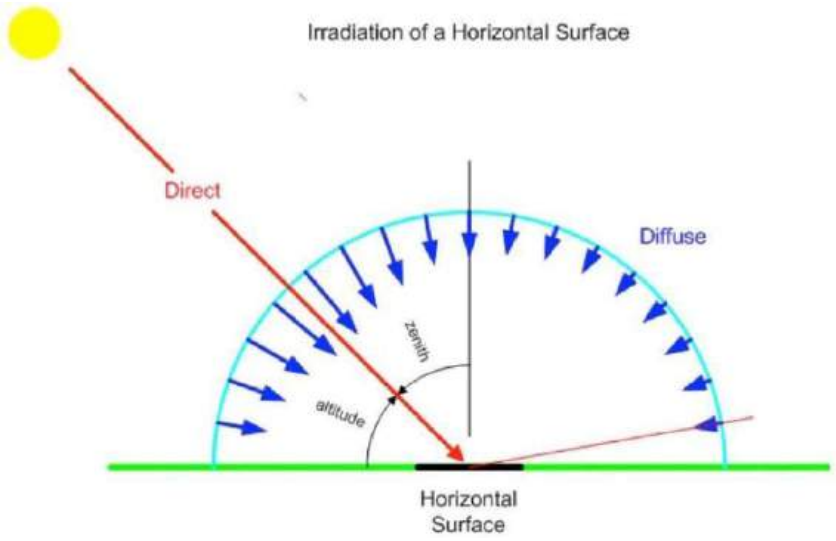


Figure 1. Illustration of solar irradiation on a horizontal surface, showing the two main components of solar radiation: direct and diffuse. [3]

Diffuse Horizontal Irradiance (DHI) is the portion of solar radiation that reaches the Earth indirectly. DHI consists of solar radiation that molecules, aerosols, and clouds in the atmosphere have scattered. Figure 8 shows various contributions to DHI, including isotropic scattering, circumsolar radiation, horizon brightening, and reflected radiation from the ground, also known as albedo. DHI is generally scattered by the atmosphere due to water vapor, aerosols, and clouds
reflecting and absorbing solar radiation, diffusing it throughout the atmosphere. On a clear day, only 5% of the total solar radiation received is DHI, but almost 100% on a cloudy day. 5 DHI is measured with a horizontal pyrometer mounted on a Sun tracker and continuously shaded from the direct Sun beam throughout the day. [4]

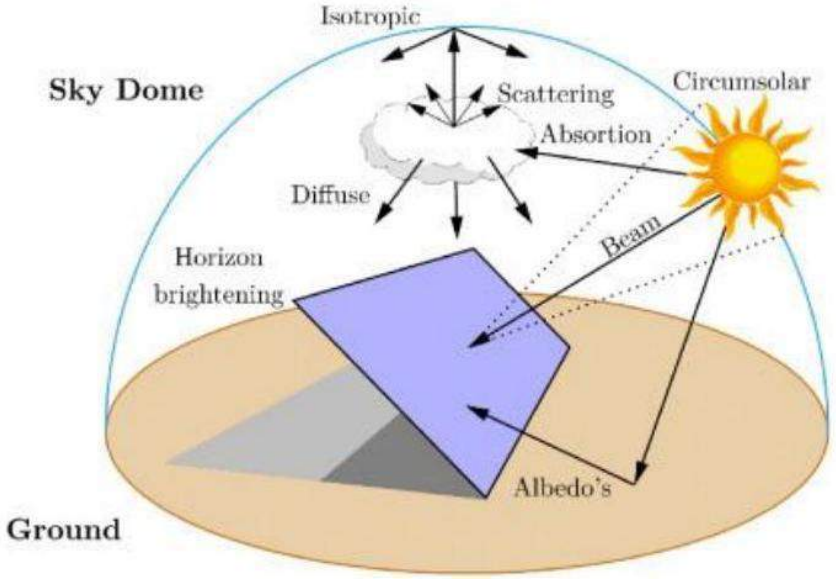


Figure 2. Illustration of the components contributing to DHI. [6]

Global Horizontal Irradiation (GHI) combines diffuse and direct components that reach the same surface. However, GHI is not simply DHI + DNI. GHI is the total solar radiation received per unit area on a horizontal surface. It comprises two main components: DNI, which comes in a straight line from the Sun and is projected onto the horizontal surface based on the cosine of the solar zenith angle (θ), and DHI, which is sunlight scattered by the atmosphere. The equation gives the relationship: $GHI = DNI \times cos(\theta) + DHI$.[7]

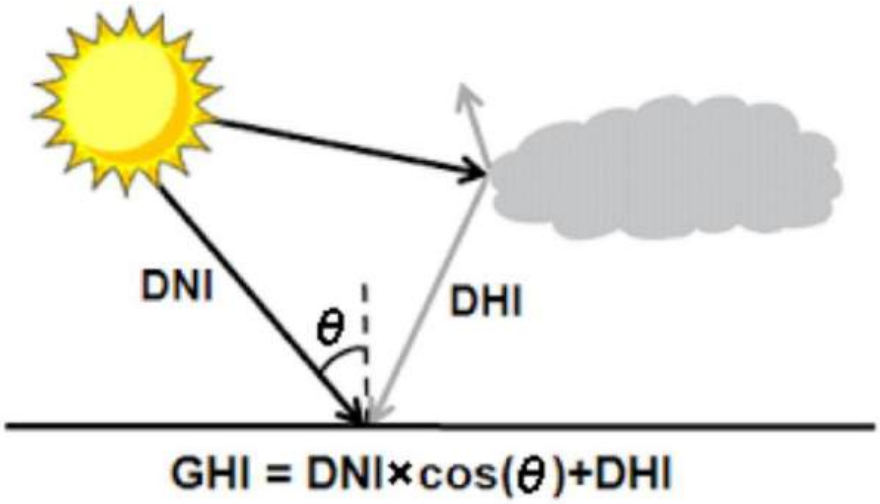


Figure 3. Diagram illustrating the components of GHI. [7]

Solar Energy Technologies

Solar energy is energy from the Sun that is converted into thermal or electrical energy. The sun emits solar radiation (electromagnetic radiation) through light. Solar energy technology captures this radiation and turns it into proper forms of energy. [8] The amount of solar radiation that reaches one spot varies by location and time due to the rotation of Earth. For example, the Earth's surface receives most of the possible radiation when the sun's rays are vertical. The two main types of solar energy are solar photovoltaic (PV) and solar thermal energy. [9]

PV System

PV technology converts solar radiation directly into electrical energy. A single PV is known as a cell that contains a semiconductor. When the semiconductor absorbs sunlight, it transfers photons into electrons. These electrons will flow through the semiconductor as an electric current. Because a cell generates Direct Current (DC), the inverter converts DC to Alternating Current (AC) since nearly all electricity is supplied as AC. [10] The AC will flow into the power grid, which allows appliances in households. A meter monitors the energy flow between the house and the utility grid, allowing excess energy to be exported to the grid. [11]

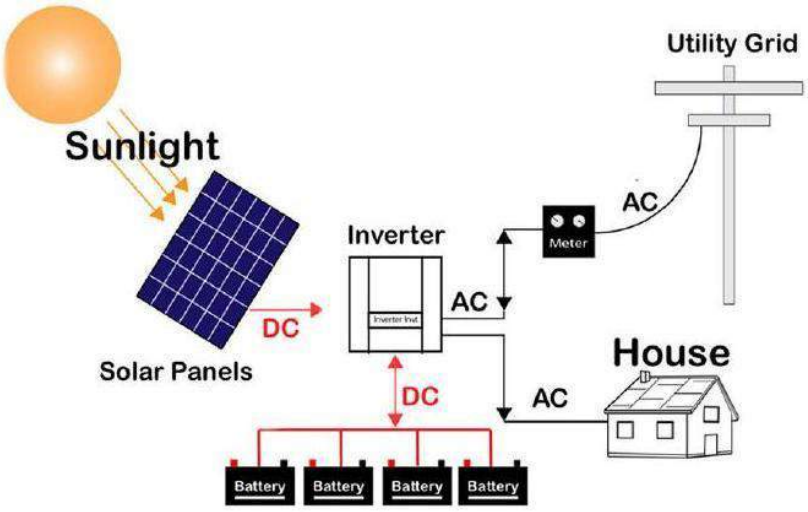


Figure 4. Diagram illustrating PV solar power system. [12]

CSP System

While PV energy converts sunlight directly into electricity, solar thermal energy uses sunlight to generate heat. The heat can be directly utilized without converting it to electricity in systems such as solar air heating systems, solar process heat systems, and solar water heating systems. However, the most common solar thermal technology is a CSP system that uses heat to generate steam, which drives turbines to generate electricity. [13] This study will only focus on solar thermal energy, especially the CSP system.

Every CSP system uses mirrors to reflect and concentrate sunlight onto a receiver. Heliostats are mirrors that reflect sunlight toward the receiver at the tower's top. In the receiver, the concentrated solar energy heats a fluid to extremely high temperatures. The fluid produced high-pressure steam that caused turbine blades to spin. As the steam drives the turbine, thermal energy is converted to mechanical energy. A generator converts mechanical energy into electricity. The system can supply power to the grid, provide heat to a steam generator for industrial processes, and deliver energy to a fuel synthesis reactor to produce renewable fuel. The remaining steam is cooled and recycled back into the system. [14]

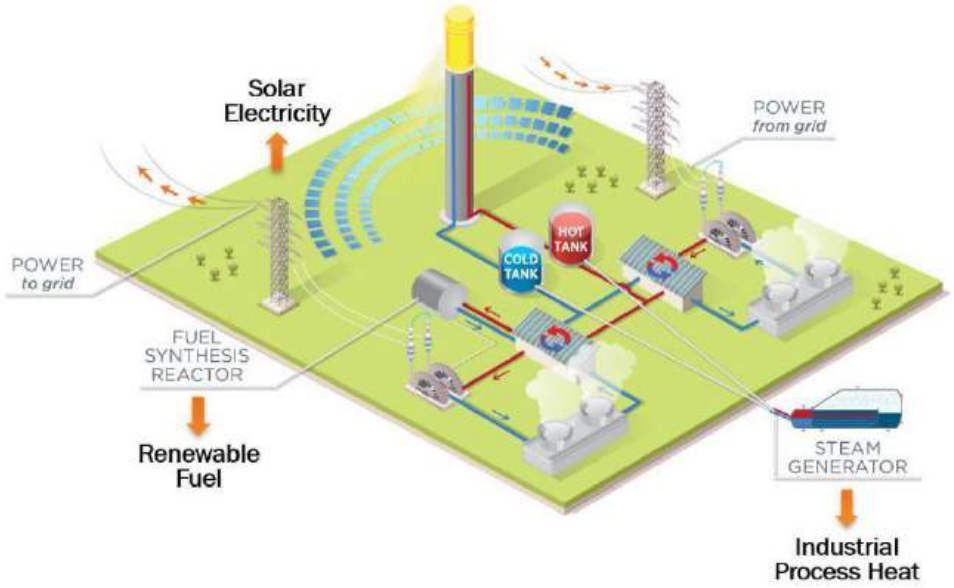


Figure 5. Diagram of a CSP system with thermal energy storage and multiple applications. [14]

Power Tower

Power Tower utilizes a field of heliostats to track the Sun and reflect sunlight to a central receiver located on top of the tower. The sunlight can be concentrated as much as 1500 times. The receiver contains a heat-transfer fluid (often molten salt) heated to very high temperatures. This thermal energy produces steam that drives a turbine and generates electricity. The high operating temperature allows for high efficiency. However, Power Tower requires a high initial capital cost, a large land area, and flat terrain. [15]

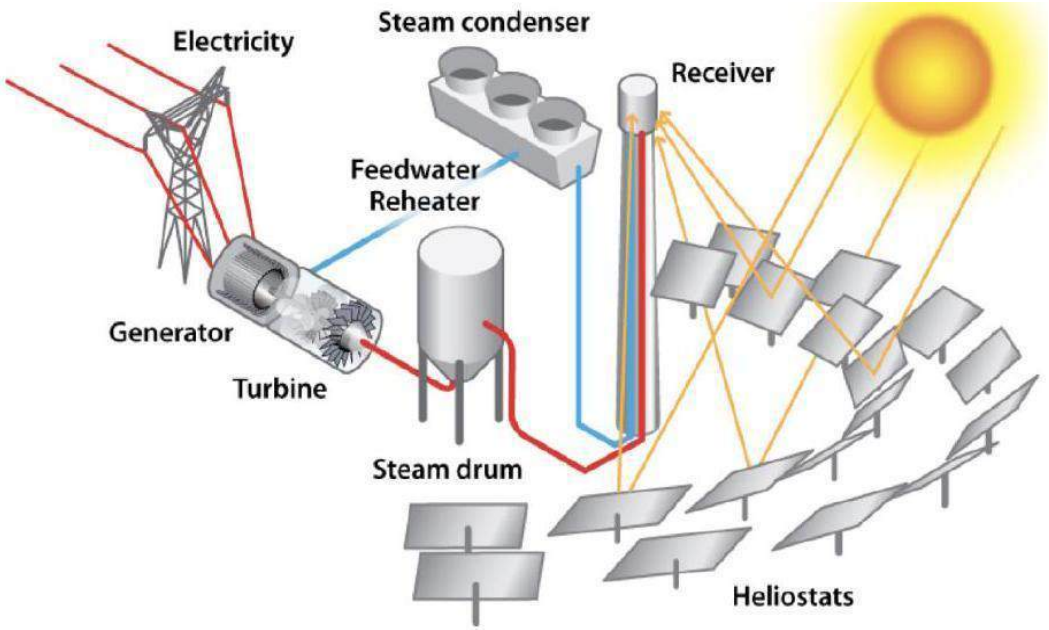


Figure 6. Illustration of numerous heliostats that focus sunlight onto a receiver at the top of a tower. [16]

Parabolic Trough

The Parabolic Trough System uses long, curved mirrors to focus sunlight onto a receiver tube that runs along the focal line of the trough. The collector tilts with the Sun to keep the sunlight focused on the receiver. The Earth rotates throughout the day. Because of its parabolic shape, a trough can focus the sunlight from 30 to 100 times its original intensity on the receiver pipe. Parabolic troughs reflect and concentrate sunlight onto a receiver. A fluid in the receiver absorbs the solar energy and is transported to a heat exchanger. The heat is then used to produce steam, which drives a turbine connected to a generator to produce electricity. Excess thermal energy can be stored in thermal storage tanks for later use. After powering the turbine, the steam is cooled and condensed back into water in the steam condenser. [17]

While it is a commercially proven technology, it has lower thermal energy than power towers, resulting in lower efficiency. It also requires direct sunlight, which is less efficient in cloudy areas. The Solana Generating Station in Arizona began operating in 2013. It is a 280 MW parabolic trough plant with 6 hours of molten salt thermal storage, allowing it to provide power even after sunset. It was one of the first large-scale CSP plants in the U.S. to incorporate storage. [18].

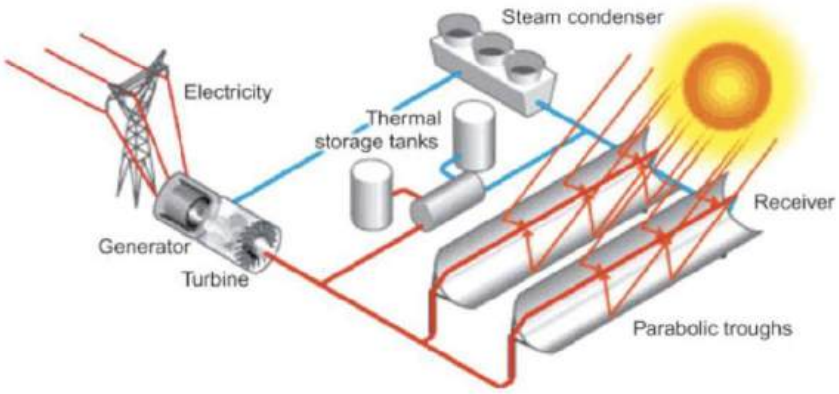


Figure 7. Illustration of a Parabolic Trough CSP system [17]

Commercial CSP Power Plants

Noor Complex, Morocco

Located near Ouarzazate in Morocco, the Noor Complex is the world's largest CSP facility, with an installed capacity of approximately $1,117MW$. It is designed to supply solar electricity to around 650,000 residents from sunrise to three hours after sunset. The complex comprises parabolic trough and solar power tower technologies and features thermal energy storage systems enabling power generation during non-sunny periods. [24]

Phase I of the project began in 2013 with the construction of Noor I, a 160 MW CSP plant using parabolic trough technology. Phase II added Noor II (200 MW) and Noor III (150 MW), which was completed in 2018. While Noor I and Noor II utilize mobile 12-meter-tall

parabolic mirrors, Noor III introduces a solar tower configuration. A fourth phase is expected to implement PV technology. [24]



Figure 10. Aerial view of the Noor III solar power tower plant, part of the Noor Complex in Ouarzazate, Morocco. [24]

Mojave Solar Project, USA

The Mojave Solar Project is a CSP facility in the Mojave Desert in California. The project is a 250 MW solar electric generating facility consisting of well-established parabolic trough technology to solar heat a heat transfer fluid (HTF). This heated HTF generates steam in solar steam generators, which expands through a steam turbine generator to produce electrical power from the twin, each feeding a $125 - MW$ power island. The layout features long rows of mirrored parabolic collectors that track the sun to maximize energy capture throughout the day. The Mojave Solar Project is projected to have an operational duration spanning multiple decades, providing electricity to over 70,000 homes for $30 - 40$ years. [27]

Due to the geography and meteorology of the Earth, some locations are predisposed to higher degrees of solar irradiance than others, making some locations more profitable options. One of these locations is the Mojave Desert. The Mojave Desert is among the hottest and driest places in the world and is second in incident solar radiation. For these reasons, The Mojave Solar Project was built by Abengoa, a renewable energy construction company. [28]



Figure 12. Aerial view of the Mojave Solar Project located in California, USA. [29]

Methods

This study used SAM to model CSP Tower Molten Salt systems across five geographically diverse locations. The goal was to analyze seasonal and annual energy output, capacity factor, and environmental parameters such as DNI and temperature, all without TES. The modeling and analysis followed a systematic process as described below.

Weather files for each location were obtained from two primary sources. First, the SAM website (https://sam.nrel.gov) was accessed to retrieve general weather data. Then, weather data was downloaded from the Climate.OneBuilding.org platform for specific simulation input. Under the North Central America Region 4, "USA - The United States of America" was selected. Appropriate weather files corresponding to the five locations were downloaded and saved for later use in SAM.

In SAM, a new project was created by selecting "Concentrating Solar Power" and choosing the CSP Tower Molten Salt. Under the "Location and Resource" settings, the downloaded weather data was uploaded to the solar resource library and selected as the weather file for the simulation.

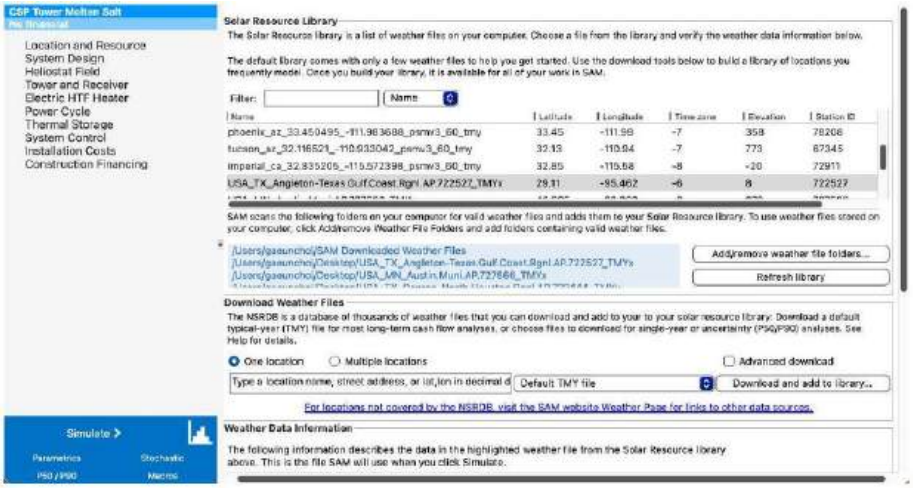


Figure 13. Configuration interface from the SAM for CSP Tower Molten Salt simulations, displaying the selection and management of weather files in the Solar Resource Library.

Under "System Design," the turbine gross output was set to 113 MWe , and the estimated net output at design (nameplate capacity) was automatically set to 100.99 MWe . To ensure that the system operated without storage, both thermal storage hours and solar field storage hours were set to zero.

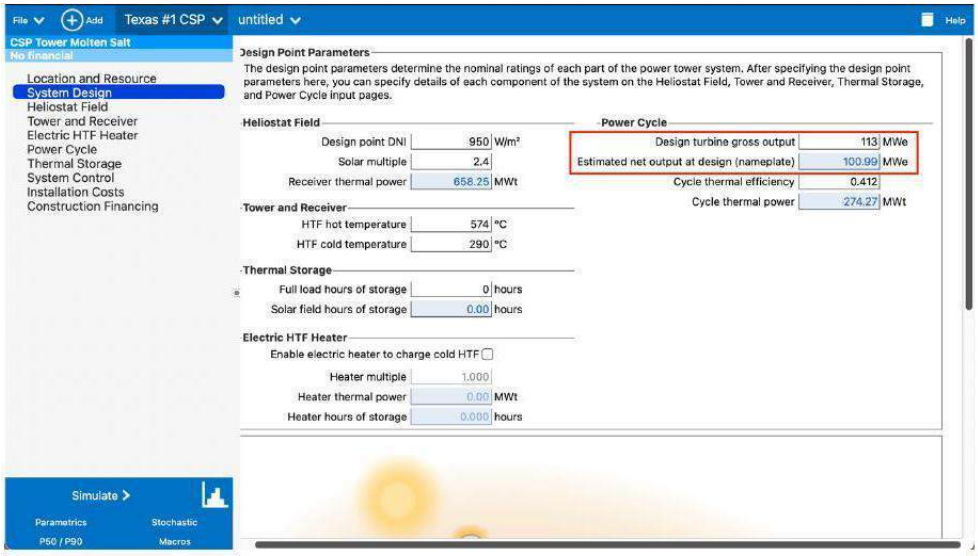


Figure 14. Configuration interface from the SAM for CSP Tower Molten Salt simulations, displaying the System Design Tab.

Next, under the "Heliostat Field" tab, the heliostat layout and tower dimensions were optimized using SAM's built-in optimization tool. All other settings, including "Tower and Receiver," "Electric HTF Heater," "Power Cycle," "Thermal Storage," "System Control," "Installation Cost," and "Construction Financing," were left at their default values. Once the configuration was complete, the simulation was run to generate performance output for each location.

Key output data were extracted from SAM's summary table and data tables. The following values were recorded in an Excel spreadsheet from the summary table: Annual AC Energy (Year 1), Capacity Factor (Year 1), and Annual Water Usage. From the data tables, the following single-value outputs were extracted: Capacity Factor (%), Annual Net Electrical Energy w/ Availability Derate (kWhe), First Year kWh/kW, System Capacity (kWe), Total Land Area (acre), and Tower Height - Out (m).

Hourly data for System Power Generated (kW) were also extracted from the data tables and recorded in a separate Excel spreadsheet. The total monthly energy generation was calculated for each location by summing hourly values and converting them into kilowatt-hours (kWh). These monthly values were then used to compute the total annual and average monthly energy generation for each site.

To supplement the simulation results, two additional datasets were collected externally. First, monthly average Direct Normal Irradiance (DNI) values were obtained from the Global Solar Atlas. The GPS coordinates of each site were searched, and the corresponding report spreadsheets were downloaded. Second, monthly average temperature values ($^{\circ}C$) were gathered by searching each city name on weatherforecast.com.

Multiple visualizations were created to interpret and compare the CSP performance data. For each of the five locations, two graphs were generated:

1. The first line graph shows months on the x -axis and $DNI\left(kWh/m^2\right)$ and average monthly energy (GWh) on the y -axis. The y -axis ranges were set as $0 - 350$ for DNI and $0 - 1000$ for energy.
2. The second line graph shows months on the x -axis and average monthly temperature ($^{\circ}C$) and average monthly energy (GWh) on the y -axis. The temperature range was set from 0 to $40^{\circ}C$, and the energy range remained 0 to 1000 GWh .

Next, we created a summary table of data values from all five locations. In addition to the individual location graphs, three comparative graphs were created to synthesize findings across all five sites:

- A scatter plot was developed with annual energy generation (GWh) on the x-axis (range: $150,000 - 250,000GWh$) and Capacity Factor (%) on the y-axis (range: 20-40%). A colored dot represented each location: Brazoria County (TX) - navy, Bastrop County (TX) - orange, Grimes County (TX) - green, Boulder City (NV) - blue, and Calexico (CA) - purple.
- A bar chart compared the five locations' annual energy generation (GWh) and average temperature ($^{\circ}C$). The x -axis represents the location names. The left y -axis (range: $0 - 250,000GWh$) was used for energy (navy bars), and the right y-axis (range: $19 - 23.5^{\circ}C$) for average temperature (orange squares).
- A stacked monthly bar chart was created to visualize the average monthly generation (GWh) across all five locations. The x -axis represented the 12 months, and the y -axis ranged from 0 to $30,000GWh$. Each location was distinguished by color: Brazoria (navy), Bastrop (orange), Grimes (green), Boulder City (blue), and Calexico (purple).

Results

The results section is organized into six parts. Each part analyzes two graphs from five different locations. A schematic (Figure 13) illustrates the configuration of the CSP Power Tower Molten Salt system simulated in the SAM. The process of power generation starts from the left, a heliostat field reflecting and concentrating sunlight onto a central receiver mounted on a tower. The focused sunlight heats the molten salt inside the receiver, located at the top of CSP Power Tower. The heated molten salt creates a steam which spins the turbine to generate electricity. The

schematic also illustrates auxiliary systems, such as cooling towers and fluid pumps, which support efficient heat exchange and system operation. The molten salt steam is then cooled down in the air-cooled condenser, traveling back to the receiver. Although thermal storage is included in the schematic, both thermal and solar field storage were disabled in the simulation to evaluate CSP system performance without energy storage.

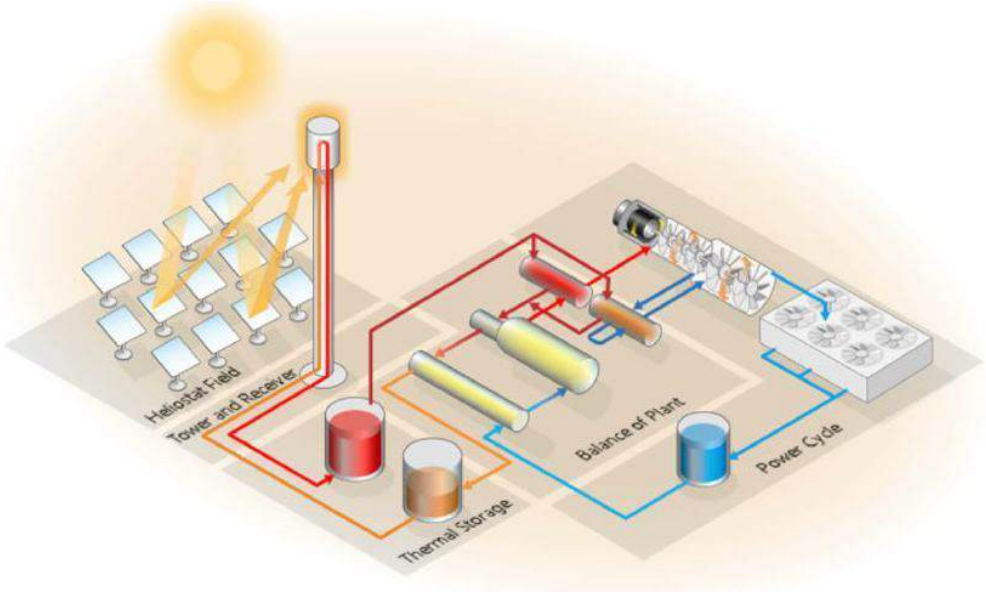


Figure 15. Schematic of the CSP Power Tower Molten Salt system generated in SAM.

Brazoria County, Texas

Energy generation in Brazoria County was the highest in August, reaching approximately $20,000GWh$, while the lowest output occurred in February at around $10,000GWh$. The average monthly generation was approximately $15,000GWh$, leading to a total annual production of about $170,000GWh$. The seasonal variation aligns with the trend in Direct Normal Irradiance (DNI), which peaks in June and July before experiencing a significant decline during the winter months. Additionally, the temperature pattern exhibits a similar trend, with average monthly temperatures reaching their highest point in August and decreasing in January and February. This temperature trend corresponds with the fluctuations in energy generation throughout the year. The peak in energy generation in August while DNI peaking earlier in June and July may be due to longer daylight hours and more consistent clear skies during late summer. In contrast to August, the sharp decline in February's generation corresponds with the lowest DNI, which may be caused by shorter days and increased cloud cover that reduces solar input.

Although no extreme anomalies were detected in the graphs, atmospheric dust, equipment degradation, and maintenance interruptions, which are not considered in the simulation, could influence energy output as well. The simulation, however, confirms us that in the absence of thermal energy storage, CSP systems are highly susceptible to variations in DNI and thus require strong, consistent solar conditions to achieve optimal performance.



Figure 16. Graph that shows the correlation between average monthly energy generated and average DNI values in Brazoria County, Texas.

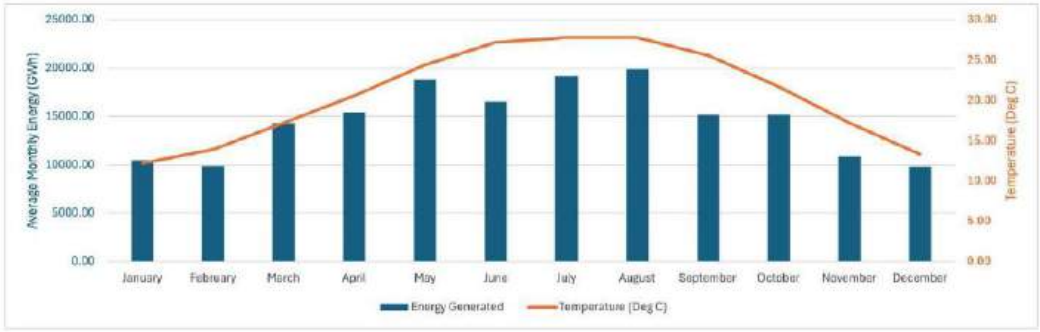


Figure 17. Graph that shows the correlation between average monthly energy generated and average temperature values in Brazoria County, Texas.

Grimes County, Texas

Energy generation in Grimes County was the highest in August, with monthly output exceeding $20,000 GWh$. The lowest generation occurred in February, dropping below 10,000 GWh. This seasonal trend closely corresponds to the trend in DNI. In Grimes County, DNI rises in the spring, peaks in July, and gradually declines through the winter months. The monthly average temperature also has a similar trend, with the highest temperatures recorded in July and August and the lowest in December and January.

Although DNI had the highest in July, August had slightly higher energy output. This discrepancy may be due to longer daylight hours or more stable irradiance conditions in August. Another possible reason for the increase in DNI but small decrease in energy generation in October could be due to reduced plant efficiency, curtailment, or grid limitations, which are not reflected in the simulation.

The temperature-energy relationship shown in the graph appears strong and reasonable. While higher ambient temperatures can reduce heat losses, they may also increase thermal losses or reduce component efficiency. However, such circumstances are not evident in the graph data. The performance of the CSP system in Grimes County underscores its dependence on strong and stable DNI. The simulation confirms us that in the absence of thermal energy storage, CSP systems are highly vulnerable to seasonal solar variability.

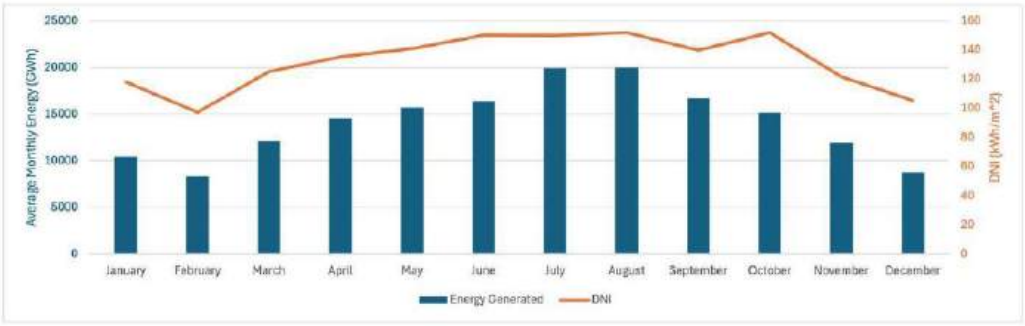


Figure 18. Graph that shows the correlation between average monthly energy generated and average DNI values in Grimes County, Texas.

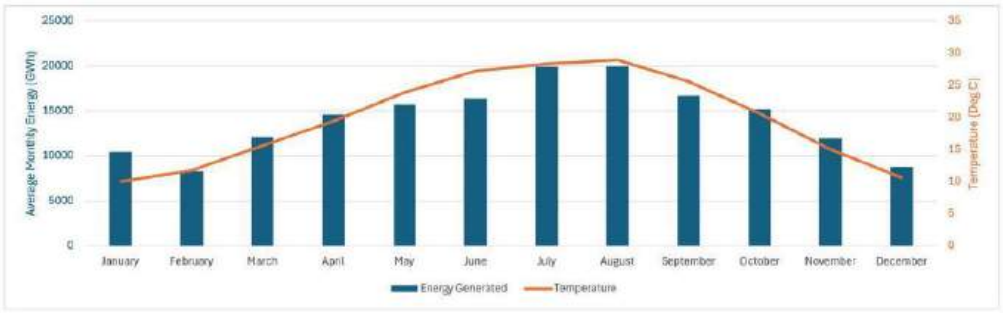


Figure 19. Graph that shows the correlation between average monthly energy generated and average temperature values in Grimes County, Texas.

Bastrop County, Texas

Energy generation in Bastrop County peaked in July, reaching just above $22,000GWh$, followed by a slightly lower but still high output in August. The lowest generation occurred in December, with values falling below $10,000GWh$. This seasonal pattern closely aligns with the trend in DNI, which gradually increases from February, peaks in July and August, and declines sharply toward the winter months.

Similarly, average monthly temperature increases steadily from January through July, peaking around $32^{\circ}C$ before declining throughout the year. The parallel between energy generation and temperature indicates a potential secondary influence of temperature on system performance, especially in warmer months when thermal efficiency is enhanced.

A slight irregularity is observed in April: although DNI remains relatively stable compared to March and May, energy generation drops slightly. This result could be due to temporary atmospheric conditions such as increased cloud cover or haze, which may have reduced the actual solar irradiance despite a stable monthly DNI average. Additionally, operational factors such as system maintenance during that period may have contributed to reduced output.

Another irregularity appears in September. While DNI decreases moderately compared to August, energy generation drops more sharply than expected. This could be attributed to increased atmospheric interference (e.g., humidity, dust, or partial shading) or an early seasonal

transition with more variable weather patterns that are not fully captured by monthly average DNI values.

Overall, the results confirm that CSP systems in Bastrop County without thermal energy storage exhibit strong seasonal dependence on DNI. While temperature plays a supportive role in maximizing output during peak months, energy generation is primarily driven by the availability and consistency of solar irradiance.

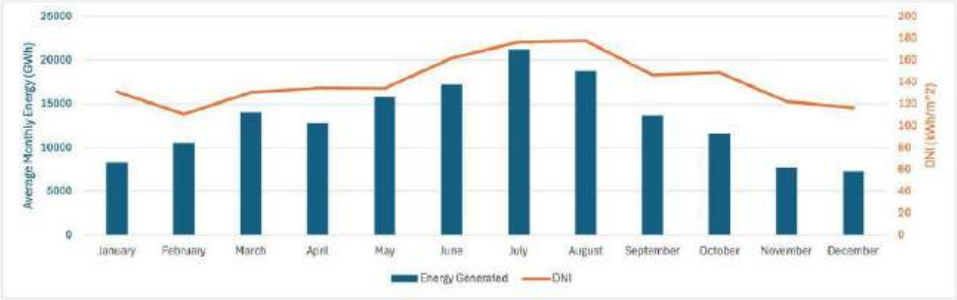


Figure 20. Graph that shows the correlation between average monthly energy generated and average DNI values in Bastrop County, Texas.

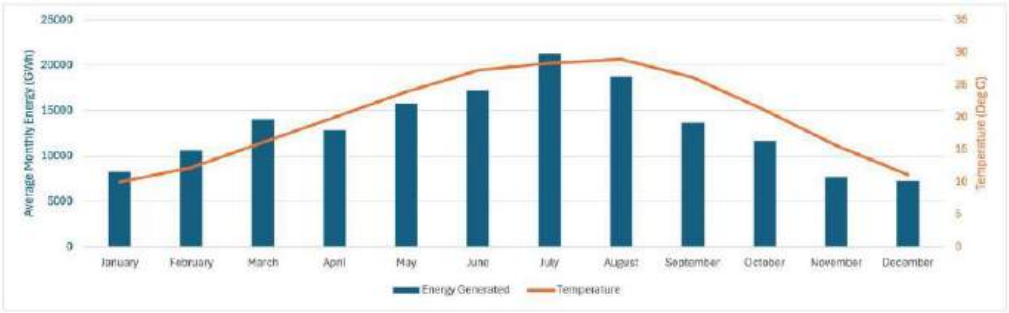


Figure 21. Graph that shows the correlation between average monthly energy generated and average temperature values in Bastrop County, Texas.

Calexico, California

In Calexico, California, energy generation correlated with a strong seasonal trend, peaking in July at nearly $28,000 GWh$ and reaching its lowest point in February, with output just above $15,000 GWh$. This trend correlates with the DNI pattern, which steadily increases from February, peaks in July, and then declines during the fall and winter months.

The high correlation between DNI and energy output in Calexico can be attributed to the region's consistently sunny and arid climate. Located in the Imperial Valley, Calexico frequently experiences minimal cloud cover, low annual rainfall, and clear days throughout the year. The temperature trend further supports this observation. Average monthly temperatures in Calexico rose from around $15^{\circ}C$ in January to nearly $35^{\circ}C$ in July, closely correlating the energy generation curve. Nevertheless, the temperature does not drive energy output as directly as DNI, so warm conditions may enhance thermal efficiency during the summer months. However, the exceptionally high temperatures observed in July and August do not appear to cause performance degradation, suggesting that the system is suitable to Calexico's desert climate.

No significant anomalies were observed in the data. The data from Calexico reinforces that CSP energy output without thermal energy storage is highly dependent on DNI. The consistently high DNI levels and desert-like weather conditions make Calexico an ideal site for efficient solar energy production.

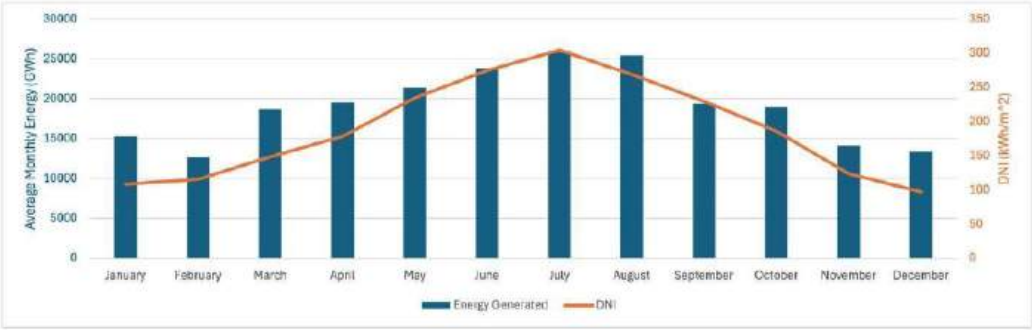


Figure 22. Graph that shows the correlation between average monthly energy generated and average DNI values in Calexico, California.

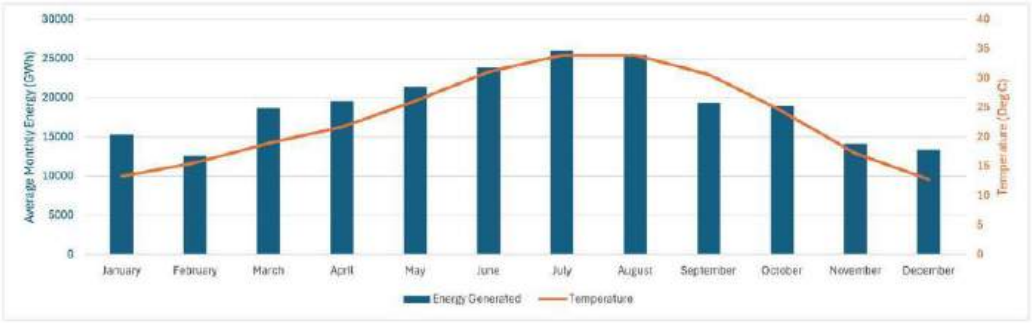


Figure 23. Graph that shows the correlation between average monthly energy generated and average temperature values in Calexico, California.

Boulder City, Nevada

Energy generation in Boulder City, Nevada, showed a strong seasonal pattern, with output gradually rising from January to May at approximately $26,000GWh$. After May, energy generation remained relatively high throughout the summer, with a slight decline in July and August, before decreasing steadily into the winter. This pattern also follows the trend of DNI, which also peaks in June and drops starting in September.

The strong correlation between DNI and energy generation in Boulder City indicates that solar irradiance influences the CSP's energy output. The city's desert climate with low precipitation, minimal cloud cover, and consistently sunny days favors high and stable DNI for most of the year.

Interestingly, while DNI peaks in June, the highest energy generation occurs in May. This anomaly may be attributed to minor modeling inconsistencies in the simulation. Additionally, extremely high summer temperatures in July and August could lead to increased thermal losses or slight reductions in efficiency, possibly explaining the small drop in output despite high irradiance.

The temperature curve also rises gradually from January to July, peaking at around $36^{\circ}C$, then declines into winter. Warmer conditions in spring and early summer may boost thermal efficiency. Still, extremely high ambient temperatures in midsummer could slightly hinder performance, which aligns with the decline in energy output during summer months.
The graphs do not show major anomalies, and the overall trends strongly support the conclusion that CSP systems without thermal energy storage perform best in regions where DNI is consistently high.

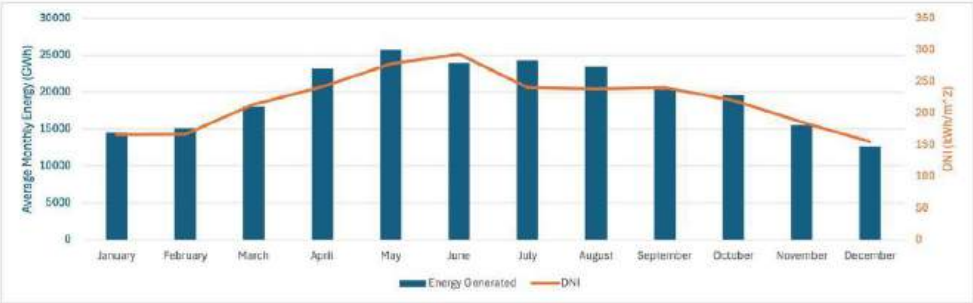


Figure 24. Graph that shows the correlation between average monthly energy generated and average DNI values in Boulder County, Nevada.

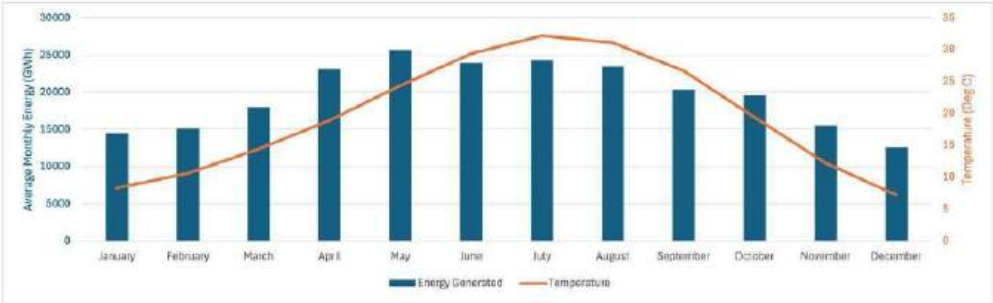


Figure 25. Graph that shows the correlation between average monthly energy generated and average temperature values in Boulder County, Nevada.

Comparative Analysis

The simulations of CSP with Power Tower Molten Salt System across showed that Boulder City, NV, and Calexico, CA, consistently outperformed the two Texas sites in annual energy generation and capacity factor. Each region outputted over $230,000 GWh$ of energy annually, and capacity factors exceeded 34%. In contrast, Brazoria, Bastrop, and Grimes Counties in Texas generated between 160,000 and 180,000 GWh and maintained relatively lower capacity factors which ranged from 24% to 27%.

Interestingly, higher average temperatures did not correlate with higher performance. For instance, Boulder City reported the lowest mean temperature but had the highest energy generation, indicating that heat alone does not positively affect the CSP energy output. Instead, the ability of a location to provide strong, stable DNI throughout the year is crucial in system efficiency and output.

When analyzing monthly trends, all sites showed peak performance in the summer months, particularly June through August, which is when DNI is highest. However, Boulder City and Calexico maintained relatively high generations even in the spring and fall, demonstrating less seasonal variability. In addition, the sites in Texas experienced sharper declines during winter. This suggests that CSP systems without storage are more sensitive to changes in DNI.

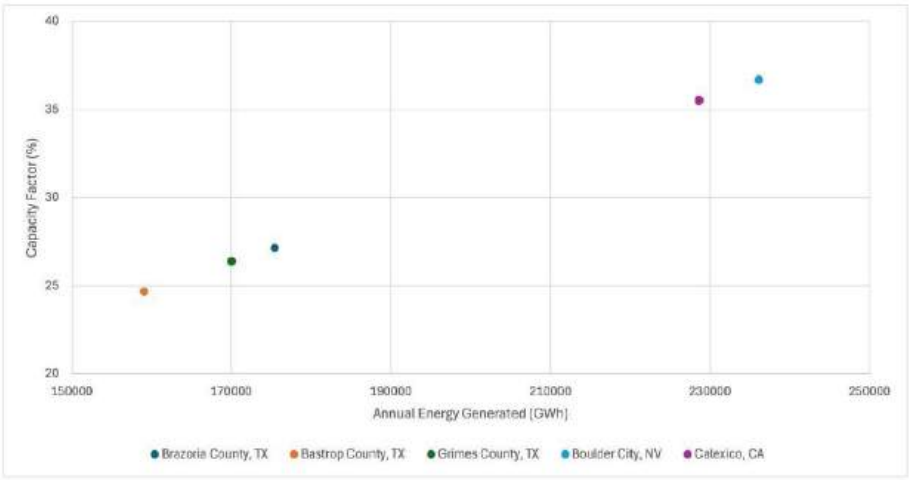


Figure 26. A scatterplot showing the relationship between annual energy generated (GWh) and Capacity Factor (%) of five locations.

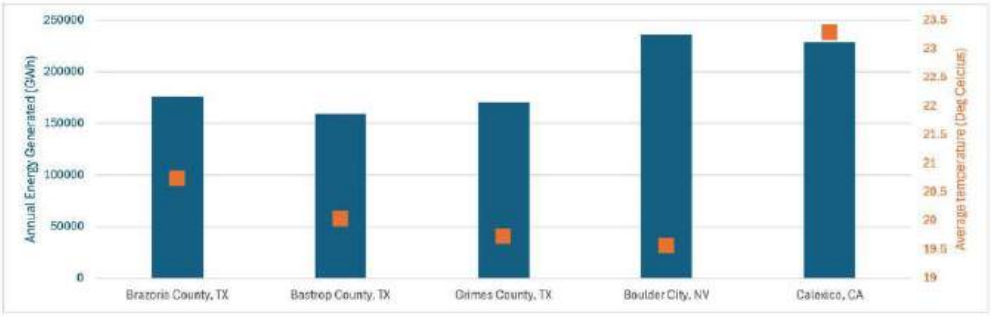


Figure 27. A bar chart that shows the correlation between annual energy generated (GWh) and average temperature (degrees Celsius) of five different locations.

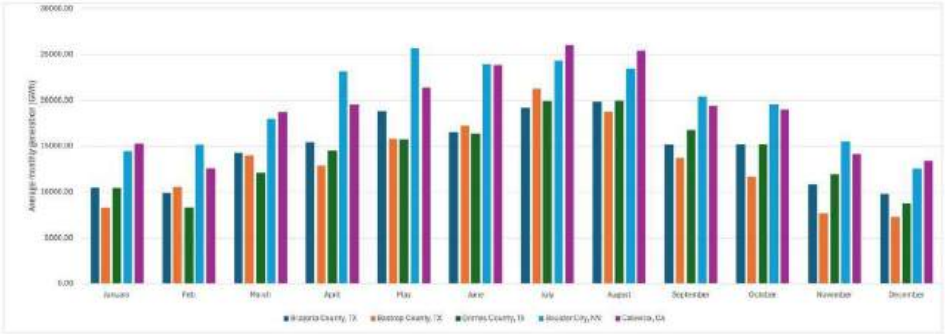


Figure 28. A stacked monthly chart showing the annual energy generated (GWh) in five locations.

Conclusion

The results obtained from the graphs affirm that CSP systems without TES are highly sensitive to geographic location, and changes in DNI. The findings underscore the significance of site selection in CSP implementation and suggest that, in the absence of TES, locations with desert climates and minimal DNI variation are essential for maintaining optimal energy output. Surprisingly, temperature showed a modest correlation with energy generation; it did not prove to be a reliable predictor of system performance. For example, Nevada recorded the highest average ambient temperature but did not generate the highest energy annually. Therefore, it is ultimately the quality and consistency of DNI that determines the viability and output of storage-free CSP systems.

Other research can validate or build on the takeaways of this study by providing a more profound understanding of the performance of CSP systems. For instance, studies that incorporate TES can be compared against this research to find specific benefits of storage in mitigating seasonal variability. Additionally, research analyzing long-term system degradation, maintenance impacts, and environmental influences such as dust accumulation, humidity, or aerosol presence can help explain the cause of anomalies and irregularities observed in the energy output. Regional studies using real-world operational performance of existing CSP plants without TES could help support the findings of this simulation-based analysis. This way, future research can contribute to developing more adaptive CSP implementation strategies for non-storage scenarios.

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What Kinds of Behaviour Are Engendered by the Hope of Profit? Is Such Behaviour Better or Worse, on Balance, Than the Behaviour We Should Expect if All Enterprises Were Owned by Charities or Governments? By Dante S. Ielceanu

In the 1980s, the U.S. National Institute of Health funded genetic research without immediate commercial potential, establishing the foundation for cancer treatments like Herceptin. Herceptin, developed by the private U.S. company Genentech and commercially launched in 1998, saved thousands of lives. The combination of government interest and for-profit incentives enabled genuine value creation and a better outcome for society.

Economic systems have been evaluated in the literature using several criteria, including economic efficiency (Smith 1776/2015; Hayek 1944/2005; Friedman 1962/2020), consumer responsiveness (Smith 1776/2015; Hayek 1944/2005), environmental sustainability (Ostrom 1990; Stern 2007), ability to meet public needs (Arrow 1974; Stern 2007), innovation dynamics (Schumpeter 1942/2008; Mazzucato 2013), and social justice (Piketty 2014; Sen 2011). These studies suggest that mitigating the harmful effects of profit-seeking requires a measured strategy, where governments enforce strong public-interest oversight and regulations in profit-based systems.

This essay examines how profit-seeking influences behaviours at the individual, firm, and market levels using two fundamental concepts: profit motive, or the internal desire for economic gain, and profit incentive, or external conditions such as competition or institutional rules. In the next section, I analyse these behaviours within pure profit-based systems (defined as systems in which profit-seeking drives economic decisions). While such systems often create outcomes beneficial to society (hereafter referred to as "good"), they may also damage public welfare in areas like foundational innovation, economic inequality, resource overuse, and environmental harm. I also examine how public-interest systems (defined as systems in which charities or governments own all enterprises, and societal welfare drives decisions) can mitigate harmful behaviours driven by profit-seeking. Public-interest systems cannot operate markets on their own. While they champion universal welfare and fairness, they can become overly bureaucratic and disconnected from market realities. I conclude that a state-guided capitalist system that integrates the strengths of profit-based and public-interest systems can consistently produce good outcomes from profit-seeking behaviours. The role of government is, therefore, not to choose between state and private ownership, or capitalism and communism. This either-or framing is a false dilemma that leaves out other possibilities. Instead, the government should enable public-interest and profit-based systems to complement each other to ensure a well-functioning economy. On balance, behaviours engendered by profit-seeking, when such behaviours are moderated by institutions that safeguard public welfare, are better than those expected if enterprises were exclusively owned by governments or charities.

Behaviours Engendered by Profit-Seeking and Public-Interest System Remedies

At the individual level, in profit-based systems, profit-seeking motivates individuals to work hard and develop specialized skills because they expect effort to lead directly to rewards (Smith 1776/2015; Ricardo 1817/2018; Mill 1848/2018). In reality, people do not respond to incentives perfectly because their decisions are distorted by cognitive biases—thinking mistakes—and limitations in judgment (Kahneman 2011). They often do not make the best possible choice because their reasoning has limits, they lack information, or they feel overwhelmed, leading them to make decisions based on emotions and mental shortcuts (Simon 1957). Chasing profits also pushes people to innovate and take risks, notwithstanding the chance of failure. Yet, the risk and uncertainty involved can backfire, causing them to overestimate potential losses or become too confident in their chances of success (Kahneman 2011). When individuals compete for profits, they do not act randomly; they make strategic choices by thinking about what others might do and adjust their behaviour to gain an advantage (Nash 1951).

Public-interest systems remedy many of the behavioural distortions present in profit-based systems. Such systems focus primarily on public service rather than self-interest and emphasize fairness over profit. They shape the behaviour of public workers through training and institutional norms, guiding them to protect public wellbeing and serve everybody equally, regardless of income or status (Sandel 2012; Stiglitz 2012; Simon 1957). Public-interest systems also reduce overconfidence issues by being transparent about how they work and making decisions based on objective evidence (Kahneman 2011; Simon 1957). They prevent corruption through regulations and oversight (Ostrom 1990; Stiglitz 2012). Still, public-interest systems have limitations. Public employees can become complacent, avoid taking risks or pursuing innovative ideas, and resist change because job security is high and advancement is not usually tied to performance (Simon 1957). The lack of competition may also lead them to follow processes rather than solve problems. The inefficiencies and bureaucracy that result can eventually stifle initiatives that would otherwise benefit society (Kahneman 2011; Simon 1957)**.** In conclusion, at the individual level, the hope for profit motivates hard work, specialized skills, innovation, and strategic decision-making. Yet in the real world, these behaviours are distorted by thinking errors that lead individuals to not always choose the best course of action. Public-interest systems, through their focus on public service, fairness, and transparency, can provide a remedy.

At the firm level, in profit-based systems, profit-seeking pushes businesses to improve their products, reduce costs, and boost productivity, leading to a more efficient use of resources and delivering real benefits to society. Nevertheless, it pushes jobs to countries with cheaper labour and weaker laws and regulations, leading to lower wages, more pollution, or a drop in quality. Profit-seeking also drives strategy: firms make deliberate decisions such as competing on price or value, zeroing in on target markets, or collaborating with others. All the while, they observe their rivals, anticipate their next moves, and shift their behaviour accordingly. As firms repeatedly adjust their strategy based on others' responses, they eventually settle on a strategy that cannot be improved by acting alone, a concept known as the Nash equilibrium (Nash 1951).

Firms constantly compete to stay ahead, pushing out new innovations to remain relevant and grow profits. However, under pressure from their stakeholders who want quick results, they often focus on short-term innovation that offers immediate gains. The short-term perspective creates an innovation bias where firms do not invest enough in foundational research essential for long-term scientific advancements because it lacks immediate commercial potential, representing a key limitation of profit-based systems (Mazzucato 2013). Another limitation is the misalignment created between business owners who seek maximum profits and business managers who seek goals like job security and prestige, called the principal-agent problem (Jensen and Meckling 1976). This interest misalignment, along with common thinking errors like overconfidence and loss aversion, often leads managers to make poor strategic decisions and creates internal firm conflicts (Kahneman 2011).

Public-interest firms such as the national postal service or public schools operate differently. Instead of focusing on financial returns, cost-cutting, and increasing efficiency, they focus on serving the public by providing universally accessible services like education or healthcare. Their goal is to help everybody, regardless of socio-economic background, and ensure that disadvantaged groups are not left out (Stiglitz 2012; Ostrom 1990). Public-interest firms also make investments in long-term projects that lack immediate commercial potential, such as foundational research, infrastructure, or services for low-income populations (Mazzucato 2013; Simon 1957). Because these agencies respond to the public rather than shareholders, they are designed to be fair and transparent about what they do and how they do it, to keep public trust. (Stiglitz 2012; North 1990). However, public-interest firms also have weaknesses. When lawmakers force them to "balance their books" or be "self-sustaining," meaning cost-cutting and generating revenue, public-interest firms start acting like profit-driven firms. Consequently, mission drift occurs; short-term goals replace long-term goals, and agencies prioritize making money over public service (Ostrom 1990; Mazzucato 2013). For instance, public universities may start accepting more international students who pay full tuition instead of local students, and hospitals may reduce free care and concentrate on higher-paying patients (Sandel 2012; Mazzucato 2013). In conclusion, at the firm level, profit incentives motivate firms to increase productivity and efficiency, yet when pushed too far, societal problems like poverty or environmental harm may be ignored. Profit-seeking primarily encourages short-term innovation driven by immediate profitability, but neglects foundational innovation needed for society's long-term well-being. In contrast, public-interest enterprises focus on public service, foundational research, and long-term investments with clear societal benefits, and aim to be transparent and fair.

At the market level, in profit-based systems, profit incentives encourage firms to respond quickly to market demand by making what consumers want most and use capital and labour efficiently, leading to an "efficient allocation of resources" (Smith 1776/2015). Under free trade, competition drives prices down and improves quality. While driven by self-interest, the system ultimately benefits society by creating more wealth and efficiency (Smith 1776/2015), and by driving innovation that improves productivity and lowers costs. However, it can also lead to

irresponsible use of resources, excessive waste, environmental damage, and continuing harmful yet profitable practices. Therefore, profit-seeking behaviours should be evaluated not only by how efficiently firms use resources now, but also by how much they consider long-term consequences. Their stewardship matters because long-term success depends not only on generating profits today, but also on avoiding harm to future generations. Free markets promote efficiency and individual freedoms (Friedman 1962/2020), but exclusive focus on efficiency leads firms to overlook social problems like poverty, inequality, and environmental harm (Stiglitz 2012; Mazzucato 2013; Sandel 2012). Even so, market competition continuously pushes firms to innovate, replace existing products through "creative destruction," and create new value and growth (Schumpeter 1942/2008). Sustained growth over time, nonetheless, requires strong institutions that protect property rights and reward risk-taking, hard work, and creativity (Acemoglu and Robinson 2013). For this reason, governments and regulatory bodies should guide market expansions with rules that ensure fairness, competition, and discourage collusion (Stiglitz, 2012). Without such oversight, excessive profit seeking, whether driven by internal motives or external market competition, can create cycles of boom or bust caused by investors being overly optimistic or underestimating risks, resulting in economic instability (Kahneman 2011). Instability ignites harmful populism and weakens institutions, exemplified by protectionist tariffs (Acemoglu and Robinson 2013).

In contrast, public-interest systems show behaviours that profit-based systems often lack, such as ensuring public basic needs are met by offering free or low-cost services like education, water, or healthcare. They encourage investing in long-term projects with wide societal benefits like public transit, disaster preparedness, or environmental protection, despite lack of immediate profits (Mazzucato 2013; Ostrom 1990). They shape fair markets by passing labour laws and anti-monopoly policies, and protecting natural resources (North 1990; Stiglitz 2012). For vulnerable resources like forest and water, public-interest systems help communities work together to avoid "tragedies of the commons"—situations where shared resources are overused—and protect them for the future (Ostrom 1990). When profit-seeking replaces public interest, governments start acting like for-profit businesses (Mazzucato 2013; Ostrom 1990). Their focus drifts from fairness and helping everyone to charging higher prices and cost-cutting. Healthcare, public education, and other public goods stop being rights and become commodities. People who can pay more receive faster or better service, while those who cannot are left behind (Sandel 2012; Mazzucato 2013; Stiglitz 2012). To prevent mission drift, governments must put in place protections for vulnerable groups (Ostrom 1990; North 1990). In conclusion, profit motives and incentives drive behaviours such as efficient use of resources, strategic decision-making, and innovation. However, whether these behaviours lead to good or bad outcomes depends heavily on the rules and regulations established by governments to guide economic activity.

Conclusion

Profit-seeking engenders behaviours that lead to good outcomes for society overall, such as hard work, innovation, strategic decision-making, efficient use of resources, and rapid

adaptation to market changes. However, when pushed too far and left unchecked, such behaviours can create long-term social harm such as economic inequality, irresponsible resource use, underinvestment in foundational research, and increased vulnerability to economic instability and harmful populist policies. Public-interest systems can help correct these limitations but also have drawbacks, such as bureaucratic delays, disconnection from market realities, inefficiency, resistance to change, and likely to drift towards profit-oriented behaviours during financial pressures. Therefore, neither profit-based nor public-interest systems are better on their own; society does not need to pick one, as such a choice is a false dichotomy. A more effective approach is a state-guided system that combines market flexibility with smart government oversight to keep things stable and fair.

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Skies of Conflict: Aviation and Strategy from WWI to Vietnam By Jacob Gottschalk

From the barbed wire trenches of the First World War to the densely-trapped jungles of Vietnam, the evolution of military strategy and tactics have been shaped by profound shifts in technology, politics, and global power structures. Over the span of the 20th century, three major forces consistently drove these changes: the quickly evolving geopolitical landscapes in which wars were fought, the rapid advancement of aviation, the emergence of nuclear weapons. Each conflict between the First World War and the Vietnam War was not an isolated event, but part of a broader continuation of military innovation and strategic adaptation.

During the First World War, evolving geopolitical landscapes and aviation advances were the primary drivers of military strategy and tactics. It was a war that was front-loaded by decades of political disputes and unrest primarily between Germany and European countries, including Britain, and military alliances protected by treaties. The Triple Alliance treaty ensured a defensive partnership between Germany, Austria-Hungary and Italy. To counter this alliance, other countries like Britain, France, and Russia formed the Triple Entente treaty.

In July of 1914 the war began, one month prior the assassination of Archduke Franz Ferdinand of Austria-Hungary (current day Bosnia) occurred. Ferdinand was killed by a group called the Black Hand, a secretive Serbian national group that had an end goal of uniting all Serbs including those within Ottoman and Austria-Hungarian territory. This sent the region further into chaos. Any small action could trigger an all-out war in the Balkan region; a phenomenon termed the Balkan Powder Keg. As these alliances set the stage for growing tensions in Europe, new technologies were also beginning to influence the battlefield, with airplanes making their first appearance as tools of war.

Despite their use as lethal weapons with reconnaissance and bombing capability during their time in the Italio-Turkish war[1] in 1911, the beginning of the First World War saw them as only being useful for reconnaissance with their rudimentary cockpits and lack of necessary equipment. Pilots gathered intelligence and shared the airspace with pilots from other countries. “Pilots from opposing sides would wave as they flew by each other, in a sort of ‘camaraderie of the sky.’ This arrangement did not last [as the war progressed]” (McDermott, 2022). This simple act did not last because countries started to see the advantages of ruling the skies over their enemies, such as aerial intelligence.

Air power quickly changed and assumed not only the roles of reconnaissance and tactical bombing, but also that of plane-to-plane combat, or dogfighting. With these strategic uses, planes helped rule the skies. The allies stopped Germany from invading France. Germany shifted from bombing with airships to air raids with bomber planes. Countries that once felt safe from ground attacks because of geography (i.e., Britain) now had something to fear. Bomber air raids changed the threat of warfare. This new vulnerability accelerated their need for better aircraft and led to the first-generation of the fighter plane being born.

[1] Jay Wertz, WWI in the Sky: Advancements in Aviation, (MagellanTV, 2025), 1.

Britain was the pioneer to enter the race with the first-ever fighter monoplane, the Vickers F.B.5 (Vickers Limited). It was designed with the engine and propeller located behind the pilot with the machine gun fitted at the front. France entered the arms race shortly after, retrofitting their MoS-3 (Morane-Saulnier L)with a machine gun and designing the new MoS-5 C1(Morane-Saulnier N)with them. However, one of the major breakthroughs in WWI biplanes and monoplanes technology was the creation of the synchronization gear. Both France and Germany were researching this gear which allowed machine guns to fire through the arcs of the plane's propeller blades. The machine gun's firing mechanism was linked to the engine's rotation, ensuring that the gun would only fire at specific timings so that the blades would be clear of the fire line. The Germans were the first to implement the gear into the first model of the Fokker E.I (an armed version of the Fokker M.5K) and lead to the Fokker's successor, the Eindecker. The Eindecker started an era of German air superiority called the Fokker Scourge[2]. To compete, the French developed smaller and faster planes (i.e., Caudron R.4, Breguet 14, and SPAD S. VII) to match the Eindecker's functionality. Britain attempted to do the same with the Airco DH.2 and the F.E.2b; however, they were quickly out classed by new German planes.

With the rapid advancement of aviation, countries recognized the need to create independent air forces rather than structuring them under army jurisdiction. As countries like Germany, Britain, and France started to use planes more frequently for operations, they realized that planes need to have their own category and rankings in the military in order to showcase their own capabilities. In Germany, they created the Feldfliegerabteilungen[3] (Different Air Units). Each air unit had 34 flying sections, comprising of six aircraft and an additional two as escorts per section. Britain initially created the RFC (Royal Flying Corps) but later changed that during the war to the RAF (Royal Air Force).

After WWI, the geopolitical landscape of the Second World War was constantly shifting, a key driver of military strategy. Battles were fought among countries in the hopes of halting another country's expansion into their territory. There were four major battles that turned the war in favor of the allies. The U.S. stopped Japanese advancements in the Pacific Ocean such as in the Battles of Midway[4] and Guadalcanal[5]. During the Battle of Midway, the U.S. stopped Japanese expansion into the Pacific and paved the way for the U.S. to use their island-hopping strategy. This strategy consisted of capturing one island and turning that island into a base to launch more attacks. The Battle of Guadalcanal took place in the southern part of the Solomon Islands in which they captured the Mariana Islands. This helped the U.S. push the Japanese back and stopped their advancements toward Australia. The Soviet Union pushed back against the Germans in the Battle of Stalingrad[6], and Britain fought against Germany and Italy during the Battle of El Alamein[7]. El Alamein prevented Germany and Italy from capturing the Suez Canal, a crucial piece in the overall control of the Mediterranean Sea. These battles signify key

[2] Jade McGee, The War in the Skies: How the First World War Changed Aviation (History Guild, 2022) 1.
[3] Dana P. McDermott, Aircrafts: World War I (EBSCO Information Services, 2022) 1.
[4] The Battle of Midway (The National WWII Museum, 2025) 1.
[5] Battle of Guadalcanal (Encyclopædia Britannica, 2025) 1.
[6] Battle of Stalingrad (A&E Television Networks, 2025) 1.
[7] The Battle of El Alamein Begins (A&E Television Networks, 2025) 1.

moments of when the war started to turn around in favor of the allies and how the shift in power changed dramatically.

Over the course of the war, both the characteristics and the roles of planes expanded. The type of plane that saw the most significant upgrade was the bomber. An example of this was the B-29 Superfortress[8] bomber developed by the U.S. Army Air Force. The B-29s were considered to be the most sophisticated propeller-driven bomber of the Second World War and had highly advanced navigation systems compared to the First World War bombers. They had a central fire control system that allowed two people to direct four machine gun turrets, APQ -7 "Eagle" radar that provided high-resolution target identification, Barometric altitude, and temperature data. The B-29s were capable of carrying between 500-1,000 pound bombs while cruising at an unimaginable height of 32,000 feet. It was able to deliver a variety of bombs from conventional bombs to atomic bombs.

The Germans further developed bomber capabilities. The bomber, German Junkers Ju 88[9], served as a bomber, dive bomber, torpedo bomber, and even a night fighter. The Second World War bombers served many roles including that of strategic bombers. They weakened enemy morale through The Doolittle Raid[10], caused widespread damage in the Firebombing of Tokyo[11], and targeted the enemy's war-making capabilities.

Fighter planes on the other hand improved in their own way. From their maneuverability to their lethality, fighter planes became a greater force to reckon with. Some of the most popular planes during the war were the American P-51D Mustang, British Supermarine MK 24 Spitfire, and German Messerschmitt BF 109[12]. Each of these planes served different purposes. The P-51D Mustangs were used for ground attacks, reconnaissance, and as long-range escort fighters. The Mustangs were most well-known for their roles as bomber escorts in both the European and Pacific theaters during the war. The Supermarine Spitfires were used as interceptors, trainers, reconnaissance, and fighter bombers. The major role the Spitfire played in the war was as an interceptor during the Battle of Britain where it helped to take out all of the Junkers Ju 88s and Heinkel He 111 bombers. Lastly, the German Messerschmitt BF 109 was a fighter that was also a bomber escort, ground attack aircraft, and reconnaissance plane. It dueled as an interceptor and stellar in air-to-air combat fighter. It was most known for its operations in the Battle of Britain, Invasions of Poland and France, and the Battle of the Atlantic.

While the war was being fought on the ground and in the air, the Second World War brought about an undercover project created by Canada, Britain and the U.S. called The Manhattan Project[13]. Their goal was to quickly end the war and develop the first nuclear weapon in hopes of beating other competing countries, Russia and Germany. This was crucial in the case of the U.S. because it was stuck between either invading mainland Japan and risking the lives of thousands of soldiers or dropping the newly-made atomic bombs. Ultimately, they decided to use

[8] World War II Aviation (National Air and Space Museum, 2006) 1.
[9] John F.Guilmartin, John W.R. Taylor, Interwar Developments (Encyclopædia Britannica, 2025) 1.
[10] Doolittle Raid (Encyclopædia Britannica) 1.
[11] Seth Paridon, Hellfire on Earth: Operation MEETINGHOUSE (National WWII Museum, 2020) 1.
[12] John F.Guilmartin, John W.R. Taylor, Interwar Developments (Encyclopædia Britannica, 2025) 1.
[13] Manhattan Project (National Parks Service, U.S. Department of the Interior, 2025) 1.

the atomic bombs against Japan. Each was given a different name. “Little Boy” was dropped on Nagasaki, and “Fat Man” was dropped on Hiroshima. These bombs decimated Nagasaki and Hiroshima and mentally shook the world. This kickstarted a strategic tactic called atomic diplomacy. Atomic diplomacy is employed when a country uses nuclear weapons as a bargaining chip and a threat that was later seen in Vietnam.

Less than five years later the Korean War began, the geopolitical landscape also drove military tactics. The Korean War was unlike any other 20th century war up to that point. Though a major event in history, it was only a proxy war between the U.S. and the Soviet Union given each was a third-party to the truly warring parties or North and South Korea. Hence a reason why the Korean War was given the nickname “The Forgotten War.” Helping South Korea after the North Korean invasion gave the U.S. the opportunity to test its containment policy, a strategy started in the late 1940s aimed at stopping the spread of communism by the Soviet Union. It was formally adopted by the Truman Doctrine in 1947 and again later in the 1957 Eisenhower Doctrine. In September of 1950, in coordination with the United Nations and U.S., the South Koreans managed to accomplish their goal and push the North Koreans, Chinese, and Soviets out of the Korean Peninsula. General Douglas MacArthur, the U.S. Army General leading the U.N. and U.S. troops, wanted to keep going. MacArthur was a firm believer in the containment policy[14] and had great expectations of taking over China to wipe out another communist country. Ignoring reports about the location of Chinese Communist Forces, he advanced his troops toward the Yalu River, the border separating North Korea and China. This was MacArthur’s major blunder and things did not go as planned. In October of 1950, Chinese communists poured across the river in the hundreds of thousands taking MacArthur and his troops by surprise and forcing a mass retreat. After being forced far past the 38th parallel line MacArthur demanded for reinforcement of U.S. troops as well as permission to use nukes on China. Neither of which were granted. This action led to his dismissal in 1951 for disrespecting not only President Truman but also the military.

Aviation technology also continued to advance from the previous wars. The switch from propeller-driven planes to jet propulsion planes changed air capabilities forever. Although fighter jets like the Lockheed P-80 Shooting Star[15] and Messerschmitt ME 262 Schwalbe[16] were created towards the end of the Second World War, they did not become popular until their use in the Korean War. Some of the most popular fighter jets used during the war were the American McDonnell F2H Banshee[17], Republic F-84 Thunderjet[18], F-86 Sabre[19], and the Soviet Mikoyan Gurevich MiG -15[20]. Each of these planes had separate, special purposes in the war. The F2H Banshee, also referred to as Banjo, served its time in the war as mainly a reconnaissance plane

[14] Containment (Encyclopædia Britannica 2025) 1.
[15] The 10 Best Fighter Jets of the Korean War (Aero Corner, 2022) 1.
[16] Daniel G. Graetzer, Aircrafts: World War II (EBSCO Information Services, 2022) 1.
[17]The 10 Best Fighter Jets of the Korean War (Aero Corner, 2022) 1.
[18] The 10 Best Fighter Jets of the Korean War (Aero Corner, 2022) 1.
[19] The 10 Best Fighter Jets of the Korean War (Aero Corner, 2022) 1.
[20] MiG-15 (Encyclopædia Britannica, 2025) 1.

but would also function as an escort aircraft. Although its max speed was 580 mph, it was one of the slowest fighter jets of its time. The Republic F-84 Thunderjet was used as an air-to-ground attacker, which achieved 60% destruction of all U.S ground targets. It was capable of carrying rockets, bombs, and the later developed Mark 7 Nuclear Bomb.

Another extraordinary plane was the F-86 Sabre. It helped re-establish U.S air supremacy over Korea and was one of the first planes to engage in jet versus jet battles. This type of jet plane fought mainly in MiG Alley, located in North Korean airspace and notoriously known for having a large concentration of MiG fighters.

Last but most definitely not least, the MiG - 15 was one of the best early jet fighters created by the Soviet Union. It was one of the few planes that gave an edge during the Korean War. The MiG -15 was designed as a bomber interceptor but also functioned as night and day fighter. This capability allowed it to have some great success against a few U.S. Aircraft, namely the P-80 Shooting Star as well as B-29 Superfortress bombers.

A new driver in military strategy was nuclear capability. After the Second World War, many countries joined the race for nuclear weapons. In September of 1951, the U.S. created the Mark 7 nuclear bomb. This bomb was what many would consider to be a last resort weapon. MacArthur wanted to attack China, but the U.S knew if it were to commit to nuking China, this would cause a terrible escalation. A domino effect could occur and lead to: 1) a push for communist powers to grow stronger, 2) significant destruction of Korean geography and civilian casualties and suffering, and 3) the rest of the world's loss of perspective that nuclear weapons are of a different type of terrible and that they are as practical as regular explosives.

When it came to the development of technology and geopolitics, Vietnam brought a whole new perspective to war. Although it was another U.S. proxy war aimed at containing communism. It was the ultimate test of guerilla versus conventional warfare tactics. The Viet Cong, a communist movement against the Southern Vietnamese government, and North Vietnamese had mastered the art of guerilla warfare, which is a strategy that uses small, mobile groups to easily do hit-and-run tactics as well as carry out ambushes and sabotages against larger forces. Vietnam's extremely dense, rugged jungle created conditions of low visibility. The combination of this and the guerilla tactics used along U.S. supply routes were very effective. The psychological warfare alone for the U.S. soldiers not knowing where or when they would be attacked gave the enemy the advantage.

The U.S. and South Vietnam tried to use conventional warfare tactics consisting of large formations and firepower. Although this proved effective in the Second World War and the Korean War, it was extremely ineffective here. Operation Rolling Thunder[21] is a prime example of this. It was the first major air campaign against North Vietnam and ended in absolute failure. None of the key ports or air bases were hit and the U.S. lost a collective 531 planes and 547 airmen. After four years and mounting pressure at home to end support for the war, the U.S. started withdrawing its troops and slowly gave up the war, failing to complete its objective of total control of Vietnam under a democracy.

[21] Bernard C. Nalty, An Uncommon War: The US Air Force in Southeast Asia (Air Force Historical Support Division) 1.

A new era of aviation led the way at the start of the Vietnam War with armed helicopters, jet fighters, and drones. Although helicopters had been invented before the Vietnam War, their roles changed drastically between the Korean War and the Vietnam War. During World War II and the South Korean War helicopters were only used for transportation of both supplies and soldiers. It was after the Korean War that "the Army at Fort Rucker, Alabama surreptitiously placed guns and rockets on helicopters and test-fired them to assess the helicopter as an aerial weapons platform" (Lepore, 1994). Despite the Army testing armed helicopters, they were not very well accepted into many military groups. It was not until the Department of Defense accepted them in the late 1950s. The first-ever armed helicopter used during the Vietnam War was the Bell UH-1 Iroquois[22], also named Huey. Originally designed as a utility and medical evacuation vehicle, the Huey was tested in 1955 to be used as an armed helicopter. In 1962 it was put into tri-service production for the Army, Navy, and Air Force.

The roles of helicopters changed from being transporters to air supporters and scouts. A next-generation helicopter, the Bell AH-1G Cobra (Snake)[23], made its debut during the war and was based on the design of the Huey but had significant upgrades. The Cobra was equipped with wing-mounted rocket launchers, a minigun, and a grenade launcher. They moved at speeds of around 140 mph while suppressing fire and creating a landing zone.

As technology advanced, UAVs (Unmanned Aerial Vehicle) or drones started to prosper. The Ryan Model 147[24] was designed for gathering intelligence and conducting surveillance over enemy territory. During its surveillance runs, the Ryan Model 147 conducted pre-raid reconnaissance, post-strike damage assessments, and leaflet drops. They served the same purpose that planes did during the start of the First World War by helping gather important data on North Vietnamese defenses and spotting the Soviet-supplied S-75 surface-to-air missile systems. The Ryan Model 147 proved that drones demonstrate resilience, effectiveness, and the ability to operate with relative impunity. It helped pave the way for more advanced drones like the Predator and Global Hawk that were later used in Afghanistan.

Although nuclear weapons were never actually used during the Vietnam War, their presence loomed in the background as a tool of threat, a shadow of nuclear deterrence. The conflict unfolded at the height of the Cold War, a period defined by the nuclear standoff between the United States and the Soviet Union that created the geopolitics that shaped the course of the Vietnam War. Both superpowers were locked in a stalemate. U.S. President Richard Nixon was frustrated by the war's length and lack of clear victory. He considered the possibility of deploying nuclear weapons to bring the conflict to a swift end. However, the political and moral consequences of such an action were huge. Any use of nuclear arms would have damaged America's global reputation, provoked international outrage, and potentially escalated the conflict into a wider war with the Soviet Union or China. Instead of risking such a catastrophic outcome, Nixon was trying to act like the Balkan Powder Keg of the Vietnam War. He pursued conflict resolution and deterrence through strategies like the Madman Theory by attempting to

[22] Stephen Harding, Bell UH-1 Iroquois (The Aviation History OnLine Museum) 1.
[23] Vietnam War in the Air (Army Air Corps Museum) 1.
[24] Christian Baghai, The Vietnam War and the Rise of UAV Technology (Medium, 2024) 1.

convince adversaries that he was unpredictable enough to potentially use nuclear weapons without actually deploying them. This psychological approach was meant to pressure North Vietnam into negotiating peace.

Each conflict has demonstrated how new air warfare technologies from reconnaissance planes to drones transformed the battlefield and forced militaries to adapt their strategies. Nuclear weapons reshaped global power dynamics and introduced a constant awareness of unprecedented destructive potential. Geopolitical pressures dictated not only where wars were fought but also how they were waged. These historical lessons resonate today with modern militaries continuing to rely on cutting-edge technology while navigating complex international politics and asymmetric threats. The patterns of adaptation observed in past conflicts show that while the tools of war evolve the fundamental drivers of technology and geopolitics remain central to shaping strategy. This is even so for wars later like the Iraq war, Afghanistan War, and later on the Russo-Ukrainian War. By studying these developments, we gain a clearer understanding of how today's conflicts are fought and how nations may respond to the challenges of future warfare.

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Using Machine-Learned Based Predictive Models for Respiratory Condition Analysis By Kirtan Chintam

Abstract

Asthma is a chronic respiratory condition known for causing symptoms of airway inflammation and obstruction. This makes quick diagnosis for effective treatment very important. Building on recent research demonstrating possible uses of artificial intelligence in diagnosis, this study aimed to create an efficient machine learning model to predict a patient's respiratory condition. A dataset containing demographic variables and spirometry measures was used, with features like the patient's Sex, Weight, and Baseline FEV1/FVC ratio being selected as classification features. The data was then split into training and testing sets, mainly to ensure unbiased evaluation of the patients. Five different machine learning models were then individually dealt with using optimized hyperparameters, after which their outputs were combined using simple averaging and weighted averaging based on model accuracies. The performance of the models was assessed using a classification report, which looked at a model's precision, recall, and more. Notably, some models exhibited overfitting, possibly because of dataset limitations or inaccurate feature selection, but it did not greatly affect their testing accuracy. Overall, the project's results support that machine learning asthma prediction models can be used effectively using spirometry ratios and other classifying features, but much research must be done before they get used. Building on this project, there are certain future improvements suggested, such as using more diverse datasets to analyze patients and integrating genomic features in patients, which could further improve the accuracy and usefulness of such models in clinical atmospheres.

Introduction

Asthma is a chronic lung condition where a person's airways become inflamed and as a result become narrower, making it more difficult for them to breathe. Some common symptoms of asthma are wheezing, chest tightness, and tight coughing. Asthma can have various sources, like indoor allergens (dust mites, mold, pet fur), outdoor allergens (pollens, mold), emotional stress, or intense physical activity. The severity of such triggers can range from mild to even life-threatening, requiring treatments like supplemental oxygen through an inhaler or nebulizer. Due to such acute effects, it is very important for Asthma to be diagnosed as soon as possible for any patient.

Asthma and other respiratory conditions have both a genetic and an environmental component, making diagnosis difficult. This is where genomic data can help identify how variations in genes that affect lung function and immune response might implicate respiratory health. Diagnosis in the clinical setting largely relies on parameters of lung function, such as FEV_1 (Forced Expiratory Volume in one second), FVC (Forced Vital Capacity), and the FEV_1/FVC ratio. These values give a measure of airway obstruction and the overall performance of respiration; this, however, does not always completely describe the condition of a patient. The

limitation of these parameters is that it is hard to differentiate asthma from other respiratory illnesses that might show similar results in these tests.

Based on this information, the problem that we want to solve is the problem of a possible inability to detect whether a patient has asthma (or other respiratory illnesses) or not based on their symptoms and tests taken. So, we wanted to make a machine learning model that would do just that, being easily accessible, easy to use, and very effective in determining the condition of a patient.

We believe this problem is important because having a model to accurately find if a patient has a common problem like asthma can help with the controlling of such a problem through treatment or other protective measures. This can immensely improve a person's quality of life if they have such a condition. Also, if there is no easily accessible and quick way to measure if someone has a certain respiratory illness, it can have drawbacks because the person's condition can become worse in the time it takes to find what treatment they need.

There were a few similar papers used as reference for the research we have done. The first one was the systematic scoping review "Machine Learning-Based Asthma Attack Prediction Models From Routinely Collected Electronic Health Records" (JMIR AI 2023), which determined that while there are a vast amount of ML-based models derived using EHRs to predict asthma attacks, there are still many technical challenges (like external validation, model explanation, and many more) that need to be taken care of before they are adopted clinically. The second one was the study "AI-Driven Data Analysis for Asthma Risk Prediction" (Healthcare 2025), which demonstrated that medical clinicians with accurate support could effectively use AI-driven acoustic analysis systems to improve the efficiency of asthma diagnosis, mainly by using features of Long-Term Average Spectrum (LTAS) and Single-Frequency Filtering Cepstral Coefficients (SFCCs). The third one was the study "AI model for predicting asthma prognosis in children" (JACI-Global 2025), which found that certain developed AI models using clinical variables from EHRs were effective in predicting asthma prognosis for children (which demonstrates the potential use of AI in patient education). The final one was the paper "Artificial Intelligence Algorithms in Asthma Management: A Review of Data Engineering, Predictive Models, and Future Implications" (Applied Sciences 2025), and it analyzed the evolution of AI from traditional Machine Learning models to Generative AI like ChatGPT. It found that there are many applications of all these types of models in Asthma care, and outlined future research directions for the actual use of AI in such situations. All these models provided us with very useful insight for my work, which was very important in the analysis and conclusions that we came up with.

Materials & Methods

In this dataset (The dataset used in this project can be accessed through this link: https://huggingface.co/datasets/ericyxy98/pulmonary-disease-airway-lung-function-dataset), there are numerous columns, consisting of the test number, the patient's race, age, weight, height, and other identifying demographic data. Then, it moves on to respiratory-related data, like FEV1,

FVC, the ratio between those two values, and some other measured data. To predict the patient's condition the columns of the patient's Sex, Weight, Height, Baseline FEV1 (in liters), Baseline FVC (in liters), and Baseline FEV1/FVC (raw ratio) were used. Based on these columns, the patient's condition was put into one of the following categories: Healthy, Cystic Fibrosis, Asthma, COPD, or other.

Before any data was inputted into the models, the general dataset was split, with 33% of the entries being classified as testing data and the other 67% being classified as training data. This split ensured a random split of the data that provided for the accurate preparation and execution testing of the model, providing an unbiased estimation of the performance of each machine learning model.

To predict the patient's condition, we tested five different machine learning models individually, then combined them using different strategies with the goal of taking the most accurate components of each model and getting precise measurements for the predictions. These five models are a decision tree model, a random forest model, a logistic regression model, an MLP classifier model, and a K nearest neighbors model. Most of these models used parameters, and to get the most optimal predictive result, the values of these parameters were optimized (known as hyperparameter optimization). The hyperparameters for each model were as follows: max_depth=40 (decision tree), max_depth=50, n_estimators=100 (random forest), hidden_layer_sizes=(175,) (MLP classifier), and n_neighbors=8, weights='distance' (K nearest neighbors). With that being said, explanations of each model are documented below.

Decision trees is another predictive machine learning concept, but it is much different than linear regression. The basis of decision trees rests on binary answers; there are a bunch of questions, or "nodes", on the decision tree (starting from the root node), and these questions all have multiple answers that are transmitted through "branches" of the decision tree. In specific, at each node, the algorithm evaluates a certain feature or condition, and based on the answer to that evaluation, the main dataset is cut down, effectively sorting it to match whatever final criteria was intended to be found. The main parameter for decision trees is max_depth, which is the number of statements in the tree. This must be defined before the model runs. Some real world applications of a decision tree model are in business for risk assessment and in marketing for product recommendations, as the different questions asked can narrow down to an answer.

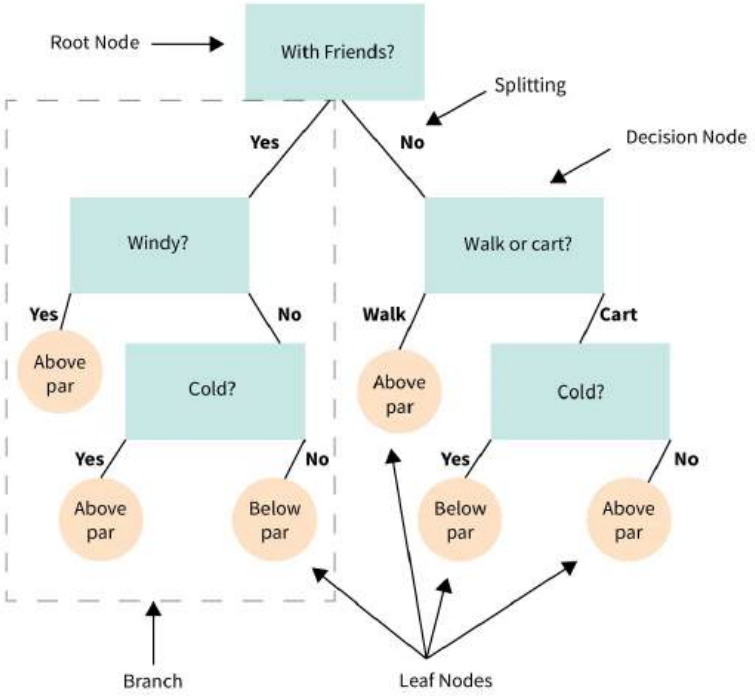


Fig 1: Example model of decision tree

Random forests are another predictive machine learning concept that involves multiple decision trees. Using the multiple decision trees and taking the average of the predictions prompted from all of the decision trees, a conclusion can be made. This is just a more nuanced form of a decision tree model, as instead of just one decision tree, there are multiple. Another key difference is the main parameter; in this case, the parameter of max_depth is still used, but the value is a little bit different. Also, there is another parameter that is called n_estimators, which is very important as it is used to determine the specific number of decision trees that must be used in the model. Some real world applications of a model using this concept are everything mentioned in the decision tree model explanation, as the same conditions apply, as well as finance with stock trading (analyzing patterns to predict stock trends) and agriculture (analysis of soil data and weather patterns to predict crop yields).

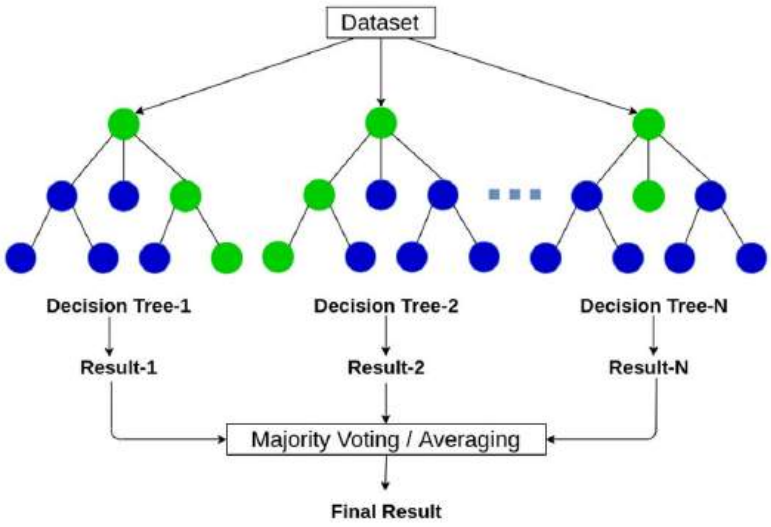


Fig 2: Example model of random forest

Logistic regression is a predictive machine learning concept used for classification tasks, specifically predicting the probability of a binary/categorical outcome. This probability can then be used to classify an input into one of two or more categories. Unlike a linear regression model, which logistic regression stems from, logistic regression models use a logistic (or sigmoid) function, which makes the output a probability score. This creates an s-shaped curve. There are multiple types of logistic regression, ranging from binary, to multinomial, to ordinal. Binary logistic regression occurs when there are only two possible outcomes, multinomial occurs when there are three or more with no specified order, and ordinal occurs when there are three or more with a natural order (like grading scale or customer satisfaction rating). Some applications of logistic regression models in the real world include classifying emails as spam or not spam, predicting customer churn, and assessing clinical risk scores.

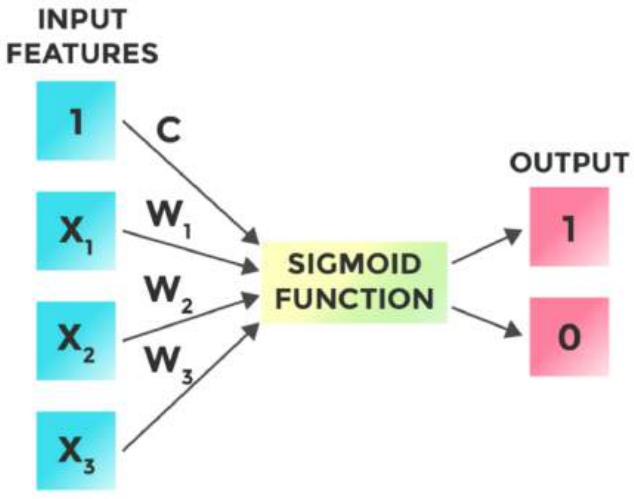


Fig 3: Example model of logistic regression

Neural networks is another predictive machine learning concept used in this project, with a particular focus on the MLP Classifier model (a type of neural network). It models the human brain, and the way it works is the following: there is an input, and there are multiple layers, and there is an output. There are connections between each layer, which are called weights, and these are used to find values that go to each layer. The way those values work is that first, the product of the input and the number on the line (the line is the weight) is measured, with all the products being added up in the case of multiple lines mapping to one neuron. This continues on until all of the layers have been passed through, and the final sum of all the products at the very end is the output. When you are training a neural network, you are finding the numbers of the lines, and when you test the model, you are finding the number which is the final output. Some useful parameters in neural network models are L2 regularization, alpha, and max_iter. L2 regularization makes sure the weight on a certain pixel isn't too big, as if the maximum weight on a specific one is not a low value like 3 or 5 percent, then the model doesn't provide a feasible solution. This is the reason the model doesn't overfit, along with making sure the alpha parameter of a model is large enough. Finally, the max_iter value makes sure that the model is optimized, as if the value for this parameter is very low, the model will not be able to go through enough loops for it to confidently know its prediction, hence the error given in the coding atmosphere. In general, using neural networks is useful in handling complex and nonlinear datasets that might pose problems to more conceptually simple models.

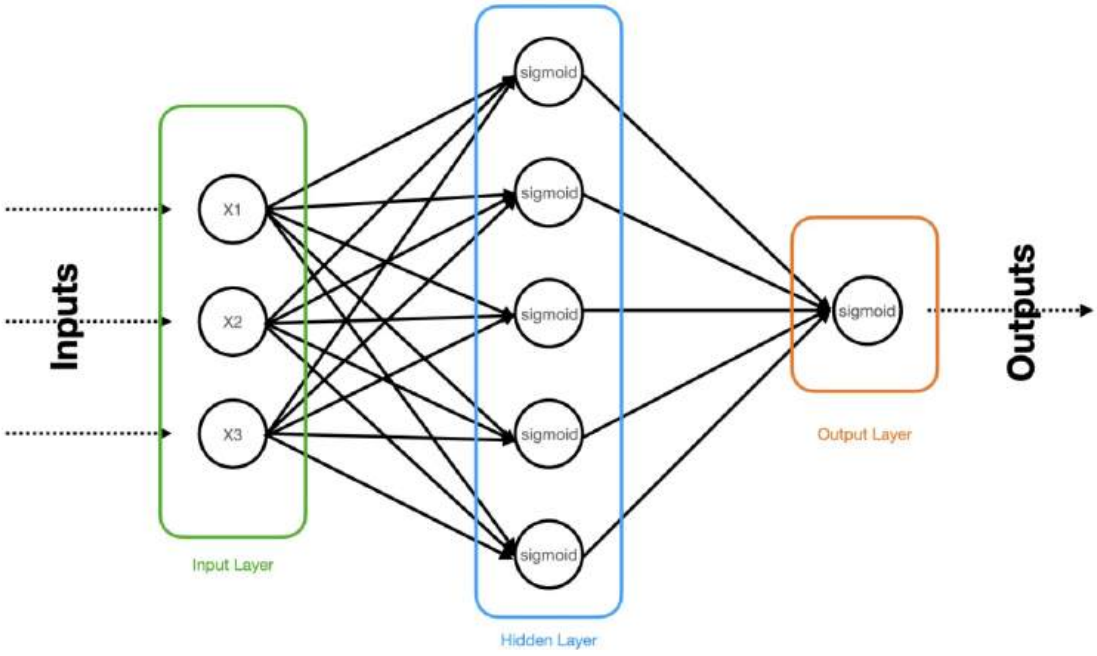


Fig 4: Example model of neural network

K nearest neighbors is another machine learning concept that is used frequently. The way it works is that a point is plotted on a plot of data, where there are two sections with different

answers/classifications. Based on a certain number of neighbors to that point, the point's nature will be determined. For example, if the two sections are one that is defined by letter A and the other defined by letter B, and there are 5 neighbors, the undefined point will be type A if more neighbors are type A, and vice versa. For this reason, this concept is very useful for classification. The main parameters in this model are the number of neighbors, as that determines how many points will be referenced in the categorization of the data point, as well as the way the neighbors are weighted ('distance' or 'uniform'), which decides whether all points around are weighted equally or weighted based on their distance to the data point. Some real world applications of a K nearest neighbors model are in recommendation systems and text and image classification, as the output can be decided based on the similar points around it.

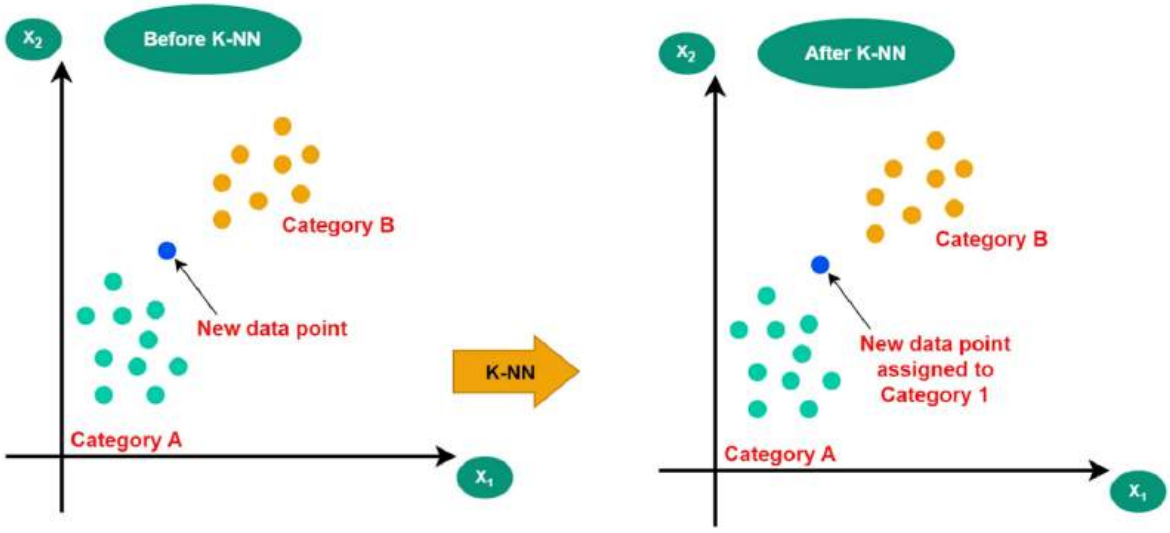


Fig 5: Example model of K nearest neighbors

These were the methods used individually, but to combine them, we used the following strategies:

As is strikingly evident through the accuracy of the individual models, there is much to be improved in pursuit of an accurate final model. The first strategy employed to tackle this problem was the simple averaging of the outputs of each model. This was done by adding the outputs of the 5 models, then dividing by 5 and rounding that result to get the final value using all of the models. This approach gave an output that was more accurate than most of the models, but it still faltered in comparison to some of the models individually, and it is definitely not as accurate as it must be in order to be used in real-life situations.

So, a second strategy was employed, that being taking the weighted average of all the models. Since some of the models were more accurate than even the combination of all of the models, it was clear that those more accurate models had to be considered more heavily when coming up with a final consensus about the output of the combined model. So, this was put into action, as by adding the accuracies of all the models and dividing the individual accuracies of each model by that total, the weightage of each individual model was determined. Then, instead

of just adding the value from each of the model outputs and dividing by 5, the individual output for each model was multiplied by the decimal weight, then rounded to get the final output. This provided a more accurate result than the regular average of all the models did, but it still was not accurate enough to be used in any real scenario.

Results

To document the results achieved by each model, a classification report was generated. This report gave various data, including the model's precision, recall, F-beta score, and support.

First, the model's precision was generated through the equation tp / (tp+ fp) , where tp is the number of true positives and fp is the number of false positives. Put into words, the precision is the ability of the classifier to not label a negative sample as a positive.

Next, the model's recall was generated through the equation tp / (tp + fn), where tp again is the number of true positives and fn is the number of false negatives. The recall is the ability of the classifier to identify all the truly positive samples,

Next, the model's F-beta score is the weighted harmonic mean of the precision and recall, which can also be described as the average of the two values while keeping the important data weighted more. In this case, the value that is weighted more is deduced by the factor of beta. If beta is equal to 1.0, recall and precision are equally important, while any value above that accounts for the amount recall is weighted more and vice versa.

The results of each model will be displayed below:

1. Decision tree (max_depth=40)

	precision	recall	f1-score	support
1	0.93	0.96	0.94	112
2	0.90	0.91	0.91	58
3	0.96	0.94	0.95	174
4	1.00	0.75	0.86	4
5	1.00	1.00	1.00	2
accuracy			0.94	350
macro avg	0.96	0.91	0.93	350
weighted avg	0.94	0.94	0.94	350

	precision	recall	f1-score	support
1	1.00	1.00	1.00	199
2	1.00	1.00	1.00	114
3	1.00	1.00	1.00	376
4	1.00	1.00	1.00	6
5	1.00	1.00	1.00	13
accuracy			1.00	708
macro avg	1.00	1.00	1.00	708
weighted avg	1.00	1.00	1.00	708

Fig 6: Classification report for decision tree model

2. Random forest (max_depth=50, n_estimators=100)

	precision	recall	f1-score	support
1	0.95	0.96	0.95	112
2	1.00	0.93	0.96	58
3	0.96	0.98	0.97	174
4	1.00	0.75	0.86	4
5	1.00	1.00	1.00	2
accuracy			0.96	350
macro avg	0.98	0.92	0.95	350
weighted avg	0.96	0.96	0.96	350

	precision	recall	f1-score	support
1	1.00	1.00	1.00	199
2	1.00	1.00	1.00	114
3	1.00	1.00	1.00	376
4	1.00	1.00	1.00	6
5	1.00	1.00	1.00	13
accuracy			1.00	708
macro avg	1.00	1.00	1.00	708
weighted avg	1.00	1.00	1.00	708

Fig 7: Classification report for random forest model

3. Logistic Regression

	precision	recall	f1-score	support
1	0.62	0.50	0.55	112
2	0.71	0.17	0.28	58
3	0.63	0.88	0.73	174
4	1.00	0.75	0.86	4
5	0.00	0.00	0.00	2
accuracy			0.63	350
macro avg	0.59	0.46	0.48	350
weighted avg	0.64	0.63	0.60	350

	precision	recall	f1-score	support
1	0.61	0.55	0.58	199
2	0.47	0.08	0.14	114
3	0.65	0.88	0.75	376
4	1.00	1.00	1.00	6
5	0.00	0.00	0.00	13
accuracy			0.64	708
macro avg	0.55	0.50	0.49	708
weighted avg	0.60	0.64	0.59	708

Fig 8: Classification report for logistic regression model

4. MLP Classifier (hidden_layer_sizes = (175,))

	precision	recall	f1-score	support
1	0.74	0.51	0.60	112
2	0.77	0.41	0.54	58
3	0.65	0.89	0.75	174
4	1.00	0.75	0.86	4
5	0.00	0.00	0.00	2
accuracy			0.68	350
macro avg	0.63	0.51	0.55	350
weighted avg	0.70	0.68	0.67	350

	precision	recall	f1-score	support
1	0.70	0.54	0.61	199
2	0.75	0.33	0.46	114
3	0.67	0.89	0.76	376
4	1.00	1.00	1.00	6
5	0.00	0.00	0.00	13
accuracy			0.69	708
macro avg	0.62	0.55	0.57	708
weighted avg	0.68	0.69	0.66	708

Fig 9: Classification report for MLP Classifier model

5. K nearest neighbors (n_neighbors=8, weights='distance')

	precision	recall	f1-score	support
1	0.94	0.96	0.95	112
2	0.98	0.93	0.96	58
3	0.96	0.97	0.97	174
4	1.00	0.75	0.86	4
5	1.00	1.00	1.00	2
accuracy			0.96	350
macro avg	0.98	0.92	0.95	350
weighted avg	0.96	0.96	0.96	350

	precision	recall	f1-score	support
1	1.00	1.00	1.00	199
2	1.00	1.00	1.00	114
3	1.00	1.00	1.00	376
4	1.00	1.00	1.00	6
5	1.00	1.00	1.00	13
accuracy			1.00	708
macro avg	1.00	1.00	1.00	708
weighted avg	1.00	1.00	1.00	708

Fig 10: Classification report for K nearest neighbors model

In some of the models (decision tree, random forest, and K nearest neighbors), there is a concept known as overfitting that is clearly exhibited. This is when the training performance is better than the testing performance to an unnatural degree, which shows that the model is very specific

to the training data even though the predictions for the testing data might still be relatively accurate. This a problem because these types of models will find difficulty in generalizing results, making them less applicable when used more often in the real world where patients will be of all different kinds. This could possibly be because of insufficient training data, meaning the data used to train the model is too little in size, or because of improper feature selection, meaning the features used from the dataset for the models to make predictions are irrelevant or redundant, causing pattern recognition that does not exist in the real world and does not correlate to actually figuring out if a patient has asthma. However, for these models it isn't the largest issue, as the testing accuracy is still quite high comparatively to the other models and in general.

Discussion

The work done in this project was intended to create an efficient way for doctors and people in general to know whether the data generated from their flow volume curves entailed that they had asthma or another respiratory illness. This was achieved by analyzing a patient's Sex, Weight, Height, Baseline FEV1 (in liters), Baseline FVC (in liters), and Baseline FEV1/FVC (raw ratio) , and deducing a patient's condition (Healthy, Cystic Fibrosis, Asthma, COPD, or other) based on that. To ensure that the output was immensely accurate, 5 different machine learning models (decision tree, random forest, logistic regression, MLP classifier, K nearest neighbors) were used to analyze the input, as well as the average and weighted combinations of these models. This provided an accurate model that can be used for patients all over the world that want to know whether they have a serious chronic respiratory condition like asthma,

In the future, the work we have done can be built on by analyzing larger datasets with different types of people. This will ensure that the model created is even more accurate, as more data can be used to train the model. Also, the inputted data can be stretched past just flow volume curves to things like genomic data, as that also relates to asthma and can be used to analyze more nuanced conditions of a patient. If this is done, then asthma can be accurately identified such models can be optimized for use in a clinical atmosphere.

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Norm-Driven Industry Emergence: The Case of Assisted Suicide By Deepthi Chandran

Abstract

This study explores how changing social norms around bodily autonomy paved the way for the assisted suicide industry to emerge. Once viewed as taboo and ethically unacceptable, assisted suicide has progressively gained legal acceptance and professional recognition in various regions. Using institutional theory, the paper develops a process model describing how moral legitimacy commonly arises before formal legal regulation. Through a historical review of activism, judicial decisions, medical debates, and cultural discussions, three key mechanisms of informal institutional change are identified: the broadening of moral vocabulary, the disruption of longstanding norms, and the development of a conditional consensus—a negotiated tolerance of morally controversial behavior. These shifts have allowed organizations to formalize the practice and integrate it into mainstream frameworks. Notably, contested markets depend not only on entrepreneurs but on a wide array of cultural actors—patients, activists, medical professionals, and legal advocates—all contributing important pre-market moral work. This model also offers a useful lens for understanding other ethically sensitive industries like biotechnology and psychedelics. It provides valuable guidance for scholars, policymakers, and industry practitioners navigating complex ethical questions in emerging markets.

Keywords

Assisted suicide; bodily autonomy; social norms; institutions; legitimacy.

Introduction

The assisted suicide industry has evolved from a once-taboo subject into a globally recognized and increasingly regulated sector (Mroz et al. 2021). Oregon was the first jurisdiction that legalized assisted suicide, through its Death with Dignity act in 1994. The assisted suicide industry's emergence can be traced back to the passing of this law. Countries such as Switzerland and several U.S. states have since then,adopted similar legislation (Emanuel et al. 2016), which reflected broader shifts in social norms surrounding bodily autonomy, dignity, and end-of-life decision-making (Hiatt et al., 2009; Fontalis et al. 2018). Assisted suicide transformed into a legalized and regulated industry from a stigmatized practice. The causes of this normative change have to be understood for explaining its emergence.(Mroz et al. 2021; Richards & Krawczyk, 2021; Emanuel et al. 2002).

Industry emergence relates to the early development of a sector featured by novel products,technologies, or business models (Kenton,2022). Scholars argue that new industries are formed when shifting social and professional norms create opportunities for legitimacy construction through affiliation, theorization and collective action (Tolbert et al. 2010; David et al. 2012).Social movements and regulatory changes can also disrupt existing practices, opening space for the industries that are aligned with the new social norms. (Hiatt et al. 2009).Along with

that, the normalization of previously unconventional behaviors allows these industries to embed and institutionalize over time (Mohliver, 2019).

While earlier studies have investigated how entrepreneurs respond to shifting norms, less attention has been paid to how norms themselves evolve and create opportunities for new industries (Hiatt et al., 2009;Tolbert et al. 2011). This paper provides a process model of norm-driven industry emergence and how diffused actors build moral legitimacy before regulations are formalized. Focusing on the moral, pre-market efforts of patients, activists, and professionals, and not solely on entrepreneurial exploitation illustrates how normative change paves the way for contested industries to emerge. (David et al. 2012; Mohliver, 2019).

Literature Review

To understand how new industries arise, it is crucial to examine shifting institutional landscapes—the norms, rules, and belief systems that guide social behavior (Hiatt et al., 2009). This section synthesizes research on legitimacy construction (David et al., 2012), organizational responses to cultural change (Hiatt et al., 2009), and how stigmatized practices gain acceptance over time (Mohliver, 2019). Together, these perspectives shed light on how evolving attitudes toward bodily autonomy have catalyzed the assisted suicide industry's development.

1.1. Institutions as Constraints and Enablers

Institutions shape entrepreneurial activity by both constraining and enabling it, determining which industries develop based on normative legitimacy rather than profit alone. Tolbert et al. (2010) discusses how entrepreneurs can influence norms but mainly view organizational reactions in isolation, missing how broader cultural shifts across diverse stakeholders loosen constraints for industries like assisted dying.

1.2. Legitimacy Construction through Strategic Action

How organizations strategically build legitimacy revealing limitations in addressing broader cultural change is what these studies focus on. David et al. (2012) demonstrate that firms can build legitimacy without formal credentials by leveraging elite institutions' reputations. Though this highlights shifting professional norms, it treats legitimacy as a strategic result, overlooking the wider cultural values underpinning such shifts. Hiatt et al. (2009) study the deinstitutionalization of alcohol norms, showing how legal changes and social movements opened opportunities for alternatives like soda production. Their research illustrates how gradual social norm erosion, rather than sudden shocks alone, creates pathways for new industries. Yet, the broader societal processes fostering this relaxation remain underexplored.

1.3. Normalization of Stigmatized Practices

Research shows how stigmatized practices normalize within networks, but often overlooks societal-level cultural change. Mohliver (2019) tracks how stock-option backdating normalized

within professional circles, focusing on network-level stigma erosion but missing how wider cultural shifts enable this acceptance.

1.4. Synthesis and Limitations

Collectively, these studies emphasize legitimacy diffusion and organizational responses but often neglect the slow cultural transformations shaping industries over decades. This oversight is especially relevant for the assisted suicide industry, where distributed changes around autonomy, consent, and dignity eased constraints and allowed legitimacy to flourish. While each paper provides valuable insight into institutional processes, the final lines of each paragraph highlight a shared limitation: the neglect of broader cultural and normative shifts that shape institutional change over time. Tolbert et al. (2011) emphasizes isolated organizational responses but overlooks how normative expectations evolve across different stakeholder groups. David et al. (2013) focuses on actors' strategic efforts to gain legitimacy, yet fails to consider how shifting cultural values create the conditions for such efforts to succeed. Hiatt et al. (2009) highlights sudden shifts in norms due to legal or activist pressure but does not address the gradual relaxation of social taboos. Mohliver (2019) analyzes normalization within networks but misses how changing public attitudes toward ethics may enable that normalization. These gaps suggest that institutional theory tends to focus on observable diffusion within organizations (Tolbert et al. 2011), while overlooking the slower cultural transformations (Hiatt et al. 2009)—such as those that enabled the growing acceptance of assisted dying (Kangas & Vestheim, 2010)—that support long-term institutional change.

Narrative of Industry Emergence

The link between broader bodily autonomy movements and assisted suicide can be traced through overlapping debates about personal sovereignty. Early reproductive rights activists, such as Margaret Sanger, reframed control over one's body as a matter of personal choice, establishing a moral vocabulary that later informed debates on self-determination in dying (EBSCO, 2020). Similarly, the Voluntary Euthanasia Society opened moral space for discussions about death (Benedict et al. 1998). These parallel movements gradually normalized the idea that individuals could make ethical decisions about their own bodies, laying the groundwork for acceptance of assisted dying (Richards & Krawczyk, 2021).

2.1. Early Struggles Over Bodily Rights

The fight began far from death, with early battles over reproductive control and state paternalism. Comstock Act (1873). Restricted birth control information, institutionalizing state control over bodies (Li, 2025). Buck v. Bell (1927) Legitimized forced sterilization (Tandy, 2022). Such practices underscored the dangers of state paternalism and seeded later demands for bodily rights. Margaret Sanger's Activism. Early resistance came from activists like Margaret

Sanger, who reframed reproductive control as personal choice (Amory, 2011). Voluntary Euthanasia Society (UK, 1935). Opened moral space for debating death (Benedict et al. 1998).

2.2. Mid-20th Century Shifts in Medical Trust and Autonomy

Social and medical crises reframed autonomy as both a cultural and ethical imperative. Thalidomide Scandals. By the mid-20th century, scandals like Thalidomide shattered medical trust (Ridings, 2012). Palliative Care Pioneers. Reframed death as a site of dignity (Redwine & Ganti, 2024). Bioethics and Feminism. Movements such as *Our Bodies, Ourselves* (Nichols, 2000) and the contraceptive pill (Kao, 2000) amplified autonomy, embedding self-determination in culture.

2.3. Legal Milestones Supporting Personal Sovereignty.

Court decisions progressively reinforced privacy and bodily rights, creating legal precedents for end-of-life autonomy. Griswold v. Connecticut (1965) and Roe v. Wade (1973). Reframed privacy as sovereignty (Griswold v. Connecticut, 1965). In re Quinlan (1976) and Cruzan v. Director, Missouri Department of Health (1990). Enshrined rights to refuse treatment (Szalados, 2007;Glover,1990). AIDS Crisis. Added urgency, as patients demanded dignity in dying (Nourse, 2011).

2.4. Activism and the Transition to Institutional Practice

Public advocacy and symbolic figures propelled assisted dying from moral debate to policy. Hemlock Society. Advanced public debate (Harris et al. 2006). Elizabeth Bouvia. Legal battles highlighted self-determination. Dr. Jack Kevorkian. Though controversial, it served as a symbolic proxy for practitioners pushing boundaries, forcing public confrontation with the taboo (BBC News, 2011).

Policy Breakthroughs

By the early 1990s, opinion had shifted: Washington's failed 1991 ballot measure laid groundwork for Oregon's 1994 breakthrough (Oregon Health Authority, 2025), after which assisted dying moved from moral debate to institutionalized practice, later modeled globally (Richards & Krawczyk, 2021).

Theoretical analysis

Norms are socially enforced rules or expectations that guide behavior (North, 1990). Initially, societal norms strongly opposed assisted suicide, framing it as morally wrong and sinful (Singer, 1993; Pellegrino, 2002). This perspective was rooted in ethical and religious reasoning: life was considered sacred, inviolable, and inherently valuable, and any deliberate act to end it was viewed as a violation of natural, divine, or societal law (Beauchamp & Childress, 2019). Institutions such as the legal system, the medical profession, and religious authorities reinforced this stance, emphasizing that human life should be preserved under all circumstances, even in the

face of suffering. Dominant ethical frameworks, particularly deontological ethics, prioritized the sanctity of life over individual choice, framing assisted suicide as unethical because it undermined the inherent worth and dignity of life itself (Gillon, 1994).

Over time, however, significant legal and cultural milestones, such as Roe v. Wade, catalyzed a broader shift toward individualism and personal sovereignty (Siegel, 2011). This gradual reorientation reframed bodily autonomy as a moral right rather than a transgression. Societal recognition of the subjective value of life allowed for nuanced ethical debates: individuals could determine thresholds for meaningful or bearable existence. In contexts of intolerable and incurable suffering, moral reasoning shifted from preserving life at all costs to respecting personal choice and minimizing suffering. Assisted suicide thus came to be framed not as the destruction of life but as an ethically defensible means of alleviating suffering and respecting individual autonomy (Quill et al. 1997).

These shifts illustrate that legitimacy for new practices emerges not solely from legal rulings or medical advances, but from broader changes in societal norms and institutional logics (DiMaggio & Powell, 1983). Institutional theory emphasizes that organizations and industries evolve in response to normative changes. The transition of assisted suicide from taboo to an accepted, debated practice demonstrates how ethical perceptions shape institutional acceptance and industry formation, highlighting that moral and cultural frameworks create space for novel practices.

3.1 Informal Institutions

Informal institutions consist of socially shared rules, norms, and moral frameworks that guide behavior without formal legal enforcement (North, 1990; Scott, 2013). They shape perceptions of what is morally and socially acceptable, influencing both individual actions and collective expectations.

Moral vocabulary expansion

One key mechanism is moral vocabulary expansion, whereby activists or thought leaders reframe behaviors previously viewed as immoral using new ethical language (Oh, 2025). Discussions initially surrounding contraception and abortion were reframed in terms of personal autonomy; over time, this framing extended to end-of-life decisions. By reshaping moral vocabulary, activists disrupted established norms, facilitating ethical debate and the gradual erosion of taboo surrounding assisted suicide.

Conditional consensus

Another mechanism is conditional consensus, defined as a social agreement reached only under specific circumstances or conditions, rather than full or unconditional acceptance (Tolbert et al. 2010). In assisted dying, societal acceptance of bodily autonomy applied primarily to terminally ill, competent patients under procedural safeguards. Conditional consensus

exemplifies bounded legitimacy, where deviations from established norms are tolerated only when framed within socially agreed-upon rules (David et al. 2012).

Symbolic exemplars and advocacy networks

Symbolic examples and advocacy networks further reinforced norm shifts. Individuals like Elizabeth Bouvia and Dr. Jack Kevorkian, along with organizations such as the Voluntary Euthanasia Society and Hemlock Society, acted as moral and symbolic reference points. By publicly challenging taboos and advocating patient choice, these actors legitimized new ethical frameworks, influenced public opinion, and exerted moral pressure on formal institutions to respond. This illustrates how norm diffusion operates through social examples, reinforcing ethical and cultural change (Mohliver, 2019).

3.2 Formal Institutions

In contrast, formal institutions are codified laws, regulations, and organizational rules that enforce behavior through legal authority (North, 1990; Scott, 2013). Formal institutions codified and stabilized norm changes rather than initiating them, in assisted dying.
The Oregon Death with Dignity Act (1994) exemplifies this process: liability for physicians reduced, procedural safeguards were established, and systematic reporting was required. Because of legal recognition, a framework reflecting and strengthening shifting social norms was provided (Emanuel et al. 2016). Organizations such as Dignitas in Switzerland further stabilized practices by demonstrating compliance, transparency, and visibility, showing how entrepreneurship embeds contested behaviors within institutional frameworks (Dignity in Dying, 2023).

3.3 Interaction of Informal and Formal Institutions

Formal institutions interact with informal ones through these mechanisms: informal institutions soften resistance via moral vocabulary expansion, conditional consensus, and symbolic examples, while formal institutions codify these changes, conferring legal legitimacy. This interaction demonstrates how normative pressures and written rules together create legitimacy that allow new industries and socially disputed practices to flourish (Hiatt et al. 2009; Tolbert et al. 2010; David et al. 2012). In assisted dying, changes to autonomy, consent, and dignity weaken restrictions which allows for legal codification and the creation of new social norms (Richards & Krawczyk, 2021).

Conclusion

This paper provided insights on how changing attitudes towards bodily autonomy spurred the growth of the assisted dying industry. Actors across the spectrum—activists, legal advocates, patients, and professionals—systemically reframed autonomy to include control over one's life and death, softening resistance from the public at large before legal sanction (Hiatt et al. 2009; Emanuel et al. 2016). As seen here, the legal sanctioning of assisted dying was preceded by its

normative legitimacy. This illustrates that the moral acceptance of a practice is often the first step towards institutionalization.

This paper contributes to the academic literature on the emergence of contested industries, specifically, the assisted dying industry, by proposing the process model of vocabulary expansion, norm disruption, and conditional consensus. Particularly the concept of conditional consensus is important today as it illustrates the limits of social acceptability of taboo practices. Of particular interest to the academic literature is how these shifts were not entrepreneur driven (David et al. 2012; Mohliver, 2019).

This framework also provides insights for other morally contested markets. Researchers and practitioners alike can identify potential markets by tracing the continuum from private reflection, public debate, and professional practice.

Declaration of conflict of interests

The author declares that there are no conflicts of interest regarding the publication of this article.

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Justice in AI-Informed Healthcare By Sydney Sutherland

Abstract

Artificial intelligence appears to be a helpful tool in medicine, and has been introduced as a healthcare technology to help diagnose disease, suggest treatments, and even to provide prognoses. AI can take us to better outcomes and solutions via its accuracy and efficiency. However, its use raises crucial ethical issues, which remain unresolved, and are very important. One of the most significant ethical issues that AI use in medicine raises is justice, because AI systems have the ability not only to reflect but also to exacerbate health inequalities—unless they are programmed and implemented in ways that prevent bias. To implement medical AI justly, we need diverse oversight teams and representative data on which AI should be trained. This article argues that (a) we must include diverse review teams to oversee medical AI, and we must use diverse, comprehensive data for AI training. Diverse reviewer teams are better positioned to identify biases than are non-diverse ones. Furthermore, AI must be trained to produce responses by drawing on information about the appropriate reference class relative to who it aims to treat. Such improvements would lower algorithmic bias, and through these mechanisms of oversight, healthcare can achieve its bioethical obligation of justice. Although AI oversight and reform cannot solve social injustice in medicine single-handedly, it is a necessary step toward eradicating the existing disparities. The concept of justice entails not only changes in the broader society, but also immediate action to protect groups from the discrimination embedded in our very technologies.

I. Introduction

Artificial intelligence is quickly entering and transforming the medical field as we know it. It is now utilized more (and more) in medical settings to help doctors diagnosing illnesses, predicting health outcomes, and even choosing treatment options. These powerful new tools can make medicine faster and more accurate, as studies show AI increases accuracy, and is a time-saving technology (Alowais et al.). However, there is a serious bioethical concern regarding justice because of the likelihood of any given AI's algorithmic bias. If AI isn't designed and implemented carefully, it can lead to tragic outcomes, such as the systematic favoring of certain groups, while harmful to others. If AI is not implemented carefully, it could introduce bias into hospitals and clinics, leading to unfair treatment that violates core bioethical principles, specifically justice. This would undermine the provision of ethical healthcare.

Every new tool brings challenges that have to be addressed before it can be trusted fully, and within reason. However, AI is a very powerful tool, and its challenges are harder to see because they are hidden inside complex systems and algorithms. Unlike a faulty machine whose malfunction can be easily identified, a biased AI tool could appear to be working normally and neutrally while silently giving worse results to some groups of patients. This can occur because the algorithms the AI tool uses may be biased. This hidden danger makes it a priority to think and act carefully about AI implementation in healthcare before it becomes mainstream, in order to prevent algorithmic bias and avoid unjust outcomes in healthcare.

Lin and Chen argue that AI bias is part of the greater problem of structural injustice. This means that broader systems of inequality shape both the data and the AI tools that depend on them. Algorithmic bias is usually a reflection of the inequalities embedded in the data used to train AI, but as Lin and Chen emphasize, this is just one problem among several. Three ways in which data can contribute to bias, per the article, are: when data training uses insufficient representation, when existing bias is embedded in the data, and when the reference-standard selection introduces bias. This last problem can be understood as the problem of selecting data from one population to train AI, but applying the results to a different population; this can result in suboptimal diagnosis, treatment, and prognosis for some groups, when disease presents differently across those groups. Lin and Chen just remind us that while diverse data is and will always be an essential step, it is not enough without structural change.

While Lin and Chen highlight many ways data can introduce bias, I'll focus on two: the need for diverse oversight teams and unrepresentative data. Overall, Lin and Chen argue that AI can be unjust when data creates disadvantages for marginalized groups and power imbalances shape how systems are built and used. To me, this means that problems in AI are not just technical issues but issues stemming from social division that are then embodied in our technology. Lin and Chen argue that bias should be seen in terms of structural injustice, where AI systems that interact with other social factors can exacerbate existing social inequalities if care is not taken to ensure the neutrality of their algorithms.

If most of the data that AI is trained on comes from one group of people or a specific idea of a group of people, then the AI might not work as well as it should for certain patient groups. To put it differently, the system's fairness depends on whether the data it was trained on is representative of the population for which the AI system is supposed to make diagnoses, treatment recommendations, or outcome predictions. If the data is unrepresentative, it can produce worse health outcomes for certain social groups, therefore making the system unjust. For example, AI tools tried to detect melanoma, a type of skin cancer, with unrepresentative data. Most of the AI models were trained on patients from the U.S., Europe, and Australia, who had lighter skin; because of that, the AI tools did not work as well on darker skin, which led to worse rates of correct diagnosis. This is a clear demonstration of how unrepresentative data can directly affect people's health (Cross et al.). If nothing is done, these built-in biases can reinforce existing prejudices, making healthcare inequalities worse rather than better. This matters immensely when we refer to the bioethical principle of justice.

Justice means that everyone gets "what is fair or what is their due," according to Vaughn. In healthcare, this means that everyone should receive the same quality of care, rather than some groups receiving better treatment than equally deserving others. By this firm logic, healthcare should be equally effective for all patients. The only reason to treat someone differently is if "there is a morally relevant reason for treating them differently" (Vaughn). Membership in a particular social group is not a morally relevant reason to treat people differently in the healthcare context. As Vaughn explains, justice isn't necessarily about treating all people the

same, but about making sure benefits and burdens in healthcare are distributed fairly–and rationally (Vaughn, 12).

If AI in medicine has bias, hidden or otherwise, then justice isn't honored, which undermines this core bioethical principle. In fact, justice is one of the four pillars in medical ethics, along with principles of beneficence, nonmaleficence, and autonomy. Any AI tool built should uphold these values, and if an AI system treats a group unfairly, it is violating at least one of these core principles, most importantly here, justice.

Justice is being violated when an AI tool makes diagnoses, treatment suggestions, and outcome predictions in a way that disadvantages a social group or set of social groups. These ethical concerns make this issue an immediate problem. So, clearly it is important to figure out how AI can be used without leading to injustice. In order to ensure justice in health care, we must eliminate algorithmic bias from AI-informed care. To achieve algorithmic neutrality, it is necessary that a diverse team of human reviewers oversee AI medical tools, and AI should receive data from multiple populations.

II. The Need for Diverse Reviewer Teams

AI should never be incorporated into hospitals without people approving it first, and not just any people, a diverse group of reviewers. Firstly, there's an issue of accountability. AI systems can't be held responsible for their mistakes because they aren't human. AI also possesses no emotion, so AI cannot "feel" bad for doing harm. AI systems by themselves have no agency, so they won't change their methods in the face of mistakes. What matters here is that mistakes, made by doctors or AI tools, are not unfairly distributed to certain social groups. Justice in medicine, statistically, should have roughly the same level of error across all groups of people. No group of people should be constantly receiving worse care than others. Responsibility should fall on the people and institutions that approve AI for use, since medical practitioners and healthcare organizations are the ones subject to bioethical standards. This would lead to clearer accountability and also keep healthcare systems from ignoring ethical problems in an attempt to save time, image, or money.

When there is no human oversight, a responsibility gap can occur (Vallor and Vierkant). A responsibility gap occurs when it is unclear who is morally or legally responsible for a negative outcome. Unlike in areas such as online advertising, where people simply see the wrong ad due to biased algorithms, bias in healthcare algorithms can contribute to unfair differences in survival rates, where some social groups have a higher risk of death. If there is an oversight team that is accountable, patients will know that there are humans standing behind the AI tool and its decisions, leading to a sense of security in that medical setting. That reassurance is crucial for building a safe and trustworthy environment. We need panels for accountability to keep medical institutions answerable for outcomes. The idea of a responsibility gap is truly concerning in medicine, because patients' health is at stake.

A dedicated team is especially crucial because AI for health is extremely complex and often opaque. Its internal workings and decisions are not easily understandable even by experts.

This kind of opacity makes it difficult to know whether an algorithm is biased or producing unjust outputs. I intentionally use the term "opacity" to signify that AI systems are not fully transparent; their functions can be hidden or difficult to interpret. With a diverse oversight group, hospitals have the ability to examine these systems, search for issues, and hold these issues accountable to someone. It is this kind of accountability that promotes transparency, where the AI itself is not transparent and is necessary for justice so that patients are treated fairly and no one is affected disproportionately by hidden biases.

Furthermore, these panels must be diverse to better prevent bias. If the review team is made up of people from a similar background, specifically a privileged one, they might miss particular ways that an AI's algorithm is biased because they don't have the same perspective as people from another social group. A more diverse group is more likely to notice when an AI tool is unfair or biased because individuals who have personal experiences or who are more likely to have researched inequality can recognize issues that may otherwise be overlooked. Their perspectives help define the proper representation of social groups. That's why it's important to have reviewers from different racial, gender, and social backgrounds.

Diversity in oversight is essential for the same reason diversity is valued in healthcare teams in general. This becomes evident when taking in the risks of non-diverse oversight. Studies show that when non-diverse healthcare professionals interact with AI, AI can learn the biases, and over-reliance on these tools pushes AI to make decisions in a way that they think that physicians would (Ueda et al.). Thus, diversity is valued as an advantage in healthcare teams, and it is also necessary to prevent AI from producing unjust results. In other words, if a doctor unconsciously favors certain groups or uses biased inferences, the AI can learn unhealthy habits and then implement these habits in their work. If the people who design or train AI have discriminatory behavior, these behaviors can be picked up and reflected in AI. Wrongful biased interactions, patients and physicians included, with the AI tools can lead to learned bias and repeated mistakes. The AI is not trained on past healthcare interactions, but it learns from communicating with healthcare professionals and patients in real time. If AI is properly trained (Ueda et al.), an oversight team that reflects a wide variety of perspectives is well-equipped to notice patterns of unfairness that a homogenous team might overlook. A system designed solely by people from privileged backgrounds is more likely to accidentally benefit those same groups best–leaving others behind. Diverse groups are uniquely positioned to identify bias and blind spots. Within AI, diverse oversight teams are vital, more likely to recognize when an algorithm is using biased data that it has inadvertently picked up from training data.

Furthermore, medical students expect AI to be handled responsibly. For example, in the article by Kimmerle et al., studies showed how students feel about AI in medicine, and they stated that while students are hopeful and intrigued by what AI can do, they also want it to be fair and transparent. This demonstrates that future doctors believe in guidelines and oversight of AI, so it does not discriminate.

Diverse oversight teams would meet those expectations and make sure hospitals are using AI in a way that patient groups and doctors can trust. For example, both AI systems and doctors

can make mistakes, but the key ethical component is that errors should not affect certain social groups more than others. Diverse reviewers can help prevent AI from making existing healthcare inequalities *worse*; reviewing algorithms for bias is to be responsible for monitoring fairness, but they are not expected to prevent all medical errors, which are quite common in medical practices. By enforcing diverse oversight, hospitals would be taking a step in the right direction towards fairness and the bioethical principle of justice.

Without this step, AI risks becoming an example of technology that works best for those who are already privileged and leaves behind those who are already vulnerable. There have been many examples historically of medical systems unconsciously and consciously reinforcing inequality, from the under-representation of women to the discriminatory ordering of who gets prioritized for an organ transplant. Diverse teams are a way to ensure history does not repeat itself in the context of AI-informed healthcare and only improves justice in healthcare.

III.a. The Need for Diverse Data in AI Tools

Even the most diverse oversight team cannot fix everything if the AI is trained on limited and unrepresentative data. If the data itself is biased, then the system must produce biased results. That is why another step is important in avoiding algorithmic bias in healthcare. We must ensure that AI tools are trained with diverse data representing people of all populations.

Nazer explains that bias can seep into AI in many ways, starting with how researchers choose which problem to solve or which prediction data to use. For example, sampling bias is a very common type of data bias. This can occur when data that is not representative of the entire population is used to develop algorithms that are meant to treat that same population. As in Nazer's article, an example demonstrating this is when an algorithm was "developed to predict acute kidney injury (AKI) using clinical data from the US Department of Veteran Affairs" (4). Even though the data was on hundreds of thousands of people, it was mostly made up of older non-Black men. This can later affect the performance of the developed algorithm as it cannot be fully reliable for predictions or diagnoses on other races, age groups, or genders.

Bias in AI often stems from datasets that are used to train these systems. When data is unrepresentative, then the AI is likely to make diagnoses, treatment recommendations, and make prognoses that are less of a fit for particular social groups. Unrepresentative data that is drawn from a smaller sample population than the population to which it is intended to be applied is one of the most common sources of unfairness in AI. A small sample does not allow for great generalizability, so the AI tool may think that the data it was given is sufficient because that is what it was programmed on; however, a larger population, if diverse, can offer a variety of data points that are beneficial for AI care.

Additionally, if the research is focused mostly on a specific group of people, then the algorithm will *naturally learn patterns that reflect only that group of people;* and will, therefore, ignore other groups. This will lead to AI misinterpreting symptoms or even overlooking important health factors, inevitably leading to misdiagnoses, non-ideal treatment recommendations, or implausible predictions.

Nazer also shows that many groups have been left out when developing healthcare algorithms. These include women, racial minorities, older people, and people with disabilities. When these groups are left out, AI ends up leading to inequalities in the efficacy of healthcare across social groups. For example, heart disease studies are often focused on men, which leads to AI tools that don't work well for women in that department, despite heart disease being more common in women than men. Older adults are also underrepresented in AI development because of changes in bodily functions, which means AI trained on younger patients may give false results for the elderly.

Even when datasets include *some* diversity, the preprocessing stage can introduce new forms of bias. For instance, efforts to "normalize" data often strip out information that appears missing or irregular, but those unusual findings may correspond to diverse groups. Nazer notes that preprocessing decisions can accidentally erase important data about minority patients needed to make algorithms *justly* fair. This mismanaging of data and outliers causes the algorithm to learn practices more in line with the majority populations. Without careful oversight, *this can reinforce inequities*–despite trying to correct them.

III.b. The Need for Relevant Reference Classes

AI models are usually validated on aggregate accuracy measures that make inequalities unclear across subgroups. There are two main features that the data must have in order to prevent algorithmic bias and to be fair. It has to be diverse enough to represent different social groups, and it has to be constructed in a way that shows the differences between these social groups when there are real differences in how disease presents across groups. Problems regarding insufficient diversity often appear during the validation and deployment phases. A system that performs with 90% accuracy overall may still misdiagnose patients in a minority subgroup; however, the inequalities can be unseen without a clear distinction of that subgroup. Nazer argues that bias testing should always look at subgroups like race, gender, and age so that unjust patterns can be caught before the AI is utilized in real-time healthcare. In other words, AI must be able to select the relevant reference class in cases where there are real differences in disease states across social groups, and distinguish this from the selection of merely unrepresentative reference classes. For example, returning to aggregation, diabetes has a higher rate of being seen in Hispanics. AI may help diagnose and treat diabetes in Hispanics, but it can lead to aggregation bias, meaning the model treats all Hispanic patients as one uniform group and ignores important differences in health and characteristics in subgroups. This can lead to the model failing to realize that there are multiple groups within Hispanics with varying health characteristics. If issues like these are left out during the development stage, the AI tool can go on to produce poor performance for some subpopulations regarding that health concern.

In healthcare, the consequences can be severe. Systems trained on the majority populations may perform poorly on minorities, producing outcomes that make inequities worse. For instance, the significance of the data implemented is crucial. As Mittelstadt *et al.* state, the common saying, "garbage in, garbage out", is used to refer to the poor outcomes of AI models

when the data they learn from is of poor quality, as noted by Stypinska & Franke. This is not just a technical problem, as it becomes a question of justice when some groups are not represented or misrepresented in the data, since those groups will face the greater proportion of errors. This indicates that data is a huge part of just AI tools, as whatever data goes into these systems is the key to how that AI tool will perform in its setting. Dermatological AI tools, for example, have repeatedly been shown to misdiagnose conditions on skin of color due to historical datasets being trained with lighter skin tones (Fliorent et al.). This is not simply a fluke; these errors recur repeatedly, harming groups that are currently underrepresented in healthcare data. Such data then fails to reflect population diversity. From a bioethical perspective, these outcomes violate the core principle of justice, which demands that all medicine deliver equitable care across social groups.

On the technical aspect, having diverse data is essential to making sure AI aligns with the principle of justice and ensures that there's no discrimination against minorities. This has significant implications for bioethics. On another aspect, justice calls for attention to the societal imbalances that mold healthcare systems. Ethical responsibility must be shared with hospitals and healthcare providers, who are accountable for how AI tools are put into patient care. Overall, I suggest that diverse data is a foundation in creating ethical AI use in healthcare for everyone, as other literature suggests. However, with diverse data alone, we will still see unjust practices unless the preprocessing stage doesn't delete unfamiliar data, and institutions also help address the structural injustices that Lin and Chen highlight. Without diverse data, algorithms will continue to produce results that advantage some groups over others, leading to the reinforcement of existing inequities. This leads to predictable unfairness for minorities, women, and older people. A commitment to both these solutions leads to a better path in medicine. Only change and inclusive datasets can improve AI-informed healthcare and help move medicine closer to its ethical pledge to justice for all.

IV. Objection

Some critics may consider an objection to this diverse oversight approach, which states that the real source of built-in bias in AI is societal unfairness and injustice, rather than the AI itself. According to this objection, AI only mirrors the world it emerges from. So, if society is unfair, then AI will also be unfair. Hence, it is insufficient to repair AI systems directly. The issue of social inequality is, at its source, deeply rooted, but should be addressed. The proposition behind the objection is straightforward. AI learns from the data, and that data comes from the very society in which we live. The problem, however, is that society is not just. Some groups have suffered discrimination, limited access to health care, and worse health outcomes long before AI. If AI systems are trained on data that reflects those patterns, then they will naturalize unequal outcomes in medicine. What this means is that they will make it appear as though health disparities reflect normal human diversity.

This means that any effort to rectify AI tools will touch only the surface of the problem. The root from which the bias emerged is social injustice itself. For instance, if one community does

not get the same access to doctors and hospitals as another, their medical data will differ from those of a better-accessed community. AI systems will notice that difference and may misjudge what those minority patients need. However, critics suggest the real issue is not the AI; the real issue is that people never had equal healthcare in the first place.

Some might also point out that too much emphasis on AI will create a false sense of progress. If a hospital has a new AI system that claims to be fair, the assumption might be that it has solved the related social inequalities. But if patients continue to suffer from discrimination or limited care, the inequalities haven't truly changed at all. The injustice is still there, but it's hidden behind a claim that AI has been "fixed". From this perspective, AI reform risks being a distraction from the deeper issues of social inequities.

This objection can be potent because it challenges the basis of AI reform. It essentially states that health care is not separable from our society and that it is and will always be a part of our world. If our society is unjust, then AI must also be unjust. The implication is that we should change society to change AI. Therefore, solving the bias of AI systems is most likely not the best way to solve the underlying social inequalities shaping medicine in the first place.

V. Response

While this is a compelling argument, it does not mean that we can disregard AI reforms. It is true that society is discriminatory, and it is true that discrimination does have an impact on healthcare. But debiasing AI *is* a way of debiasing a part of society itself. With medical AI, patients may be unfairly treated by machines that yield inappropriate diagnoses, treatments, and prognoses. Justice requires that we act today to rectify these devices, even if larger social issues continue to exist. This is important because flawed AI tools will continue to worsen inequities in care.

Justice never waits for the future. Justice is fairness now; if an AI system gives worse answers for some groups of patients, those patient groups are discriminated against presently. For example, if an AI system performs badly for some body types or chemical compositions, those patients might be misdiagnosed or treated improperly. Their health results might cause irreversible damage. Even if the larger reforms are being worked on by society, that does not mean we should allow groups to be misdiagnosed or offered inappropriate treatment at different rates. Justice requires us to fix injustice where we find it, even within AI.

Additionally, perfection is impossible, but improvement is needed. We might never be able to eradicate every trace of bias from society, medicine, or AI, but that is no excuse for inaction. The ethical responsibility of medicine is to treat each patient as well—and as equitably—as possible. Doing that requires making AI systems as fair and accurate for a variety of social groups as they possibly can be. Or otherwise, if we do nothing, then we let unfair tools entrench discriminatory practices. If we do something, we at least reduce the harm and make the system fairer than before.

Unfair AI can affect the institution by unfairly affecting doctors' decisions, as reliance and trust on a machine that is deemed to have all the right answers can lead to doctors following AI

choices. This leads to a lower trust in healthcare, and its equity. If patients feel that the technology that is used on them is discriminatory or unjust, they may stop seeking care. This is concerning because those who already face barriers in accessing healthcare are the ones who are more likely to receive less effective care. Unfair AI does not just symbolize injustice; it also reinforces it on a day-to-day basis. Reforming AI, on the other hand, helps build trust in progression, promotes equity, and protects vulnerable groups from prejudice.

When we bring together varied oversight teams, we ensure varied perspectives. These are solutions that may not fix all of society, but they clearly make healthcare more equitable. Because healthcare is so central to people, this is a big step forward. Reforming AI is not a separate fight from the fight for social justice. When we require diverse data, we make sure more groups are covered in medical research.

Finally, justice requires action on many levels. We cannot choose between solving injustice at the root or reforming AI; both are necessary. Fixing societal discrimination is the long-term solution to building a just world and fair healthcare settings. But in the meantime, changes, like the reforms I propose, must be made so people are treated well now. Society should undergo major reforms, but at the same time, AI should be rectified right now, so patients do not get harmed while waiting. Justice demands short-term and long-term fixes.

VI. Conclusion

The main claim of this paper is that AI must be carefully monitored and regulated in healthcare so that it does not reinforce social inequalities. AI has enormous potential to improve diagnoses, predict health outcomes, save patients' lives, and save time. However, if the algorithms that make up AI are biased, then the technology risks producing unjust results. In healthcare, injustice occurs when some social groups receive systematically worse care when compared to other groups. It is also when different levels in the quality of care are provided across groups. This directly contradicts the bioethical principle of justice, which requires that benefits and burdens in medicine be fairly distributed. If AI systems are not designed with fairness in mind, then they will violate this principle and harm minority groups at disproportionate rates.

To prevent this outcome, I have shown that two main changes and implementations are necessary. First, AI must be reviewed by diverse oversight teams that can identify and prevent unfairness. Second, AI tools must be trained on diverse data and trained to select appropriate reference classes so that the algorithms work equally well for all patient groups. These changes can make AI tools more neutral and just, which is essential for their safe use in medicine.

Implementing these reforms preserves justice because they directly protect patients from unfair treatment. I explained that justice in healthcare means each patient receives what is fair and what is their due based on their medical needs, not on irrelevant factors such as race, gender, or age. Oversight teams should always ensure that human accountability is upheld, and diverse data will ensure that tools work equally well for all groups. Together, these changes protect patients against a new hidden form of discrimination. In this way, the principle of justice is

actively preserved, and care is distributed *fairly*, so no patient group is left disadvantaged by the new technologies that are supposed to help them.

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Types of Black Holes , Explained by Devansh Agrawal

Have you ever wondered what happens when a giant star runs out of fuel or what might be hiding in the darkest parts of the universe? One of the most powerful and mysterious objects in the universe is the black hole. Even though we can't see black holes directly, scientists have found smart ways to study them by looking at how they affect stars, gas, and even space itself (NASA). Black holes have extremely strong gravity that pulls in everything around them, including light, thus the name black hole. They come in different sizes and are found all across the universe.

This paper will explore what black holes are, how they work. It will also elaborate the three main types - stellar, intermediate, and supermassive. It will also explain how each one forms and why they are important to understanding space.

There are 3 types of black holes: intermediate, stellar-mass, and supermassive. Each type forms through a unique process. Learning about them can help us to understand the development and its impact on the universe.

A black hole is a region in space having a very strong gravitational force. The scientific reason for this is that a massive amount of matter is fit into one small space. This creates a very strong gravitational force, which pulls in everything around it, even light cannot pass across. That's why black holes are invisible, and we can't see them directly. But scientists know they're there because of their effect on nearby objects, like stars or gas clouds. Observing the behaviour of the surroundings will help us identify the presence of a black hole nearby (Lerner).

Every black hole has two main parts. The event horizon is the edge of the black hole. Once something crosses this line, it cannot escape. One big misconception by people is that black holes pull something in. Well, that is wrong because objects fall into a black hole and are not being sucked in, that too if they enter the event horizon. Once there, they are pulled in with immense pressure until it goes into the singularity, which is the other part of a black hole. This is where all the matter is squeezed into one tiny spot with super strong gravity (Reddy).

Now that we know what a black hole is, let's look at the most common type, the stellar black holes. They form when very big stars (at least 8 times heavier than the Sun) run out of fuel and die. When this happens, the star explodes into a powerful blast called supernova. After the explosion, the center of the star goes into a gravitational collapse with the remains of the star turning into a black hole. NASA says, "When a massive star runs out of fuel, it may collapse and become a black hole" (Reddy).

Most stellar black holes are between 5 and 20 times the mass of the Sun. Some may even arise from huge gas clouds that collapse without becoming a star. When an object is falling into a black hole, it starts to glow. This occurs due to the strong forces acting on it. This phenomenon of glowing creates the best way for scientists to find the exact position. One well-known stellar black hole is Cygnus X-1, which was one of the first ever discovered (Wei).

The biggest type of black holes are called supermassive black holes. These are found at the center of most galaxies, including the Milky Way. In the Milky Way, our supermassive black

hole is called Sagittarius A. These supermassive black holes are way heavier than other ones. Some weigh more than 10 million times a solar mass. Sagittarius A is the supermassive black hole closest to Earth with a distance of 26,000 light years (Lerner).

Scientists aren't completely sure how supermassive black holes form, but they have a few ideas or hypotheses. One idea is that they start off as smaller black holes and grow by pulling in gas, dust, and even other black holes over a time. Another idea is that when the universe was created massive gas clouds collapse into a massive black hole. Some scientists propose that many small black holes may join together again and again to form one supermassive black hole (Wei).

Supermassive black holes can control how a galaxy grows and changes. They pull in gas and matter, which can heat up and give off light. Sometimes this creates a bright center in the galaxy called a quasar. These quasars can really help scientists identify where exactly the black hole is. One of the most famous supermassive black holes is in a galaxy called M87. In 2019, scientists took the first real image of it using a group of telescopes from around the world. It looked like a glowing ring with a dark center. That picture helped prove that black holes are real and gave us a better look at what they might actually look like in space (Reddy).

There's another type of black hole that's in between the small and giant ones. These are called intermediate black holes. They are bigger than stellar black holes but smaller than supermassive ones. Their size is usually between 100 and 100,000 times the mass of the Sun. Scientists think they could be the "missing link" that helps explain how supermassive black holes got so big. This is why scientists are doing further research specifically on these not so known black holes (Wei).

No one knows for sure how intermediate black holes form, but there are a few good assumptions. One such idea is that they are made in places like star clusters, where a lot of big stars crash into each other. When they combine, they can form one huge star that collapses into a black hole. Another proposal is that they were made long ago from the first stars in the universe, which were super massive and had no metals. These stars might have collapsed straight into a black hole without exploding. Intermediate black holes could also grow slowly over time by pulling in gas or joining with other smaller black holes. Similar to supermassive black holes, there are too many theories but nobody knows what is the actual answer. Scientists have started researching more on the intermediate black holes, which they think might be the missing part to find out how supermassive black holes are formed but scientists are not able to find any relevant information (Lerner) .

These intermediate black holes are really hard to find because they don't give off much light and are not in the center of galaxies. But scientists have found a few clues to locate them. In 2020, scientists in LIGO observatories found a space wave from two black holes crashing into each other (Reddy). One of them might have been an intermediate black hole. Another possible one was found in a star cluster called NGC 6397 (Lerner). The stars were moving in a way that made scientists think there was a black hole in the middle. Similar situations were noted in many other star clusters such as Omega Centauri ("NASA's Hubble Finds Strong Evidence for Intermediate-Mass Black Hole in Omega Centauri"). If more intermediate black holes are found,

they could help answer big questions about how black holes grow and how galaxies form. This can be a big discovery in science. Thus, intermediate black holes have become the center of astronomic attention as they may be the key to unfolding these secrets (Wei).

In conclusion, black holes are some of the most powerful and mysterious things in the universe. They come in different types stellar, intermediate, and supermassive and each one forms in its own way. Even though we can't see them directly, scientists have found ways to study them by watching how they affect stars, gas, and space around them. Learning more about black holes helps us understand how stars die, how galaxies change, and how the universe grows. There are still many things we don't fully know, like how the biggest black holes really formed. But as science and technology keep improving, we'll keep getting closer to finding the answers.

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Prevention and Treatment of Dilated Cardiomyopathy: Diagnostic Criteria, Gene Therapies, and Ethical Concerns By Moupriya Mukherjee

Abstract

Dilated cardiomyopathy is a disease with heterogeneous etiology with causes ranging from genetic (primary dilated cardiomyopathy) to environmental (secondary dilated cardiomyopathy) with similarly widespread symptoms, making it a difficult disease to prevent or treat. However, recent shifts in the diagnostic process of dilated cardiomyopathy have increased emphasis placed on discovering the underlying cause of the disease. By making more specific diagnostic classifications for dilated cardiomyopathy, these detailed processes can become mainstream and treatment plans can be made more efficient for each affected individual, especially in genetic cases, where gene editing therapies can be phased in as they advance.

Recently, it has been found that dilated cardiomyopathy patients often express various arrhythmogenic phenotypes and have minor abnormalities in cardiac structure that go unnoticed before obvious heart-failure symptoms or diagnosis of dilated cardiomyopathy. Coupled with the vast range of etiologies for this disease, including infectious, autoimmune, genetic, and toxic causes, this highlights the importance of observing any genetic, rhythmic, or structural differences in the heart as a way to preemptively combat dilated cardiomyopathy effectively. More specific diagnostic classifications will make it possible to personalize effective treatments based on acknowledgement of the specific underlying etiology. *This paper will explain the most common etiologies and markers of causes of dilated cardiomyopathy and highlight the need to update the classifications of dilated cardiomyopathies to make more specific diagnoses and better align with recent developments in fields such as gene editing and genetic testing.*

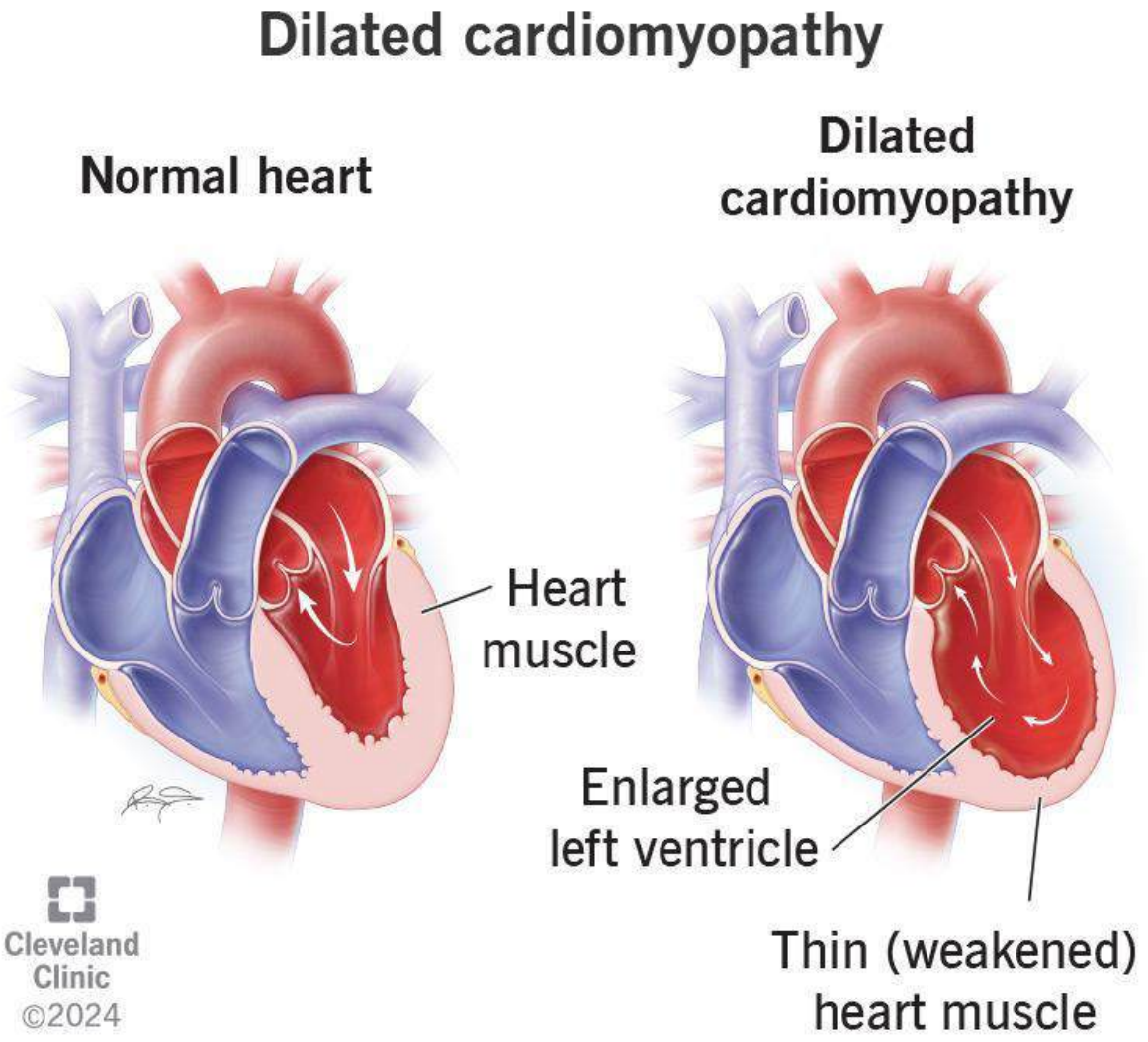
Keywords: biomedical and health sciences; genetics and molecular biology of disease; dilated cardiomyopathy; ethics; genetics; gene therapies; CRISPR/Cas9

Introduction

Dilated cardiomyopathy is the second most commonly diagnosed cardiomyopathy, affecting mainly young adults. It is a heart disease characterized by impaired contractility, or a left ventricle ejection fraction (LVEF) of less than 40%, coupled with enlargement or dilation of one or both ventricles, and is responsible for prompting most heart transplants (see fig. 1).[1, 2]

Current diagnostic criteria classify DCM into two groups, primary (of genetic etiology) and secondary (acquired).[3] However, DCM can have a broad range of causes (genetic, infectious, autoimmune, toxic, etc.).[4] Rather than being a response to specific triggers like other types of cardiomyopathies, dilated cardiomyopathy is caused by a number of factors often alongside one another.[5] For example, if someone has DCM that is partly due to or exacerbated by a disease like HIV, treating the HIV alongside the DCM would be beneficial to their health and help them recover more effectively. In this paper, I hope to discuss the need to explore more possible treatments for DCM and invest in the growing fields of genetic testing and editing.

Figure 1: A normal heart vs. a heart affected by dilated cardiomyopathy.[6]



Primary DCM vs secondary DCM

Dilated cardiomyopathy has a wide range of possible etiologies. In 2006, the American Heart Association took this into account while creating the two main classifications for DCM, primary (of genetic cause) and secondary (of viral or environmental cause).[7]

Primary DCM- The vast majority of cases that were previously considered idiopathic are now identified as genetic because of the recent increasing emphasis on identifying hereditary patterns for diseases by looking at family information and performing genetic screening.[8]

Unlike other cardiomyopathies - for example hypertrophic cardiomyopathy which was identified as a disease of the sarcomere after the discovery that 75% of gene mutations leading to hypertrophic cardiomyopathy resided in the sarcomere - dilated cardiomyopathy is very genetically heterogeneous. There are over a hundred genes that have a correlation to dilated cardiomyopathy and there is no set location or function for those most commonly found having mutations related to dilated cardiomyopathy (see table 1 for a list of the most common gene mutations)[9]. Unlike dilated cardiomyopathy from some other etiologies, genetically caused

dilated cardiomyopathy is a progressive disease.[10]This makes early diagnosis even more significant for those affected by it. Now, because of recent changes in the diagnostic process that have made it commonplace to screen relatives of people diagnosed with primary dilated cardiomyopathy, people are being diagnosed at sooner stages of the disease, leading to better prognosis.[11]

Table 1: Most commonly found gene mutations associated with dilated cardiomyopathy (adapted from McNally, Elizabeth M, et al. "Genetic Mutations and Mechanisms in Dilated Cardiomyopathy")

Protein location	Gene(s)/protein(s)	Protein function
Sarcomere	MYH7 (β-myosin heavy chain) TNNT2 (Cardiac troponin T) TNNI3 (Cardiac troponin I)	Generation and transmission of force
Cytoskeleton	TTN (Titin)	Generation and transmission of force/structural integrity
Desmosomes	DSP (Desmoplakin)	Intracellular transmission of signals/adhesion
Nuclear envelope	LMNA (Lamin A/C)	Maintain structural integrity and organization of nuclear envelope
Ion channel	SCN5A (Sodium channel, type V)	Encodes the alpha subunit of the main cardiac sodium channel responsible for keeping the inward sodium current stable

Secondary DCM- Sometimes other conditions can act as modifiers, aggravating or exposing DCM while not directly causing it, for example patients who present with dilated cardiomyopathy at the end of pregnancy. Patients like this should be monitored for dilated cardiomyopathy or any change in cardiac function in general since the hemodynamic exertion of conditions like pregnancy can reveal underlying cardiac conditions or dysfunction.[12]

Other conditions that can reveal DCM include excessive alcohol intake, chemotherapy induced cardiotoxicity, diseases like HIV, and more.[13] While those afflicted by primary DCM stand to benefit from gene therapies currently in the process of development, secondary DCM patients may benefit more from treatment of both their DCM symptoms and the aggravator of their DCM.[14] Genetic causes can be varied but the environmental causes of secondary DCM can have even more variation from one cause to the next, highlighting the importance of recognition of each case's unique accompanying illnesses.[15] What works to treat one type of secondary DCM may be entirely unhelpful to another one. For example, a patient with atrial fibrillation induced DCM may benefit from early intervention in the form of rhythm control while a patient with

viral myocarditis behind their DCM will do better with antiviral agents. Additionally, some types of DCM have a higher prevalence of recurrence, especially if the accompanying illness is also recurring or constant. Viral myocarditis, like many other illnesses that often play a part in a patient developing DCM, may be a recurring illness in many people which can lead to the return of DCM in less than five years, showing why it is important to consider different causes with DCM.[16]

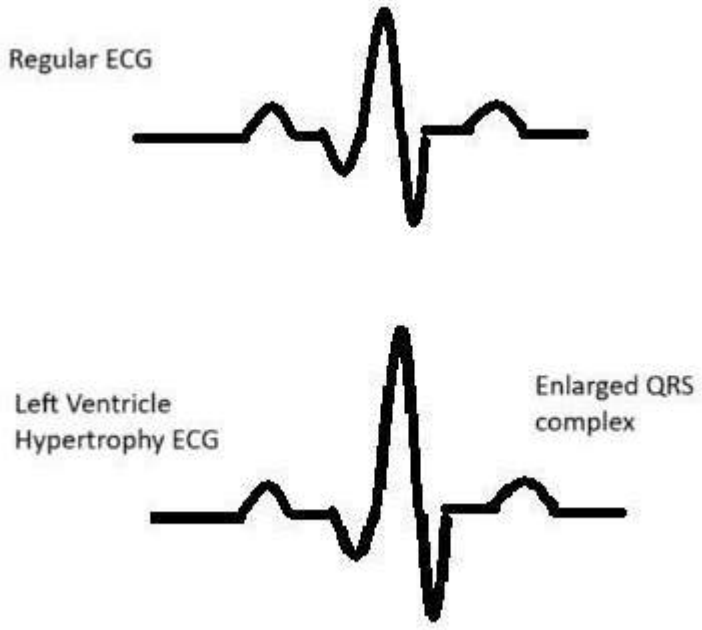
Because secondary DCM can have many different causes, it is often harder to diagnose and treat than primary DCM. For example, patients suffering DCM caused by chemotherapy induced cardiotoxicity.[17] It is still unclear what treatments would be best for their condition because of the niche nature of the condition and the fact that an acceptable definition of chemotherapy induced cardiomyopathy is yet to be developed and adopted by cardiologists and oncologists. More research needs to be conducted on secondary DCM to avoid ineffective treatment of patients afflicted by the disease.

Identifying DCM

Dilated cardiomyopathy of either type often phenotypically overlaps with other conditions (see table 2). It can also be asymptomatic and benign until triggered by onset of illness, pregnancy or other stress on or devolution of myocardial tissue.[18] Currently, diagnostic criteria require the absence of abnormal loading conditions like coronary heart disease, and other conditions are eliminated before diagnosing dilated cardiomyopathy in order to ensure most effective and efficient care for the affected individual and family members.[19]

Therefore, the first step in a dilated cardiomyopathy diagnosis is generally taking an electrocardiogram (ECG) or echocardiogram (Echo) in order to rule out other diseases.[20] For example, conditions like left ventricle hypertrophy that present similarly to DCM can be easily distinguished from DCM by viewing an electrocardiogram (see fig. 2). However, this cannot distinguish the different types of dilated cardiomyopathy. Instead, the various etiologies can sometimes be determined through examination of symptoms (table 4).

Figure 2: Normal ECG vs DCM ECG



Often, additional tests are used to aid in the diagnostic process after initial ECG or Echo. Late gadolinium enhancement cardiac magnetic resonance imaging (LGE-CMR) and endomyocardial biopsy (EMB) are commonly used when diagnosing DCM, but there are advantages and disadvantages to both (see table 3). EMB is an invasive treatment that requires a small sample of cells to be removed from the heart for inspection under a microscope. While LGE-CMR, similar to an X-ray, is non-invasive and fairly accurate in diagnosing acute myocarditis, it lacks the accuracy of an EMB in many scenarios, for example chronic inflammatory disease.[21] Additionally, it is harder to distinguish between the potential causes of inflammation in LGE-CMR than in EMB, which makes EMB more effective in identifying the etiology of the disease and then in selecting the most effective treatment.[22] For example, since EMB can distinguish between viral and genetic etiology, it can exclude causes like immunosuppression and help highlight the best treatment path. However, EMB has a low but significant rate (roughly 1%) of potentially life-threatening procedural complications, including but not limited to cardiac tamponade, sustained V-tach, AV block, etc.[23] This makes it difficult to recommend endomyocardial biopsy as a routine part of screening like electrocardiograms or echograms. Therefore, currently LGE-CMR is used as a method to identify whether a patient has DCM or not, and if there is evidence for there being a genetic etiology then EMB or genetic screening is typically performed.

Table 2: Alternative conditions/how to distinguish from DCM

Condition	Feature dismissing DCM	Methods used for identification
Ischemic cardiomyopathy	- Presence of greater than or equal to 75% stenosis in the left main stem, proximal left	- Invasive or computed tomography coronary angiography can help to identify degree of stenosis of

	anterior descending artery, or 2 or more epicardial coronary arteries - Prior myocardial infarction	blood vessels - With late gadolinium enhancement cardiovascular magnetic resonance, it is possible to identify prior heart attacks in patients without stenosis of coronary arteries
Hypertensive heart disease	- see “Identifying dilated cardiomyopathy”	- see “Identifying dilated cardiomyopathy”
Advanced hypertrophic cardiomyopathy	- previous history of hypertrophic cardiomyopathy - extensive patchy myocardial fibrosis - increased left ventricle thickness	- With late gadolinium enhancement cardiovascular magnetic resonance it is possible to find the presence of extensive patchy myocardial fibrosis - Electrocardiograms and echocardiograms can be used to identify thick left ventricle walls
Arrhythmogenic right ventricular cardiomyopathy	- disproportionate right ventricular dysfunction and remodeling - right ventricular wall motion abnormalities - localized dyssynchrony in tricuspid region (accordion sign) - arrhythmia disproportional to degree of left ventricular damage	- late gadolinium enhancement can be used to find patterns specific to arrhythmogenic right ventricular cardiomyopathy - identification of accordion sign through magnetic resonance imaging
Myocardial noncompaction	- deep, perfused intertrabecular recesses - greater than 20 percent of total left ventricle mass is trabeculated	- color doppler tests can be employed to identify intertrabecular recesses - cardiac magnetic resonance imaging to show trabeculated versus regular left ventricle mass
Athlete’s heart	- no signs of heart failure - little to no deviations from normal cardiac physiology - high VO2 max - participation in endurance	- cardiopulmonary exercise testing can be used to determine VO2 max levels

	sports such as biking, rowing, etc.	

Table 3: Pros and cons of LGE-CMR and EMB	***Late gadolinium enhancement cardiac magnetic resonance imaging (LGE-CMR)***	***Endomyocardial biopsy (EMB)***
Advantages:	- Non-invasive - High diagnostic accuracy in acute myocarditis - Has been demonstrated as an effective tool to predict and prevent dilated cardiomyopathy.[24]	- Makes it possible to distinguish between inflammation as a result of a virus vs. as a result of autoimmunity to cardiac proteins
Disadvantages:	- Less accurate regarding chronic inflammatory disease	- Invasive - A small but non negligible risk of complications (~1%)

Table 4: Common etiologies of dilated cardiomyopathy

Etiology	**Clinical features**	**Prevalence**	**Suggested course of action**
LMNA gene variant	- Limb girdle or Emery Dreifuss muscular dystrophies (skeletal myopathies) - Electrical instability (supraventricular arrhythmias and atrioventricular block often present before systolic dysfunction)	Present in ~5% of all dilated cardiomyopathy cases	- Clinical screening of relatives - Test for hemochromatosis
Desmosomal mutations	- No apparent right ventricle involvement - Excess arrhythmia	Found in 3-8% of all cases	- Clinical screening of relatives - Test for hemochromatosis
Previous myocardial infarction	- Late gadolinium enhancement cardiovascular	Found in 50-60% of all cases	- Sodium and fluid restriction - Administration of

	magnetic resonance shows myocardial scars left by trauma from prior myocardial infarction		neurohormonal antagonists -
Substances	- Varied; other etiologies have been eliminated	Undetermined	- Coronary angiogram to find blocked blood vessels - Provide patient with resources and counseling to abstain from substances
Myocarditis	- Flu-like symptoms, swelling of legs, hands, and feet - ST segment elevation on electrocardiogram - Recent infection/illness	Undetermined	- general lab tests - CMR to assess cardiac fibrosis and inflammation - Endomyocardial biopsy to confirm myocarditis - HIV serology in unexplained DCM

Identifying dilated cardiomyopathy before symptoms arise

Generally, dilated cardiomyopathy does not overtly express itself phenotypically when caused by gene mutations.[25] This is why familial screening of close relatives of patients diagnosed with idiopathic dilated cardiomyopathy is important.

Genetic testing- In relatives of those suffering dilated cardiomyopathy with genetic etiology, routine screening is advised. It is generally impossible to determine which gene is responsible for causing dilated cardiomyopathy on clinical grounds which is why multi-gene panels are commonly employed for genetic testing. In familial dilated cardiomyopathy the yield of family members also carrying mutated genes can be as high as 55%, and it has a worse prognosis than nonfamilial DCM, supporting the importance of genetic screening for relatives of affected individuals.[26]

Primary dilated cardiomyopathy often expresses itself in irregular electric activity in the heart. Some commonly found irregularities include atrial fibrillation, non-supraventricular tachycardia, and atrioventricular block. Such electrical phenotypes are associated with negative outcomes in relation to dilated cardiomyopathy.[27]

However, despite the importance of genetic testing in the early recognition of DCM in family members of an affected person, this is often inaccessible because of lack of awareness, lack of places offering it, or the price range, which can be from hundreds to thousands of dollars.[28] Therefore, steps should be taken to make genetic testing for DCM and other disorders with possible genetic etiology more accessible to the general population.

Secondary dilated cardiomyopathy warning signs- Unlike primary DCM, which has negligible phenotypic expression, secondary DCM is often accompanied by more noticeable

warning signs. One of the causes of secondary DCM is cardiotoxic cancer therapy.[29] In patients getting potentially cardiotoxic cancer therapy, overt left ventricle fraction can consistently be predicted by reductions in global longitudinal strain of greater than 10%.[30] This helps shorten the crucial period of diagnosis and averts possibly irreversible effects of the disease. These patients could benefit from serum protein biomarkers as well, since a rise in serum troponin is frequently correlated to development of dilated cardiomyopathy in those receiving cardiotoxic chemotherapy.[31]

Secondary DCM is often a result of other diseases or conditions so by treating these conditions earlier and more effectively dilated cardiomyopathy can be avoided altogether. For example, late stage dilated cardiomyopathy is often a complication of untreated cardiac iron overload.[32] The excessive iron in cardiac tissue causes conduction issues and alters cardiac function. By understanding root causes of DCM, treatment can be made more efficient and effective for each patient, as shown by the introduction of T2* monitoring in thalassemia patients in the United Kingdom.[33] Their early diagnosis and treatment of the root condition resulted in a 70% decline in mortality from complications of cardiac iron overload since 2000.

Future developments

Current DCM treatments vs. developing gene therapies- Broadly defined, current DCM treatments consist of lifestyle changes, pacemaker implantations, and a variety of medications.[34] Current advancements in gene editing therapies present promising outcomes for the development of new treatments for DCM, and possibly even a new way to reverse it that accounts for the large variability in the underlying genetic causes.[35] Gene therapy can be used to edit specific genes, and given that DCM can be caused by over 100 genes, the specificity that can be achieved by editing each gene precisely has great potential to improve prognosis for DCM patients by identifying DCM considerably earlier than currently possible.

Gene therapies- The emergence of CRISPR/Cas9 gene editing is a new horizon for dilated cardiomyopathy treatment.[36] Because of the wide spectrum of disorders that fall under the DCM umbrella, catching DCM early or even before it actually manifests is beneficial to prognosis. Recent discoveries have been made in the specific gene variations linked to DCM, which is why genetic screenings have risen in popularity as a proactive diagnostic tool among families affected by DCM.[37] Advancements in gene therapies may soon allow doctors to edit genes after variations are detected, something that could be life-changing for family members of those affected by DCM.

Risks/drawbacks of gene therapies and how they are being addressed- Gene therapies are still mostly in the early stages of their development and sometimes have unwanted effects, like off target edits.[38] They can also end up working differently than originally intended due to challenges like mosaicism, which occurs when gene editing happens after the one-cell stage of embryonic development, resulting in not all genes having a copy of the edited DNA.[39]

Overall, most scientists agree that gene editing is not at a stage to be used in medical settings yet.[40] With some more development they can become a helpful tool, but right now there are too many opportunities for error (i.e., unintentional large-scale deletions, which are the most common type of error, mosaicism, etc.) when using these technologies. One *in Vivo* study found a 6.5% rate of large deletions when observing the function of CRISPR technology introduced as a virus, whereas no large scale deletions are supposed to occur. Additionally recent studies following CRISPR/Cas9 use *in vitro* have found continuing patterns of large scale deletions, which could delete entire genes or result in misregulation of nearby expressed sequences.[41]

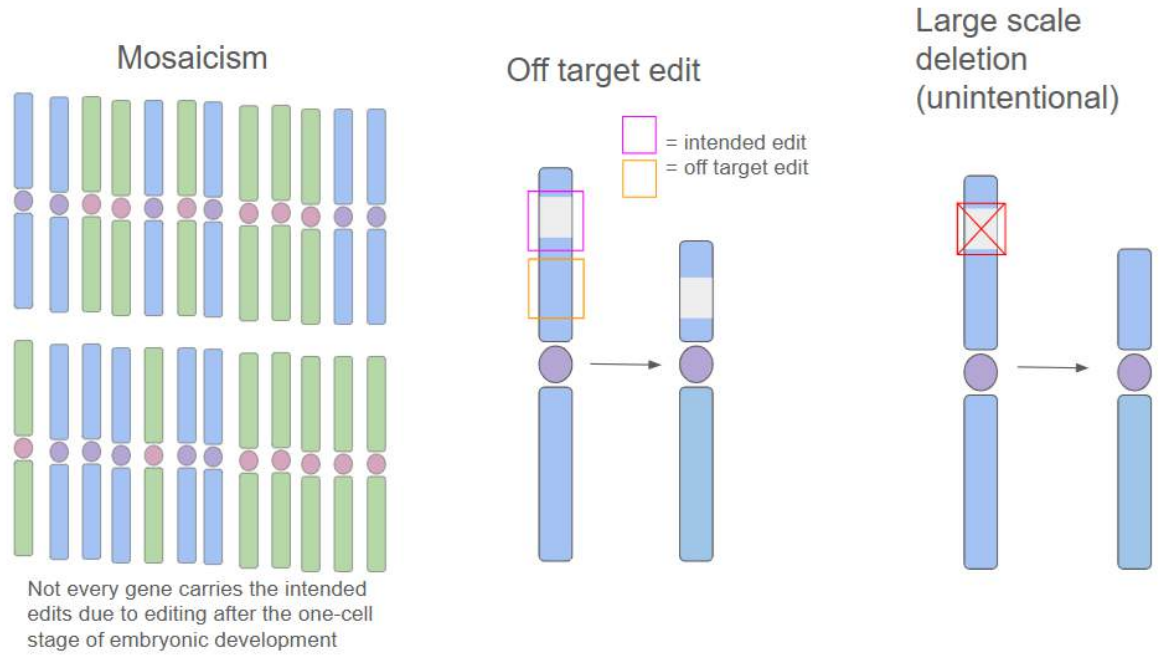
Currently, these risks are being addressed by further study of CRISPR/Cas9 technology and a weariness to release them as viable treatments in the medical field. Specifically, scientists are attempting to decode the seemingly random patterns of off-target edits and large deletions by studying the large amount of mutagenesis events.[42] So far, they have found certain unexpected results that occur relatively commonly across cases (see Fig. 3). Using machine learning tools and large dataset analysis to help make CRISPR/Cas9 function more predictable, some studies have identified key attributes of the underlying main sequence that could be used to predict the pattern of repair.[43] One of the recent reports relating to this area has already produced a successfully repaired pathogenic mutation using the predictive outcome of DSB (DNA double strand break) processing with CRISPR/Cas9 technology.[44]

Ethical concerns- While gene editing therapies are a promising emerging technology, they are associated with significant ethical concerns. The ethical discourse surrounding gene editing is not new but recent advancements in CRISPR technology have brought it into light again.[45]

One of the main concerns with gene editing therapy is the supposed inability to obtain informed consent for the procedure since when a gene is edited, this change will be passed through generations, and the people affected are embryo/future generations.[46] Often this argument is counteracted by the perspective that parents already make many decisions that affect their kids and the future generations, but it does hold true that it is unlikely to actually obtain informed consent without further research into all the possible effects of germline therapy.

Another concern is the possible exclusivity of gene editing therapy once it is developed, since it will most likely be a very expensive process, increasing disparities in medicine.[47] Others fear that it will become another enhancement tool, used for non medical purposes, that will take more time and effort to regulate than it's worth.[48] Additionally, most gene editing is currently studied using nonviable embryos, which many people have religious or moral objections to.[49]

Figure 3: common gene editing errors



Conclusion/discussion- While there have been subcategories created to more specifically define the different types of DCM, steps should be taken to make the process of treating DCM even more specifically to the causes and more research needs to be done on prevention of DCM. One could say that DCM cases are similar to magnetic filaments on a beach with two magnets placed upon its sand– while most filaments will gather somewhat proximally to one of the two magnets, there will be varying degrees of accuracy among the filaments as to their closeness to them. Similarly, DCM cases might be very similar to one another and could potentially be treated with a few broad umbrella treatments, but we are developing tools that make more personalized treatments possible and real enough to consider, and one day, instead of trying to collect scattered filaments with a small number of large magnets we can pick filaments out with highly accurate tweezers in a way that isn't excessively more effort intensive or costly. Some of the fields that hold the most potential for groundbreaking findings in DCM prevention are gene editing and therapies. By honing existing and developing technologies that allow editing of genes until they produce negligible risk of gene editing errors, the disease can be avoided completely. In this future scenario, other than occasional screenings to ensure that DCM is not present, no secondary care should be needed. However, these technologies are currently in a considerably rudimentary stage and impractical and dangerous to use on a large scale in medical settings. Therefore, immediate steps to improve prognosis of DCM patients could include spreading awareness on the importance of genetic testing for family members of those affected by DCM and improvement of programs designed to help make genetic testing more accessible to families.

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Predicting Laptop Prices Using Machine Learning and Feature Engineering By Qianlong He

0. Abstract

The prices of laptops are highly diverse depending on a blend of the hardware requirements and the brand position, and as such both consumers and retailers find it hard to ascertain their actual worth and the retailer to price the products competitively. This paper uses the machine learning method to estimate laptop prices based on features of the product in detail, using the publicly available Brand Laptops Dataset available on Kaggle, which includes specifications of 991 laptop models. The information contained on the dataset will be processor setup, memory size, storage format, monitor size, operating system and brand name. Following the initial data cleaning, the heavy feature engineering was carried out in the presence of the additional informative variables like the numerical indicators of CPU tier and the operating system type. Unnecessary columns were eliminated, and all the numerical variables were standardized to counterbalance the same contribution as they contribute to the training of the model. This was followed by the development of a linear regression model that was used to estimate price based on these engineered features. An 80/ 2 0 train- test split was used to assess model performance. The model on the training set got a Mean Absolute Error (MAE) of around 17,261, and the validation set got 15,702, which represents an average prediction error of 20 percent of the cost of the laptop. These results indicate that a fairly straightforward regression expression is capable of creating key pricing patterns motivated by fundamental elements of performance. The suggested solution offers a benchmarking tool that could help both consumers and retailers in determining the price fairness and/or the pricing strategy optimization. The future enhancements might consist of more sophisticated machine learning models and other functions like the GPU classification and the build quality metrics.

Keywords: pricing of laptops, machine learning, regression model, feature engineering, consumer electronics, predictive analytics.

1. Introduction

The diversities in the laptop market are considerable, and pricing differences are very strong based on performance in the hardware, brand perception, and positioning products. Current laptops vary diversely in the central processing unit (CPU) architecture, graphics abilities, memory bandwidth, screen technology alongside storage platforms, which support the performance and cost of a product [1]. Meanwhile, strong brand impacts have been determined on the consumer willingness to pay as older manufacturers receive better prices even when similar hardware is offered [2]. A combination of these factors complicates the pricing fairness environments and competitiveness of new products in the market by consumers and the retailers.

Machine learning (ML)[7], has emerged as a more and more effective instrument of consumer electronics price contraction analysis [3]. Previous studies have shown that the models

through regression could be used to find out the nonlinear correlations between product specifications and market value, giving price estimations that are more objective and data-driven than the ones achieved by other methods [4]. Nevertheless, most current literature uses high-end datasets or commercial retail platforms, which creates a difference in the available and clear models that may aid consumer decision-making on a bigger scale [5].

The goal of the current research is to come up with a predictive model that approximates the prices of laptops depending on the technical features and brand attributes using a publicly available dataset. Through data preprocessing and feature engineering methods (especially illustrating the usage of CPU tier representation and standardized hardware metrics) the given research intends to identify which of the specifications has the greatest impact on cost. Moreover, the given project gives some information on the comparative relevance of the performance features of RAM and storage versus the factors of branding. The final objective is to make a valuable input regarding a useful baseline model that will help consumers assess the pricing fairness and also help retailers in formulating pricing strategy guided by quantifiable aspects of performance.

2. Methods

This analysis utilizes the Brand Laptops Dataset from Kaggle, a comprehensive collection of specifications for 991 different laptops. This dataset was chosen for its detailed features, which provide a robust foundation for analyzing laptop pricing dynamics. It includes 22 attributes such as brand, model, price, processor details, RAM, storage, GPU, and display size. The richness of this data is particularly well-suited for feature engineering, allowing for the extraction of more granular information to improve model accuracy.

Before modeling, the data underwent several preparation steps to ensure quality and create meaningful features for the machine learning algorithms. The process began with data cleaning, where the dataset was checked for missing values. Fortunately, the data was complete, so this step was straightforward. The only initial modification was the removal of a redundant 'index' column.

Significant feature engineering was then performed to convert categorical data into a numerical format suitable for machine learning algorithms [7]. The 'brand' column, for example, was simplified by consolidating fewer common brands into another category, which allowed the model to focus on the market's top three manufacturers: Asus, HP, and Lenovo. The 'processor tier' feature was re-engineered into distinct numerical columns named 'core' and 'ryzen' to represent the CPU series hierarchy, such as Core i3 versus Core i7. This numerical representation better captures the impact of processor performance on price. Similarly, the 'OS' column was converted into a binary feature to indicate whether a laptop runs on Windows.

Several columns were dropped to streamline the model and avoid redundancy. The 'Model' and 'Num threads' columns were removed because processor brand and core count already provided sufficient performance information. The 'secondary_storage_type' and 'secondary_storage_capacity' columns were also excluded, as the vast majority of laptops in the

dataset lacked secondary storage. The 'year_of_warranty' was dropped as well due to its limited variability.

Finally, the prepared dataset was split into training and validation sets, with 80% of the data allocated for training the model and the remaining 20% for testing its performance. All features were then scaled using StandardScaler to normalize their range, a crucial step that prevents attributes with larger numerical values from disproportionately influencing the model's predictions.

2.1. Model Training

With the data prepared, the next step was to train a model to predict laptop prices based on their features. Given the goal of predicting a continuous value (price), this is a regression problem. For this project, a straightforward and interpretable approach was taken by implementing a linear regression model. Linear Regression model from the scikit-learn library used to observe the results.

The linear regression model was trained using the prepared and scaled training dataset. The model's initial performance was evaluated by comparing its price predictions against the actual prices in the training set [8]. A scatter plot of these predicted prices versus the actual prices showed a clear positive trend, indicating that the model was successfully learning the general relationship between a laptop's features and its cost. However, the points were scattered around the ideal diagonal line, which suggested the presence of prediction errors.

3. Results

The linear regression model indicated that it generally had a high capacity to identify the relationship between the features of the laptop and the pricing patterns [8]. Scatter plotting of the predicted and actual prices of the training data revealed that there is an obvious positive relationship that points to the ability of the model to learn the most important patterns that drive prices. But the diffusion of points about the proposed ideal diagonal line connoted the existence of prediction variance of particular settings.

Mean Absolute Error (MAE) was used as the model performance metric as it is a generally used price prediction research measure.

In the training data, the MAE stood at the figure of 17,261, which is about 23 percent of the mean price.

With the validation dataset, the MAE also got better to about 15,702, and this translates to an error of approximately 20%, which shows that there is not much overfitting and that it can be used with new samples with reasonable reliability [3].

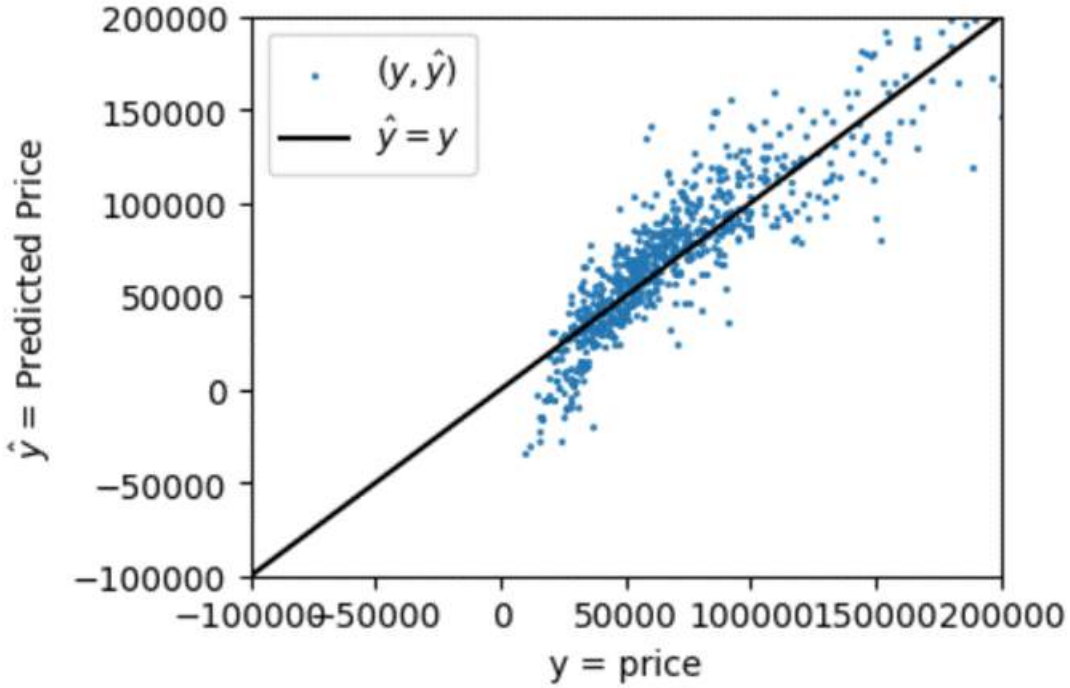


Figure 1: Predicted vs. Actual Laptop Prices on Training Data

The importance of features was evaluated with the help of standardized regression coefficients that were analyzed four times. Components related to core hardware performance, specifically tier of the processors, RAM memory, and primary memory, exhibited the largest coefficient magnitudes, which validates their key position in determining the market price [5]. Overall, such features like the type of operating system and brand category as a group did not add as significant price difference.

These findings, collectively, indicate that a basic linear regression model is capable of creating a foundation price prediction model, with a prediction within a 20 percent error margin and with strong ability to identify performance-based pricing patterns that are often prevalent in consumer electronics markets [6].

4. Discussion

This paper has elaborated a machine learning-based model in the context of predicting prices of laptops given specifications of products. The results of this paper indicate that the key pricing trends in the consumer electronics market can be represented by the use of linear regression, indicating that it is appropriate as a baseline model when performing a systematic pricing analysis [1].

The most important findings indicate that performance-based factors namely processor tier, RAM and primary storage are the most determining price factors. This corroborates prior findings that the hardware ability is closely related with the consumer-perceived value and retail pricing strategies [2]. In the meantime, secondary characteristics like brand and operating system were of relatively little significance after the performance measures had been taken into

consideration. This implies that branding does not have as much influence on consumer choices based on the price model as do quantifiable performance, but at the same time branding does not possess a strong predictive power in price modeling.

The 20% margin of error in the model is indicative of both the potential usefulness of this model and its present constraints. Linear regression is based on the assumption that the features and price are related linearly, yet the consumer electronics pricing can be nonlinear and include temporary market trends, advertising pressure, and nonlinear effects on price that are not included in the dataset [4]. These elements can explain the difference in prediction and imply that more sophisticated models can be used to achieve further accuracy.

Irrespective of these weaknesses, the predictive accuracy is high enough to be applied in practice. Such a model would help consumers to understand price fairness better in their purchasing of laptops and help retailers to maximize pricing strategies in matching products value to market expectations [5]. The next avenue of future research might be nonlinear machine learning models like random forests or gradient boosting that were demonstrated to enhance objectivity in product pricing tasks[6]. Also, one can add the information about GPU performance, display resolution and material build quality, which can improve predictor accuracy [6].

Overall, this paper offers a useful and comprehensible model of predicting the prices of laptops, which proves that the scientific method may be effectively used to facilitate consumer and retailer decision-making.

5. Acknowledgement

The author would like to acknowledge his/her research mentor who has helped in the process of developing this project and assisted him/her with constructive comments when writing. The administrators of Kaggle are also given the credit of making the Brand Laptops Dataset publicly available, and thus, open and reproducible machine learning research is made possible.

6. Conclusion

In conclusion, this project successfully developed a machine learning model capable of predicting laptop prices based on their features. The process involved comprehensive data cleaning and feature engineering to transform the raw dataset into a format suitable for modeling. Using a linear regression model, the final prediction accuracy on unseen data was within a 20% margin of error on average. The analysis also confirmed that performance-related specifications, such as the processor, RAM, and storage, are the most significant factors in determining price. This model serves as a valuable tool for consumers seeking to assess fair value and for retailers aiming to create competitive pricing strategies. While the linear model provides a strong baseline, future work could explore more complex algorithms like neural networks to potentially improve prediction accuracy further.

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The Correlation Between Redlining, Greenspace Accessibility, and Healthcare Disparities in Urban America By Sreeya Nair

Abstract

Redlining, the historical discriminatory lending practice that segregated housing in the United States, still has a lasting legacy on the quality of life today. One of these legacies, the unequal access to green spaces (parks, gardens, tree canopy), has several effects, including its negative implications on public health.

This study examines the long-term effects of redlining in Los Angeles County, focusing on the interactions between reduced exposure to green space and lower health outcomes. It will compile past literature regarding this topic and have its own study analyzing public data available to see the trends and correlations between redlining and healthcare. In doing so, it will shed light on the spatial and racial lines of health disparities and gain insight into how cities and public policy can work towards addressing those legacies.

Key Words: Urban Heat Islands, green space, redlining, healthcare

Introduction

Cities are warming at twice the rate of rural places (Mohajerani et al., 2017). A phenomenon known as Urban Heat Islands (UHIs) occurs when urban areas experience significantly higher temperatures than their surroundings due to the geometry, composition, and overall anthropogenic factors that cause heat to get trapped (Li et al., 2024). Buildings and street pavements have a high thermal inertia, increasing surface temperatures (US EPA, 2024). Combined, these factors can increase cooling energy demands, air pollution, and have adverse effects on the health of humans and urban biodiversity (Leonard, 2023). Rising temperatures cause more frequent and intense heat waves, which disproportionately harm low-income communities (Cornwell, 2022).

Figure 1

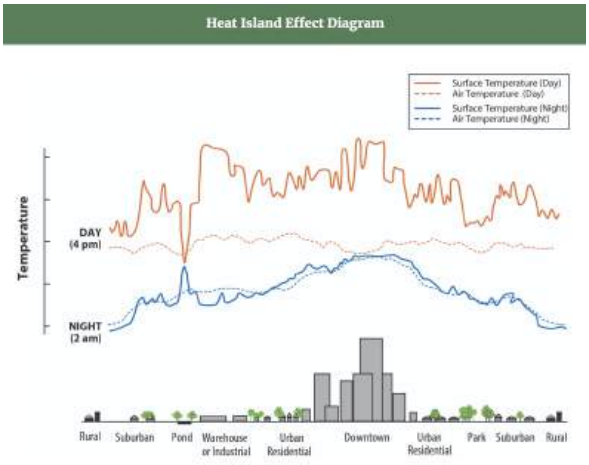


Figure 1: A comparison between daytime and nighttime temperatures in different settings. Temperatures around downtown urban locations are much higher than their rural counterparts, and surface temperatures are much hotter than the air temperature in downtown settings during the day.

Access to green space is crucial to addressing UHIs (Aram et al., 2019). However, due to historic redlining and other reasons, green space is not distributed equitably (Cornwell, 2022). Lower-income neighborhoods have fewer available green spaces, and this proportionately reduces the safety of the area. Green spaces play central roles in cooling neighborhoods, so urban planning and climate adaptation efforts must accommodate green spaces into urban environments and historically redlined neighborhoods.

This study will focus on Los Angeles (LA) County. LA has a history of redlining and large amounts of public data available to analyze. It also has its fair share of extreme climate risks, such as recent wildfires and droughts. LA is also a frequent location for wildfires and droughts. Los Angeles has continued to see to it that the climate hazards facing it are abated, yet issues still linger, like balancing green infrastructure.

Based on the empirical research on redlining and UHIs, this study aims to connect land surface temperature, green space availability, and socioeconomic and racial makeup. The study aims to map and analyze how land surface temperature, green space area, and socioeconomic elements correlate with neighborhoods in Los Angeles. By identifying patterns of environmental inequality, this study guides just and fair urban greening and climate adaptation planning.

Background

Inequitable Green Space Access:

Redlining, the historical process of withholding home-loan funds from people of color, causes many disparities in low-income neighborhoods (Jackson, 2021). This form of housing discrimination was government-sponsored, in that the government aided segregation and lowered quality of life (Segregated by Design). Los Angeles County was heavily redlined throughout the 30s, discriminating against locations with a primarily black or Latino population. These decisions still affect many cities in the county, one of which is the lack of equitable green space access (Yan et al., 2024).

The government utilized redlined neighborhoods to support their wealthier counterparts (Nardone et al., 2021). For example, in 1963, Interstate 5, a highway connecting Northern and Southern California, was built in the Barrio Logan, a region in San Diego; a place primarily inhabited by Chicanos (themetropoleblog). Thousands of Chicanos were forcibly removed from their homes and lost their businesses. Additionally, the highway increased air and noise pollution, reduced the quality of life, and lowered property values. The construction of a highway led to a heavy loss for the community, leading to heavy generational trauma as children of Chicanos could no longer afford college, buy houses, or grow their wealth. To this day, redlining still impacts the quality of life in Los Angeles (Nardone et al., 2020). Affluent neighborhoods

remain wealthy while many redlined areas lack crucial resources, such as safe schools or quality medical care.

Urban heat islands (UHIs) occur due to the modification of land surfaces, building materials and structures, and air pollution, among other causes (Alvarez, 2013). They are also caused by a lack of sufficient green spaces; therefore, historically redlined neighborhoods have higher UHI levels than non-redlined neighborhoods. A 2020 study of 108 U.S. Cities found that 94 percent had augmented land-surface temperatures in formerly redlined areas compared to their non-redlined counterparts, over 12 degrees Fahrenheit (Newsome, 2023). These communities also have a more difficult time having access to green spaces, lack financial resources to plant and maintain trees, and do not have enough political power to resist the destruction of further heat-generating complexes.

LA Fires and Redlining

A natural disaster especially prevalent in Los Angeles is wildfires. This ongoing issue has disproportionate harms for redlined neighborhoods. A UCLA study on the Eaton Fire in Los Angeles, for example, highlights how systemic inequalities and redlining practices contributed to the vulnerability of many particular communities, particularly the Black community in Altadena, to the fire's devastating effects (Bonner, 2025; Rojanasakul & Pumer, 2025). Altadena was particularly vulnerable for several reasons. It is located in a transition zone where residential neighborhoods meet wild, highly flammable vegetation. This provides a fuel source for fires to ignite and spread. Other factors include weather patterns and topography (Muyskens 2025). However, despite its potential to be caught in fires, it lacks resources to fight these fires. Traditional fire-risk models underestimate the fire risk because they use static models based on natural terrain and vegetation without fully considering wind patterns or the urban layout of Altadena, where homes are densely packed together. These homes are not built with modern fire defense mechanisms, so they were susceptible to them.

Green Spaces and Health of Communities

UHIs have a negative correlation with health and safety in communities (Guttman et al., 2021). Historically redlined communities also suffer from a prevalence of chronic illnesses such as asthma, cardiovascular disease, and depression. This can be inherited or acquired due to the less than adequate living conditions. Additionally, UHIs have higher instances of heat-related illnesses and emergency department visits.

UHI impacts are exacerbated by climate change, as heat waves grow more prevalent (Tong et al., 2021; Heaviside et al., 2017). Abrupt changes to temperature can be very dangerous to human health, leading to cerebrovascular, cardiovascular, or respiratory diseases (Hubbart & Bradford, 2023). Longitudinal cohort studies have found that increased exposure to green spaces around residential areas is associated with lower all-cause mortality rates (Rojas-Ruerda et al., 2019). This effect has been observed across diverse populations and countries, suggesting that green spaces serve as a way to reduce premature death. In addition, green spaces have added

mental health benefits, including lower levels of mental distress, anxiety, and depression (Barton & Rogerson, 2017). This is probable because increased green spaces improve air quality, reduce noise, and mitigate the effect of urban heat (Thompson & de Oliveira, 2016). They also promote restoration, psychological relation, and social cohesion. Additionally, they greatly benefit physical health and have been associated with a reduced risk of cardiovascular diseases, hypertension, type 2 diabetes, obesity, and respiratory conditions such as asthma (Nardone et al., 2021).

This access to green spaces is correlated with reduced healthcare utilization, including fewer emergency room visits and lowered healthcare costs (De Nocker et al., 2023). People in greener neighborhoods report better health outcomes, resulting in reduced demand for services. This suggests that urban green spaces can reduce the pressure on healthcare systems due to its potential in disease prevention and mitigation.

How increased ER Visits harm low-income neighborhoods

UHIs negatively impact healthcare systems as well. Due to redlining, there is less quality healthcare in redlined areas. In a 2024 study, researchers revealed a substantial overrepresentation of neurosurgeons in non-redlined communities in comparison to their redlined counterparts (Kabangu et al., 2024). Increased heat levels overburden the emergency rooms each year, and many low income neighborhoods are not fit to deal with an influx of emergencies (Vaidyanathan et al., 2023; Li et al., 2022). The increased use of the ER has detrimental consequences for individuals, public payers, and the hospitals themselves.

Figure 2

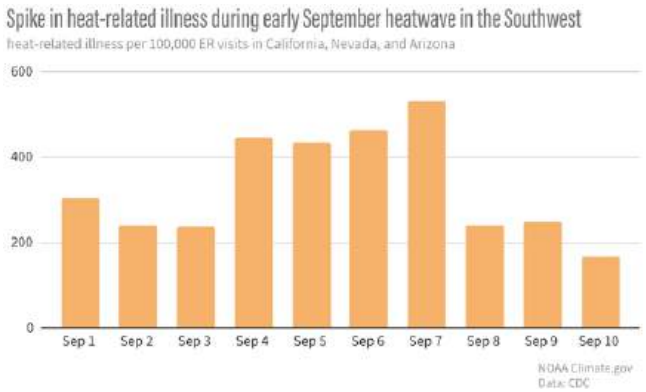


Figure 2: A study by the EPA shows the spike in heat related illness during a heatwave in the Southwest from September 1-10, 2024. The data was collected per every 100,000 ER Visits in California, Nevada, and Arizona. ER visitations nearly doubled.

Emergency rooms are ill-equipped to deal with non-emergencies such as preventive care (Shi et al., 2020). However, many low-income individuals and families may delay treatment if it is absolutely necessary, hence resorting to the ER. Children may miss well-child appointments, which track their growth and well being, which make them more vulnerable to different diseases.

In addition, low-income communities also face more barriers to receiving care from primary care providers. The delay in seeking initial care leads to increased use of the ER, which leads to overcrowding in a low-income neighborhood with a higher poverty percentile.

Overcrowding has several negative outcomes. The first is the reduction in quality patient care. For example, in Los Angeles Community Hospital, located in East Los Angeles, only 11.3 percentile of people in that relative location is above poverty. Additionally, its UHI Index is 68.5, a relatively high number, due to its low tree canopy levels. In contrast, Cedar-Sinai Hospital, one of the best hospitals in Los Angeles, finds itself situated in a location with low poverty levels (80.5 percentile of people live above poverty) and a lower UHI Index of 46.2. Its heat index is 16.5, compared to that of LA Community Hospital, which is 58.5. They are only 14.2 miles apart in distance.

Summary:

While awareness of the need for green space increases in LA, this only applies to relatively affluent neighborhoods. Inequitable green space access, impacted by years of redlining practices, has disproportionately caused UHI effects among low-income neighborhoods. In turn, the quality of healthcare goes down while emergency visits increase.

Methodology

Objective

This analysis aimed to examine the relationship between Urban Heat Island (UHI) strength, green spaces, and hospital access in Los Angeles County between 2010 and 2025. It also examined the impact of redlining and unequal access to care, in particular through insurance status on the health effect of intense heat. Through the integration of geospatial, health, and climate data, this analysis aimed to present a quantitative estimate of the ways in which environmental and structural inequities impact at-risk populations. This is a correlational study, and the results should be used to support further research, not to identify causes.

Data Sources

Data was obtained through publicly available sources. The primary geospatial dataset was the UCLA Heat Map, which included high-resolution thermal imagery and UHI classification for Los Angeles County. It contains region-specific surface temperature data that indicates areas with higher heat exposure. In addition, other ArcGIS datasets were obtained to estimate the number of uninsured people in each city.

Climate historical data was collected from the NOAA Hawthorne weather station in California, selected for being in the middle of Los Angeles County. Temperature data (minimum, maximum, and average) were collected by month between 2010 and 2023 to track long-term patterns in heat exposure during extreme summer heat.

Data Processing

The data were integrated with and processed using Python (v3.10). Pandas was used to filter and spatially and temporally align the data and clean the data.
Population percentages were calculated by dividing the count of uninsured people with the population in each tract or city. These percentages were then matched with temperature ranges based on their designation in the UCLA Heat Map dataset. The cleaned dataset was exported to Google Sheets for final computation and visualization.
Table 2 was created to emphasize the level of UHI, insurance premium, and population for every geographic unit.

Variables

Each independent variable was separately analyzed, and the dependent variable was the number of people without health insurance in each city. Different independent variables were analyzed to see which had the greatest impact on health insurance. For example, UHI levels were correlated with health insurance to see if there was a notable trend in the dataset. Other independent variables were heat indices, poverty levels, and tree canopy levels.
Results
This section presents key findings from the data analysis, including observed patterns, graphs, and descriptive statistics. There has not been too much of a change in Los Angeles County temperatures in the past fifteen years.

Figure 3

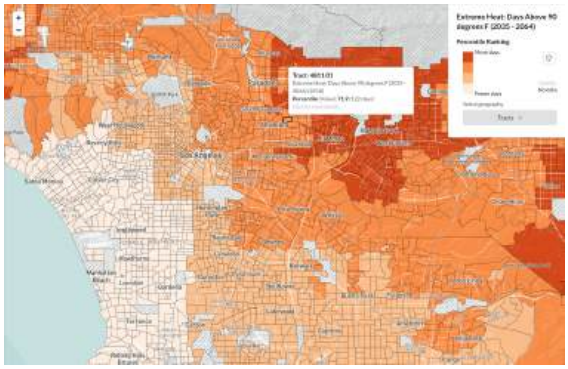


Figure 3: UCLA Heatmap Screenshot

Different heat levels in different cities in LA County. Darker red means more days experience heat above 90 degrees Fahrenheit. Taken from UCLA's California Healthy Place Index: Heat Edition.

Figure 4

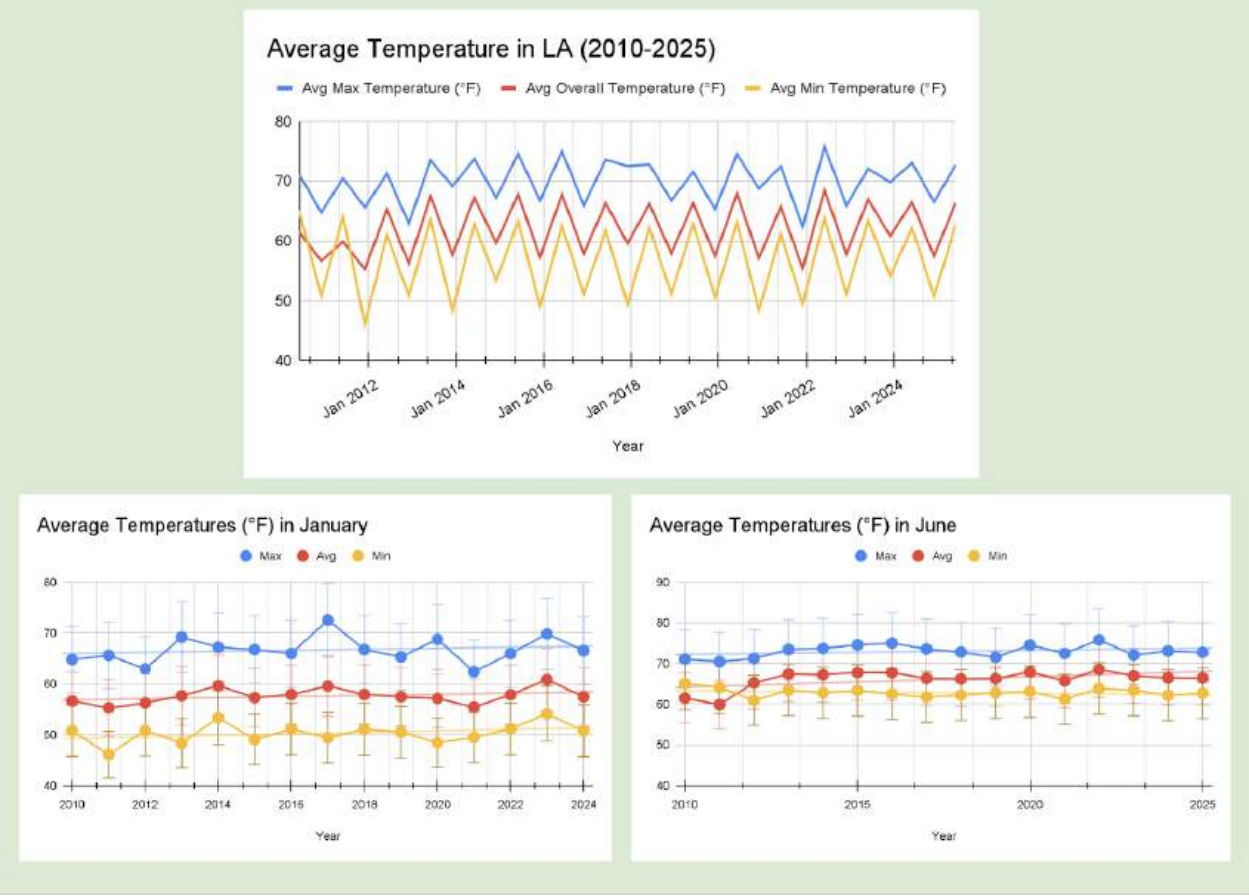


Figure 4: Graph of the temperatures in Los Angeles 2010-2025

Utilizing the values from Table 1, the values from January and June are separated in the bottom two graphs to show how temperatures change in the winter versus the summer. Marked on the lower two graphs are the standard error margins and regression line. No perceptible change as the error bars overlap.

The average temperatures in LA City from 2010-2024. It shows a slight increase in temperatures, but many factors go into the increase so it is difficult to tell from this dataset whether the increasing heat is a trend or an outlier, as it does not exceed the p value.

Table 1 (Continued in Appendices)

Cities	Heat Index	Percentile of People above Poverty	UHI Index	Tree Canopy	Uninsured (%)
Agoura Hills	32	89.3	54.8	53.9	2.25
Alhambra	52.6	38.7	80.6	43.6	4.45
Arcadia	80.5	67.3	86.6	54.6	N/A
Artesia	25.1	49.6	56.9	21.9	7.19
Avalon	87.1	25	32.3	32.3	8.01
Azusa	80.1	37.3	89.4	22.1	10.36
Baldwin Park	29.7	34.9	84.3	18	7.56
Bell	52.8	10.1	59.8	25.7	11.1
Bellflower	26.9	36.6	57	17	8.71
Burbank	37.9	63.6	6.3	46.8	4.27
Calabasas	47.2	93	53.2	63.2	1.88
Carson	14.7	59.6	27.6	26.5	7.4
Cerritos	29.2	84.8	56.7	25.3	3.32
Claremont	49.3	76.7	92.4	42.3	3.06
Commerce	45.5	23.8	66	27.7	10.63
Compton	16.7	14.6	37	29.3	12.75
Covina	74.9	51.7	88	21.5	8.19
Cudahy	36.2	8.5	58.7	23.5	14.84
Culver City	10.1	82.4	9.3	45.7	3.05

Table 2: The Heat Index, tree canopy levels, UHI Index, percentile of people above poverty, and uninsured population per city in Los Angeles County.

The correlations have been analyzed with five categories: UHI Index, Percentile of people above poverty, the percent of people without health insurance, the green canopy levels, and the heat index. There is a definite correlation between higher heat levels and increased poverty rates.

There are five categories being measured here. A higher heat index means that the city has more days with temperatures greater than 90 degrees Fahrenheit. A higher above poverty percentile means that the county has less poverty. A higher UHI index means that the county struggles more with UHIs. Finally, higher tree canopy levels means that the county has more tree coverage.

Figure 5

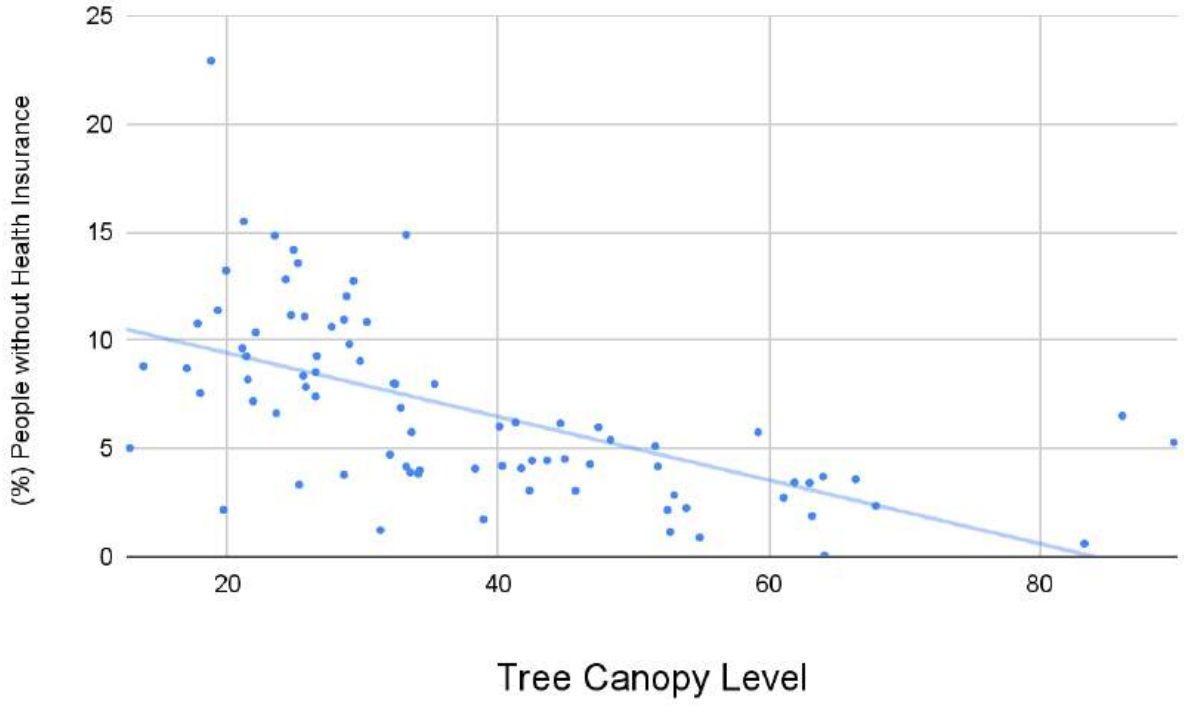


Figure 5: The correlation between the tree canopy levels and percentage of people without health insurance.

As tree canopy levels increase, more people have health insurance. The regression line above is shown, and it has a slope of -0.146789 and has an r-value of -0.594, indicating the trend that as tree coverage increases, fewer people are uninsured.

Discussion

The results showed two tables. The first one was an analysis of heat levels purely in Los Angeles City to determine the level of temperature change occurring in Los Angeles County. Results showed that while there has been some increase in the numbers, it could have just been chance statistically and there was not that significant of change. The graph just analyzed the highest temperature average, lowest temperature average, and average temperature overall for each month; therefore, any spikes in temperature could not be identified.

The second table was a detailed analysis of each city in Los Angeles, covering 88 cities. It covered each county's heat index, their tree canopy levels, poverty levels, Urban Heat Island Index, and uninsured population level. A definite correlation was seen between poverty levels and uninsured population. For example, Beverly Hills has an above poverty percentile of 82, and

their uninsured population is 1,509 people. However, Huntington Park has an above poverty percentile of 8.9, and their uninsured population is 9,954 people, a 599% increase. Additionally, Beverly Hills has a heat index of 13, indicating a low number of days with very high heat, while Huntington Park has a heat index of 23.1.

The hypothesis explored in this paper was that reduced green spaces led to reduced healthcare quality in Los Angeles County, and that this effect is worsened with rising climate temperatures. The results from Table 2 clearly indicate that this effect is pronounced in the cities of LA County, as the richer neighborhoods have more green space and also have more people with insurance. While the research did not indicate a significant increase in climate in Los Angeles, it did not account for any heatwaves or spikes in temperature as it only measured averages. According to NASA studies, the number of heatwaves have been increasing throughout the 90s into the 2000s (Tamrazian et al., 2008).

Connections to Literature Review

The data indicates that regions that have more tree canopy coverage also have more people with health insurance, showing the legacy of redlining. Historically redlined neighborhoods did not have enough green spaces, and there is a correlation between a lack of green spaces and the number of people able to go to hospitals for non-emergencies. This effect could also be seen with the UHI Index, but not as much.

There is not a close correlation between heat index and health insurance, however. A reason contributing to this could be because a wealthy neighborhood can have a high heat index, plenty of green spaces, and quality services. Heat index does not have as much of a correlation as tree canopy. This contradicts the earlier previous hypothesis that states that a higher heat index correlates with worsened hospital services.

This study shows the importance of having green spaces in communities and mitigating the impacts of harmful redlining in cities across the United States. In general, wealthier neighborhoods in Los Angeles County were positively redlined, and they were labeled as good investments for banks. On the other hand, places that were negatively redlined were labeled as poor investments for banks, and they were also most populated with people of color. This racist legacy colors almost every corner of our human society, and this extends to the environment. This study should be taken into account when promoting green initiatives across US cities, especially among vulnerable communities.

Conclusion

Historical redlining practices have a major impact on the quality of life of many communities. Because it prioritized white homebuyers, and forced the other buyers into unsafe communities, it has led to years of generational trauma, which still continue to harm families and communities. It impedes quality services such as healthcare, education, and transportation.

This effect is exacerbated by the warming climate. As the climate changes, heatwaves increase in number and intensity. Increased emergency room visits, lowered primary care

support, and less consistent insurance protection can be seen in the Los Angeles community, especially after the wildfires. Green spaces can directly combat these issues. As communities that are wealthier have more green spaces, they also have the best quality of life. Communities that were historically redlined were denied these green spaces, reducing their property values and making the neighborhoods more unsafe. As shown in the study, green spaces have a direct correlation to the Urban Heat Index and the poverty levels of the community.

Although creating more green spaces will not undo years of oppression and injustice, it is a tangible way to restore these historically neglected communities. Therefore, urban planners should prioritize planting trees or other gardens, maintaining parks, and making them safe and accessible to all to protect future generations. Investing in green infrastructure also improves environmental conditions and fosters more resilient communities.

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Automation and Opportunity: A Global Review of AI's Impact on Employment By Nikol Mari Saveleva

Abstract

Over the last few years, the rapid growth of Artificial Intelligence (AI), especially following the COVID-19 pandemic, has spurred intense discussion regarding its impact on the labour market. Further research estimates that, by 2030, as many as 300 million jobs could be lost to the compounding effects of automation and AI. This literature review analyses the evolving effect of AI on work patterns and reflects upon its wider impact on global development trends. The reviewed literature is categorized into three themes: automation of routine and repetitive work; new forms of work and skill demand; and uneven global distribution of AI-induced benefits and displacements. While most research postulates the existence of AI-caused displacement in certain sectors or industries, others emphasize the ability of AI to augment rather than substitute human work. The nature and size of the impact of AI also seem to vary considerably based on the particular task involved and the degree of skill in the occupation.

This review contends that the dramatic structural change in the labour market will not be job displacement alone, but also the creation of new jobs based on changing demand and the limits of prevailing AI technologies. Furthermore, the pace and scale of disruption created by AI are bound to differ substantially across different geographies and socioeconomic environments and thus raise the question of escalating global inequalities.

Introduction

Similar to the Industrial Revolution, artificial intelligence is riding in a new wave of technological change that includes both disruption and opportunity. However, compared to then, there is significant global ambition for artificial intelligence, and the distributional effects for jobs seem to be more uneven than at any point in modern history. Artificial intelligence (AI) emerged in the middle of the twentieth century as a completely new high-technology product that was unlike any past mechanization period. Since Alan Turing's proposal (1950) asking whether machines can think (which indirectly advanced the development of artificial intelligence, Copeland & The Editors of Encyclopaedia Britannica, 2025), AI was formally founded at the Dartmouth Conference in 1956 (Russell & Norvig, 2021). AI began chiefly as basic rule-based automation and later evolved to machine models that were capable of greater complexity and automation. As technology matured, automation became more than just factory automation; it contributed to more routine, mental, and administrative work (Autor, 2015). If we fast forward to today, AI not only automates a more complex web of tasks, but it also demands skills across sectors, resulting in dislocations, transformations, and reallocations of benefits (Agrawal, Gans, & Goldfarb, 2018).

There is extensive literature exploring this new intersection of AI, automation, and work. For example, Acemoglu and Restrepo (2019) looked to understand the relationship between job loss and task creation, allowing them to put AI into a machine that could both create and destroy

jobs. Bessen (2018), on the other hand, found that artificial intelligence could also create jobs in sectors because of productivity, not lost jobs. Also, in his 2024 paper, Autor included that AI could create middle-class jobs because it could remove complexity and offer even more avenues for work.

Artificial Intelligence (AI) and Automation work hand in hand in transforming the future of the labour market; however, the risks they pose vary slightly, though they largely overlap. Automation focuses on optimizing human labour through replacing certain repetitive or manual elements of it to enhance productivity. On the other hand, AI takes it to the next level as it is able to replicate some of the cognitive processes that previously were just unique to humans. Moreover, recent innovations in the area are now developing its abilities further through its being capable of predicting and creating completely new content.

Some other pieces refer to the unevenness of the impacts of AI, in particular, on sectors and places. Badet (2021) and Tiwari 2023) noted that routine-based occupations are particularly vulnerable to automation. Gmyrek, Berg, and Bescond (2023) demonstrated that generative AI could actually exacerbate global inequalities, as AI experiences and behaviours differ and impact workers in different economies in different ways. Likewise, the World Economic Forum (2025) produced a 'future of work' report suggesting 39% of necessary job skills, by 2030, will change with differential impact by occupation and geography (Leopold et al., 2025). The public is understandably apprehensive about lost jobs (Anderson, 2014) but equally uncertain about the unexplored capabilities of AI (Glover, 2025).

This paper offers a critical review for a task-based analysis of the changes in the labour force due to AI and considers how these two trends vary by region around the world through the employing a scoping methodology. In this way, the author seeks to get a better idea of how work is changing and who may be most set aside or affected. AI is not merely displacing work; it is reshaping the nature of the labour market by influencing how work is organized and produced, what types of competencies are required, and even spawning new types of work (Autor, 2015; Bessen, 2018). That said, many studies argue the potential of AI to augment human work, especially in a job that requires creativity, judgment, or social skills–which AI simply cannot do at the moment (Acemoglu & Restrepo, 2019; Autor, 2024)- as opposed to simply the possibility of automating fairly mundane routine cognitive and manual work (Badet, 2021; Tiwari, 2023). Certain predictions are that displacement will matter little for high-income countries, which have trained professionals and knowledge workers and may benefit from these changes, while low-income countries may feel the most displacement (Gmyrek et al., 2023; World Economic Forum, 2025). Again, emphasizing issues of inequity, unequal access to reskilling, and the global state of labour outcomes (Leopold, 2025; Glover, 2025). In recognition of this, it is crucial to understand in what areas and capacities AI will offer opportunity and in what areas it may displace jobs, which is what this paper is examining based on the principal question: to what extent will AI and automation create or displace jobs? This paper also operationalizes these findings via 3 sets of policy recommendations which look at tackling the issues related to the

inequality of AI's impact. Moreover these policies are then tied to key instruments like KPI's, funding, responsibilities and objectives allowing to further monitor and maintain the impact policies are having.

This literature review suggests that AI is not likely to result in significant employment losses on a large scale, but rather a transformation of employment. This would represent simultaneous job destruction and creation, dependent on specific jobs and skills. In high-income contexts, existing jobs would be augmented by AI, while in low-income contexts, AI would displace jobs primarily in routine or lower-skill occupations.

When investigating whether AI and automation will displace or create jobs, the paper employed the scoping review methodology (Arksey and O'Malley, 2005). This method is mostly appropriate when mapping conceptually diffuse and methodologically heterogeneous scholarly areas, and, therefore, enables the researcher to map and synthesise the existing literature and conduct research in greater depth with a more thematic focus. As this subject area is relatively recent, exploring a wide variety of sources was essential. To ensure a comprehensive understanding of the topic, this review incorporates evidence from peer-reviewed journals, reputable working papers and policy reports with transparent methods on AI/automation and labour outcome produced in the time frame from January 2014 to June 2025, which were sourced entirely through Google Scholar. In order to thematically search for these pieces of research, Boolean search strings were utilized through combining technology and labour terms, e.g.: ("artificial intelligence" OR "machine learning" OR automation) AND (employment OR inequality OR displacement OR "job creation"). Although the author has been mindful of popularity bias, when selecting the articles priority was given to those with the highest number of citations as these tended to be the most searched for hence appeared first or second on the window. However, to minimise the risk of retrieval bias, multiple pages of search results were reviewed, and attention was given to sources beyond the first page to avoid overlooking valuable material. After identifying key sources covering the foundations of AI and automation, we extracted recurring themes and ideas for deeper analysis, such as inequality in relation to technological change. This methodology provided an overview of the consensus across the literature and enabled a deeper understanding of the current situation, forming the basis for developing policy recommendations.

The review proceeds in three parts in order to examine the literature with a thematic focus and ultimately draw a grounded conclusion. The first part of the review examines the displacement of regularity/repetitive physical and cognitive work and the types of occupations that would be disrupted due to automation. The second part takes into consideration how production differentiates roles and skills it displaces (often for productivity reasons) instead of only replacing human capacity. The final part discusses the rationale for these trends being inconsistent in different world regions, suggesting a principled comparison of high- and low-income economies and AI's potential effects on economy-wide productivity.

Automation and Displacement of Routine Labour

This section aims to examine the considered disruption of routine and repetitive work, which has been one of the most widely seen and apparent emerging outcomes of the future impact of AI and automation. Jobs that are characterized by rule-based systems and repetitive activities are mainly found across jobs such as manufacturing, clerical support, retail, and logistics. As AI's abilities are rapidly growing, allowing it to achieve these tasks with ease and uniformity, many companies are resorting to automation, which can thereby result in job losses. Consequently, it contributes to decreasing demand for human workers. Cross-country exposure studies indicate high potential substitution in routine tasks, particularly where routine employment shares are large; however, estimates vary with measurement and do not imply realised job loss.

We see a similar trend internationally. Gmyrek et al. (2023) estimate that roughly 26% of job categories of that nature globally are automatable and that these jobs are at very high automation risk globally. This is especially observable in middle and low-income countries where task-based, routine jobs are more prevalent. Leopold (2025) has a similar observation from his review of data, which has noted that we have already seen automation establish itself in job categories, such as transport, financial services, and assembly-based manufacturing. A single cost-driven automation could overlay an entire workforce, if not create and construct cars with components of AI, and erase numerous layers of workers who perform similar related task categories, within a manufacturing business. PwC (2018) makes note of the depth of the changing nature of jobs and occupations, if they are to be believed, estimates that presume as much as 30% of occupations in the UK, which are stated as " high risk of automation by the next decade". The largest sectors at risk of through-trend job-loss situations through automation are in manufacturing (46%), transport and storage (56%), and retail trade (44%). The expectations articulated in 'the report' show a definite relationship between human and machine-based labour in process-altering jobs that signifies a transition of permanence that has begun.

However, to understand how AI is changing work, we need to better understand the skillsets required rather than the occupations themselves. Acemoglu and Restrepo (2019) caution that automated processes cannot delete occupations; rather, automation replaces tasks that are either codified or repetitive. They describe a "task-based framework" (pg.3), where technology substitutes for only part of a job, leaving the other parts, which are invariably more complicated, interpersonal, and creative, to the human workers. Thus, in many instances, jobs will be altered rather than lost altogether to automation. Hence, occupation-level risk indices can overstate job loss.

Bessen (2018) maintained that the job displacement risk depends on the degree to which automation is causing net demand declines. This argument therefore suggests that automation will likely replace certain specialised tasks like for instance diagnosing specific radiological conditions. Nevertheless, the overall impact of it may be limited due to the concept of rebound demand. Due to an increasingly growing aging population, the demand for radiologists is

expected to rise, which can potentially exceed what it was previously. In this case automation would be replacing the repetitive and analytical aspects of the job, while the radiologist would be able to provide the psychological support and human interactions, where machines are simply unable to substitute human expertise. Similarly, Badet (2021) indicated that the displacement of certain types of tasks has generally been occurring alongside new complementary tasks that are suited to human capabilities that rely on oversight, judgment, ethical decision-making, and interpretation. Furthermore, many of the new tasks are now more complex and professional and possibly require a different level of fluency with technology and much more flexibility/adaptability in the employee to do the work as the work changes. Autor(2024) provides some judgement as we have moved beyond many years of trying to automate manual-labour. AI systems are now even automating forms of low-level cognitive work that we did not think a machine could do. Yet, they are summarizing legal documents, classifying customer complaints and issues. What we know is that AI is doing things we would not have given to even AI. This is troubling, because jobs with elements of repeated thought and analysis are in some cases becoming under a high risk of automation.

This raises questions about who will benefit from the technology and who won't. Evidence suggests that, despite AI taking certain jobs, marginalized workers are the ones most at risk of experiencing the impacts of labour. They are the workers with the least education, digital skills, and opportunities for professional development. Tiwari (2023) points out that generally, lower-skilled workers have more trouble finding work post-displacement. This may be an issue of the generalized poor fit in lower-skilled contexts and the exit skills needed from the job that was lost. Gmyrek et al. (2023) highlight that while job displacement is a significant issue in developed countries, the impact increases exponentially in least developed countries, which is also compounded by routine work encompassing a larger proportion of total employment. This paper also highlights that their economies are fragile at best, rapid loss of a share of routine jobs would destabilise already fragile labour markets. We will investigate this aspect of AI impacts further in the third section.

Another significant area of concern found across the literature is the loss of routine and repetitive jobs leading to increased economic polarization. As automation begins to automatically automate mid-skill jobs that would provide stable middle-income work, we will see increased polarization of high-skill vs. low-skill jobs in the labour market, as these are more likely to be retained. It is now commonly understood that economic polarization exists. The World Economic Forum (2025) surveyed over 800 companies across 45 economies at the end of 2024, outlining that the most at-risk jobs for at-risk populations are primarily in sectors well below level two of education of the total. Therefore, those people who had access to limited economic opportunities will also appear to have the greatest job losses. Dispensation of these jobs leads most displaced workers to enter more precarious employment patterns, as part-time or gig work with no social protections or opportunities for regular long-term work opportunities.

Additionally, Anderson (2014) warns that AI may unintentionally destroy whole

categories of occupations, and a large segment of the population may be permanently displaced from meaningful employment without some intervention to change the scope of development. Anderson suggests that there is the risk of a growing underclass of individuals, not only pushed to the margins economically, but with diminished structural participation pathways to connect with the labour market. In this sense, the ongoing development of AI is increasing economic divides through destructive employment practices.

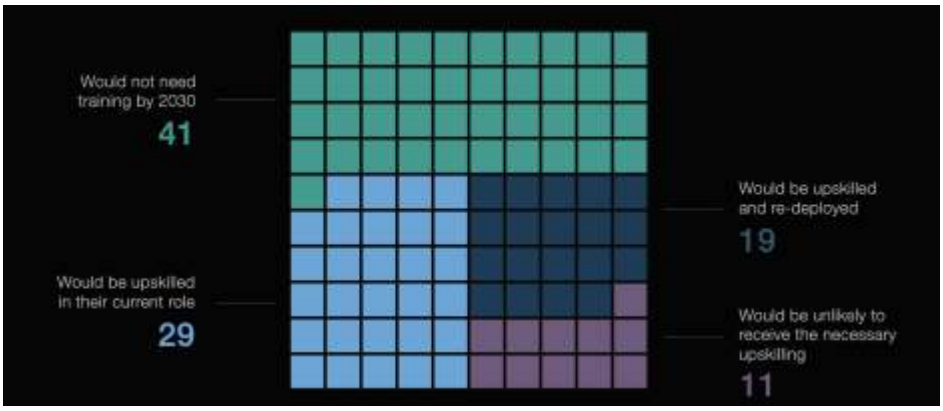


Fig. 1: Upskilling and Reskilling Outlook 2025-2030

Figure 1 demonstrates that by 2030 there will be 41% who will not need to be retrained; 29% will need to be upskilled to remain in their current jobs; 19% will be deployed after upskilling, which indicates a change in jobs. Importantly, 11% are workers who may not receive training at all and so are at risk of displacement (World Economic Forum, 2025). These predictions validate the research of Tiwari (2023) and Gmyrek et al. (2023), who conclude that unequal access to reskilling will increase the exclusion of low-skilled workers from the labour market.

With the reflection above, there appears to be a consensus in the literature: AI is destroying routine and repetitive work in a variety of sectors, starting with jobs easiest to automate and coded tasks. Although we see that automation displaces jobs by changing how they are done, rather than eliminating them, the 'new job' carries a higher entry cost, greater expectation of education, and digital literacy. Those workers who take low-level work in vulnerable roles would face a longer-term vexation if they were unable to find work in the same manner. Additionally, literature suggests that AI has only begun to take over low-level cognitive tasks in some roles, meaning that, as the capabilities that can be deployed grow, AI could have an impact on many white-collar jobs too. Even if these jobs could emerge in the long run, it is unlikely that the same groups being displaced will have access to them, since workers have virtually no opportunity to capitalize on existing jobs, unless there is a deliberate inclusion through an equity lens for the displaced workers. The next section will outline to what extent there could be chances for AI to be an avenue for job creation and, if so, whether these jobs will also be sustainable and accessible job opportunities.

AI-Driven Job Creation and Emerging Opportunities

The story of artificial intelligence is transforming the world labour market not only into a story of displacement, but also into jobs which will be created, transformed, and many tasks augmented. As people lose routine jobs, many people rightly maintain that AI is creating jobs and new opportunities for paid work through a new generation of hybrid jobs, productivity enhancements, and sectors built upon human-AI collaboration. This section investigates how AI is creating novel modes of work, shapes of work, and socio-economic conditions affecting access to such jobs.

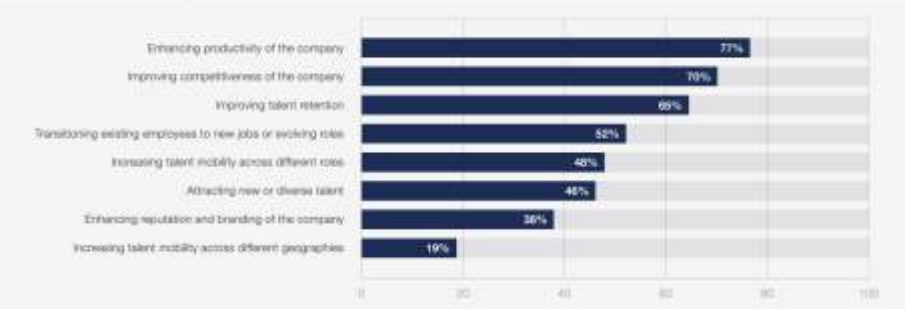


Fig. 2: Expected Outcomes for Investing in Training 2025-2030

Figure 2 (World Economic Forum, 2025) demonstrates the expected benefits that companies anticipate from their workforce transformation strategies in reaction to AI adoption. The top benefits reported are enhancing productivity (77%), improving competitors (70%), and improving talent retention (65%). Fewer companies viewed enhancing branding (38%) or cross geographic (19%) as the primary benefits.

One of the most explicit ways AI is creating jobs is through new job categories. According to Badet (2021), the adoption and growth of AI technologies have resulted in new roles emerging over the last 5 years like Machine Learning Engineer, data annotator and AI ethicist. However, Gmyrek et al. (2023) notes that the main growth includes the demand for non-technical coding AI jobs required for maintenance of the systems like data cleaning or checking quality on generative systems in real time. These roles are skill-intensive as they bring together digital skills with sector-specific skills. The World Economic Forum (2025) suggests that jobs in analytics, AI development, cybersecurity, and human-machine interactions are the world's fastest-growing job categories. This indicates that, in addition to removing tasks, AI is likely to generate entire environments of new capacity of work.

Despite the emergence of new forms of work, AI is innovating and upgrading jobs. Autor (2024) argues that AI is able to “assist with restoring the middle-skill, middle- class heart of the US labor market”(pg.20), hence adding to employment rather than destroying it. In the health sector, AI may relieve professionals of their diagnostic or administrative tasks, so doctors may spend more time with patients. These examples give credence to the idea that AI may improve productivity and job quality by reducing lower-level tasks and providing additional time and

cognitive bandwidth for higher-level thinking or creativity. For example, Bessen (2018) notes that productivity enhancements often have an increase in an output constraint of some kind, meaning increased production generates jobs and further job growth through complementary job creation across the value chain. The emergent rise of types of roles supporting fields such as content moderation for digital content, automated systems integration, and custom experience design are industry examples.

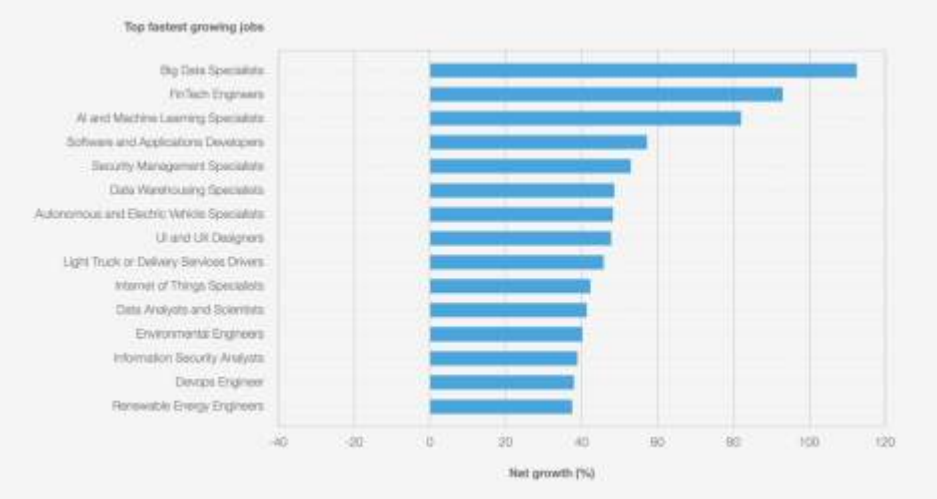


Fig. 3: Largest Growing Jobs 2025-2030

Figure 3 (World Economic Forum, 2025) shows globally the fastest-growing job roles and projected net growth across a geographic horizon for the coming years. Expected growth is highest for Big Data Specialists (~110%), FinTech Engineers (~90%), and AI and Machine Learning Specialists (~82%). The data portrays lots of fast-growing jobs as technology-based jobs that require advanced digital skills and thus could contribute to a growing accessibility and inclusion gap for workers lacking knowledge.

However, as opportunities arise, the literature shows that the workers do not evenly distribute or have equitable access to jobs that rely on AI technology. Tiwari (2023) highlighted that the majority of job opportunities are often represented by types of jobs that require advanced understanding in technology, extensive learning, and specialization; hence are unable to capture those workers who have been displaced from their routine jobs. This then results in these workers no longer having access to retraining. Gmyrek et al. (2023) capture concerns for regions that are likely most impacted by the labour automation displacement yet are least prepared to partake in the AI economy. Balogh, Reka, et al. (2024) touches on the fact that these jobs left are often lower-paying and have even been found harmful to users' psychological well-being. It is important to note that while artificial intelligence will expand and innovate tasks that humans do, it could also continue the trends of fragmentation that only further alienate and limit the steady and meaningful employment opportunities in the labour market.

Ultimately, as AI continues to replace routine and codifiable work, the evidence increasingly shows that it is also creating jobs, especially in new, digitally intensive roles found in the increasingly growing field of Artificial Intelligence development, cybersecurity, and data analytics. These not only add new sources of employment quickly but also transform the work of occupations that existed previously. This is consistent with this review's main argument that AI is not resulting in net job loss but rather in a dynamic reconstruction of the labour force with more jobs created than lost. However, this transition is not automatic or guaranteed. The inclusivity and sustainability of AI growth depend on the investments in education and the digital industry to ensure that there is a greater benefit than loss, which we elaborate on in the next section. Nevertheless, the literature demonstrates that with appropriate support, the emergence of new jobs that are associated with AI has the ability to not only deter displacement but also widen and benefit the labour market.

Global Distributional Impacts of AI on Employment

While AI adoption is creating more jobs worldwide than it is destroying, it is not uniformly the case. Advanced economies that created or contributed in some way to AI have strong innovation, a highly skilled workforce, as well as very good digital infrastructure are reaping most of AI's employment benefits. This section explores the uneven geography of AI's labour market impacts and suggests some policies that have been recognised across the literature to benefit and promote a more equitable outcome.

The World Economic Forum (2025) reported an above-average regional difference of potential impacts. For example, recent data showed that in North America and Western Europe, over 50% of the employers surveyed expect AI to create new jobs, primarily due to the demand for AI specialists and machine learning experts. Moreover, as shown in Figure 4, regional AI adoption is highest in North America/Europe as well, but adoption does not imply employment gains without complementary investments in skills. Conversely, due to their high exposure to automation in agriculture and manufacturing, low-income services, regions like Sub-Saharan Africa and South Asia will only see job creation with major job displacement. This is unless there is a major investment in restructuring the sectors and skills. However, this data reflects entirely the employer sentiment rather than actual labour outcomes. WEF regional case studies point out that while jobs might be created, they are usually created in the modern 'AI hubs' with technology systems that can develop AI further, while peripheral rural areas get left behind.

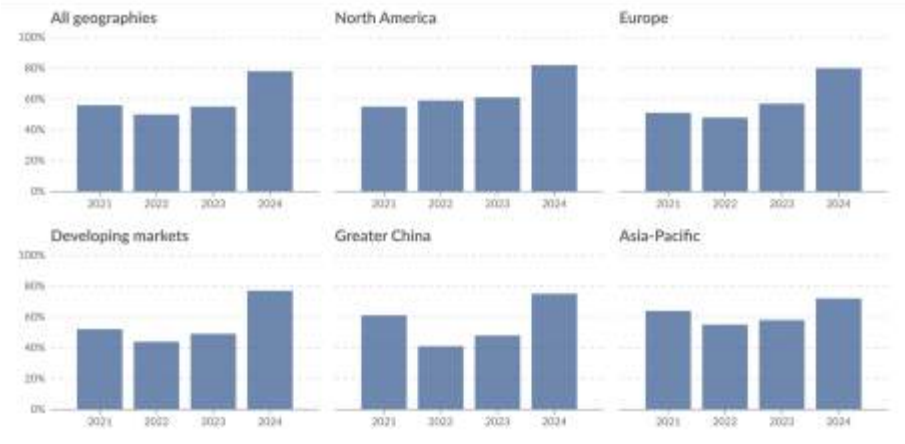


Fig. 4: Share of jobs using AI globally

Figure 4 (McKinsey & Company Survey via AI Index, 2025) displays the percentage of companies using AI in at least one business function from 2021-2024 by region. Global adoption increased from ~55% in 2023 to around ~80% in 2024, led by North America and Europe. Developing markets like Greater China experienced high growth rates from lower starting points. On the other hand, the Asia Pacific experienced a slower growth trajectory, demonstrating that while uptake of AI increases, regional disparities remain.

Jones (2023) and Capraro (2024) support these regional assessments by arguing that AI adoption is 'path dependent'. Therefore, suggesting that countries with prior research and development capabilities, innovation clusters, and high numbers of tertiary sectors will obtain significantly more benefits from AI if its productivity gains are driven by innovation. Gries and Naudé (2018) also highlight that inconsistency in national occupation structures influences AI's labour market. The paper also mentions the fact that those economies dependent on routineised, but expert-led manufacturing are not particularly exposed to job loss, but instead, when the offshoring automation results in onshoring production in developed countries. A similar theory is echoed across Gmyrek et al. (2023) paper, where they observe that upwards of 55% of jobs in certain low-income and middle-income economies are at a high risk of automation. They also elaborate that retraining in such economies is highly problematic.

This disparity is not only between countries, but it exists and is currently growing within countries as well. Badet (2021) states that firms or sectors that were already operating at the technological frontier of productivity may receive productivity gains from AI faster than others. This could aggravate the income disparity between high-paid and low-paid job roles. Similarly, Bessen (2018) states that AI can increase output and demand for jobs, complementing AI, but

this depends entirely on the market demand (more likely in advanced economies). Overall, automation and AI appear to reinforce existing global inequalities, as high-income countries benefit from technological innovation while low-income countries struggle to keep pace. An emerging trend of onshoring production to wealthier nations may be hindering developing countries' ability to generate export-related employment. This trend, and its implications for global labour distribution, should be a key focus for future research. If market demand for new AI-complementary job roles remains limited and inclusive policies are not implemented, the literature suggests that income disparity and digital exclusion linked to AI are likely to intensify on a global scale.

Policy Pathways to Inclusive AI-Driven Growth

To tackle these inequalities and disparities, it will require governments and international agencies to better implement strategically well-designed policies that are based on partnerships, action items, and lasting results.

First, governments need to invest more in human capital. At a minimum, the literature calls upon governments to be diligent in expanding their investment toward training the relevant digital & cognitive skills (through subsidies, training, and collaborations with industry to identify the workforce training needs of the labour market). The creation of apprenticeships would allow individuals to be educated by the professions specialising in AI development from the 'AI Hub' allowing to not only give them practical experience but also employ skills essential for the future world of work. Illustrative models include Singapore's Skills Future credit systems and Finland's vocational reforms aimed at adaptability in the labour force, which proves that the apprenticeship route could be highly beneficial.

Second, diffuse AI to lagging firms. Specifically, through AI implementation in ways that complement and augment the workflows of human beings. Often, for developing economies, we have seen through the literature, AI needs to translate into AI-complementary completions. Some implementations will be AI in assisted agriculture, telemedicine, and renewable energy manufacturing. A way of ensuring that AI and Automation is giving the desirable impacts is through implementing an organization or regulatory authority, which carefully monitors the impacts which AI is having on employment and industry generally acting as the guidelines to set certain policies or restrictions. This would allow control over how much and what kind of impact AI is really having while at the same time developing a policy unique to the country's economy as certain indicators like GDP or unemployment would largely influence what kind of policies are employed. In the analysis of differential productivity of AI, Jones (2023) and Capraro(2024) emphasizes that without policies advocating for equitable AI systems, the economic value of AI will be excessively centralized in high-income metropolitan regions and hence reside within a small number of 'AI hubs'.

Third, protect workers and speed up re-employment. This can be done through investment in people or at a minimum protecting the labour market in ways that are feasible. Wage insurance and mobility grants are some of the programs that offer financial and social

resources to displaced persons in need of help with entering the labour market again like in markets with informal sector investment and some displaced continuing trends. Kim (2021) indicates that there is a need that employee and human structure design is embedded with illustrated safety mechanisms to ease long-term pressures of unemployment. According to Leopold (2025) and the World Economic Forum (2025) organizations should focus on redeploying and strengthening job quality safeguards in AI-mediated work (minimum pay standards, exposure caps, etc.) instead of laying off displaced workers when faced with temporary financial shortfalls.

To ensure the effectiveness of such measures, policymakers and organizations should incorporate Key Performance Indicators (KPIs) that evaluate the real-world impact of innovation-driven policies. These could include re-employment rates, average time taken for displaced workers to find new roles, and the proportion of workers transitioning into AI-complementary occupations. The use of such KPIs would enable policymakers to monitor progress, identify shortcomings early, and adjust strategies to ensure that technological advancement translates into inclusive economic growth and doesn't aggravate the divide further.

In order to begin to close the global divide around the adoption of AI, the need for international cooperation is critical. While national policies can be effective in promoting responsible AI adoption, only large-scale global collaboration will ensure that the benefits of this technology are distributed more equitably across nations. Gries and Naudé (2018) present several options for multilateral strategies to mitigate extremes of vulnerability relating to AI through varied travel agreements, joint AI research projects, and skills-based initiatives that are funded by global institutions like the World Bank and the International Labour Organization. This matches with Tiwari (2023), who warns that if some global agreement is not reached to mitigate or close a global divide that has been created by AI, then at best, developing country economies will only be locked into lower-end segments of the future global supply chain.

To wrap up, evidence of the above is that there is growth in jobs from AI, as there is an increase in jobs around the world, and it also appears unevenly distributed across regions in the world. Advanced economies, in particular, seem to be well-positioned to absorb some of the job growth generated by AI. In comparison, many of the low and middle-income economies may not only remain subject to lost dislocation because to the extent that they will not be able to create any new jobs or be employed due to skill deficits.

Conclusion

This review has examined whether AI will ultimately lead to a net loss or gain in employment. The evidence has suggested that even though AI will increasingly replace routine, codifiable, and repetitive jobs, it will also be creating new jobs in emerging and technology-driven areas (Badet, 2021; Bessen, 2018; World Economic Forum, 2025). The literature does indicate that job displacement and creation is occurring simultaneously, and the net balance is on job creation. This may be the case, but these jobs will not be open to everyone because they rely on advanced skills that require an ability to adapt. This tends to be

concentrated in advanced economies and among highly educated workers.

The first section demonstrated that routine is highly vulnerable in manufacturing, clerical services, and administrative sectors because AI will thrive in predictable, rule-based environments (Badet, 2021; Gmyrek et al.,2023; Acemoglu & Restrepo, 2019). The World Economic Forum (2025) reported that 43% of companies expect to reduce roles like data entry and payroll in the next 2 years. The second section showed that AI is also changing work, though creating roles in AI development, data science, and cybersecurity (Autor, 2024; Glover, 2025; Leopold, 2025). These results will often occur in parallel with job displacement in the same sectors, as displaced workers do not transition into newly developed jobs.
The third section demonstrated that at the international level, net job increases tend to only occur for economies with developed innovation systems and digital infrastructures, as the evidence suggests (Oxford Academic, 2023; Gries and Naudé, 2018; WEF, 2025). Most low and middle-income countries will have less job-creation capacity, but that comes with greater displacement risks.

In summary, the evidence argues that AI will generate more jobs than it displaces, but also that many of those jobs will not be accessible to everyone without intense efforts made to support those individuals. Large-scale and workforce-wide skills development, industry diversity, labour protection, and cooperation globally will be important to ensure that the economic benefits of AI are more evenly distributed (Tiwari, 2023; Leopold, 2025). Future research will therefore also have to make better attempts at identifying effective reskilling models for creating an industry driven by AI in low-income economies. More thought will also have to go into developing governance frameworks and emergent systems that promote equitable outcomes globally. Getting a better understanding of these areas of AI will be crucial in order to ensure that AI drives accessible growth and does not act as another contributor to world inequality.

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AI for Inclusive Learning: How Artificial Intelligence Can Personalize Education for Students with Learning Differences By Aryan Goyal

Abstract

Artificial intelligence (AI) is transforming education at an unprecedented pace. However, most AI-based learning tools still assume that all students learn in the same way. Many bright students with learning differences—such as dyslexia, ADHD, or auditory-processing disorders—struggle when instruction relies only on text or lectures. This paper explores how AI can create inclusive, effective, multisensory learning experiences that adapt to each student's unique strengths. By reviewing current adaptive-learning technologies and drawing insights from an educational therapist, the paper proposes a new framework called the Talking Video Model. This model combines speech synthesis, visual storytelling, and real-time feedback to make learning both easier and more engaging. Ethical design principles—privacy, transparency, and fairness—are emphasized to ensure that personalization benefits every learner. The goal is to show how thoughtful use of AI can transform classrooms from standardized settings into adaptive environments that recognize and support each student's learning needs.

Impact Statement: *This paper proposes an ethical, practical way to use artificial intelligence to make education accessible for all learners.*

Keywords: *Artificial intelligence, inclusive education, accessibility, learning differences, adaptive learning.*

Introduction

Every student learns in a unique way. Some students learn best by reading, others by listening, and some by watching or moving. In many schools, however, lessons are still taught in the traditional style—often through textbooks or long lectures. This can make learning especially difficult for students with learning differences. These students are often highly intelligent and creative, but they need lessons that align with how their brains learn best.

Artificial intelligence (AI) offers a way to make learning more personal. It can adjust the speed of a lesson, give instant feedback, and choose the most effective style for each learner. Some apps already use AI to teach subjects such as math, languages, or science, but very few are designed specifically for students with learning differences. This paper explores how AI could create more efficient, multisensory learning experiences that help every student succeed. It also introduces the Talking Video Model, an idea that combines voice, images, and interaction to make learning easier and more enjoyable for all students.

Current Challenges in Inclusive Education

Many students with learning differences face challenges in school because lessons often rely on reading and memorization. For example, a student with dyslexia may find it difficult to

read a long passage, even if they completely understand the ideas. A student with ADHD might have trouble focusing during a long lecture, even when the topic interests them. When the teaching style doesn't match their needs, students can become frustrated and lose confidence in their abilities.

Teachers often want to support all students but don't always have the time or resources to create multiple versions of each lesson. Even schools that use technology may still rely on standard, one-size-fits-all lessons. As a result, students who learn differently may fall behind—not because they lack ability, but because the system isn't flexible enough to fit their learning needs. Making education more inclusive requires tools that adapt to each learner, while keeping lessons engaging and accessible.

AI Solutions and Existing Tools

AI is already shaping the way students learn. Many modern apps now use AI to adjust lessons, give feedback, or help teachers understand what their students need. For example, language programs such as Duolingo use AI to study how quickly a learner answers questions and then adjust the difficulty of the following exercises. Math and reading programs, such as Khan Academy or IXL, analyze student responses and provide extra practice in weaker areas. These systems show how AI can personalize learning and make it more efficient.

AI can also aid students with learning differences. Text-to-speech programs read written text aloud for students who struggle with reading. Speech-to-text tools let students with writing difficulties express themselves through speaking. Some apps even use AI to convert printed text into audio or into another language. While these tools are helpful, they often focus on single tasks rather than providing full lessons that match a student's learning style. This gap creates an opportunity for new designs—like the Talking Video Model—that combine multiple senses and teaching methods in one place.

The Talking Video Model

The Talking Video Model is an idea for an AI-powered learning system that teaches through short, personalized video lessons. Each video would combine narration, on-screen text, images, and movement so that students can both see and hear the lesson at the same time. Instead of reading a long paragraph or listening to a long lecture, the student would watch an animated explanation that pauses or repeats automatically when the system notices signs of confusion.

The model uses AI to study how each student interacts with the lesson. If a learner replays certain parts, the AI would slow down the pace or provide extra examples. When a student answers correctly several times in a row, the app would increase the pace or offer a more challenging question. This kind of adjustment loop helps every student learn at an appropriate speed, while keeping lessons efficient and engaging.

Another important part of the Talking Video Model is that it presents different ways to learn the same idea. A math concept could appear as text, spoken explanation, animation, or all

three combined. By giving students control and variety, the model aims to make learning engaging, effective, fun, and accessible for everyone.

Comparison to Existing Models

Many adaptive-learning models already use AI to personalize education, but most focus only on performance data, such as quiz scores or response time. Systems like Khanmigo and Duolingo's Smart Path adjust question difficulty but rarely adapt the format of instruction itself. They mainly provide more of the same type of exercise. In contrast, the Talking Video Model focuses on how the content is presented, not just what the next question should be. By combining animation, voice, and visual storytelling, it creates a multisensory environment that supports different kinds of learners. This makes it more inclusive for students who struggle with reading, focus, or memory, while keeping lessons engaging for everyone.

Ethics and Accessibility

When designing AI tools for education, it is important to make sure they are fair, private, and safe for every user. Since AI systems collect data to learn about students' ways of learning, the information they store must be protected. Educators, developers, and parents must always be aware of what data is being collected and how it is used. The Talking Video Model would include clear settings that let families control what information is shared and allow data to be deleted at any time.

Fairness is also an ethical goal. AI must work equally well for all students, no matter their background or ability. If a system is trained mostly on one group of learners, it might give less accurate help to others. To avoid this, the Talking Video Model should be tested with diverse students and adjusted to remove bias.

Accessibility is another important principle. All students—including those with vision, hearing, or motor challenges—should be able to use the tool easily. This means adding captions, adjustable fonts, and voice-control options. By following strong ethical and accessibility guidelines, AI can become a useful and trustworthy tool in education that helps everyone learn.

Preliminary Example

A small classroom pilot could demonstrate how this framework works in practice. For example, a one-minute AI-generated animation explaining a math or science concept could be shown to a classroom. Observing whether students replay certain parts, answer questions more quickly, or express greater interest afterward would provide early insight into engagement, comprehension, and overall effectiveness. Even simple observations like these could help educators and developers refine the Talking Video Model before a large-scale study.

Future Work

Future studies could test how effective the Talking Video Model is compared with traditional teaching methods. Small classroom trials could measure student engagement,

understanding, and confidence after using the model. Collecting feedback from teachers and students with learning differences would also help improve the design. As AI continues to advance, future versions of this model could include emotion recognition, sign-language options, or language translation, so students from all backgrounds can benefit.

Conclusion

AI has the power to make education more efficient, useful, personal, and inclusive. By learning how each student understands information, AI can adapt lessons to match individual strengths and weaknesses. The Talking Video Model shows one way this could happen—through short, interactive videos that combine sound, images, and feedback to help every student learn in the way that suits them best.

Although this model has not yet been tested, it represents an important step toward a future where classrooms are adaptive and fair for all learners. When AI tools are built thoughtfully—with privacy, fairness, and accessibility in mind—they can help teachers reach every student more effectively. Inclusive technology has the potential not only to improve education but also to remind students that learning differences are not disadvantages, just different ways of thinking.

The Talking Video Model could also complement existing accessibility technologies such as Microsoft's Immersive Reader and Google's Read&Write extensions. These tools already assist students by reading text aloud or simplifying digital content. By combining their accessibility features with adaptive AI personalization, the Talking Video Model could provide a more complete and inclusive learning experience for every student.

With thoughtful design, AI can become a creative partner that helps all students succeed.

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Holly Jackson's *A Good Girl's Guide to Murder* Trilogy: A Study of Authorities, Technology, and Confessions By Audrey Kuang Zhang

Abstract

Throughout Holly Jackson's *A Good Girl's Guide to Murder* trilogy, the themes prominent in every book are the uselessness of police, the pervasiveness of technology, and how confessions drive the plot and lead to further themes. Jackson demonstrates how the police constantly fail to meet expectations in life-threatening situations, how the characters begin to depend on technology as the trilogy continues, and how the confessions lead to resolution for both the readers and characters. Using a comparative, structural analysis of notable motifs within the series, the plot development was evaluated in a progressive manner. The results illustrate that Jackson's novels often follow a similar plot structure, that involves a crime or disappearance, a period of investigation, a confession from the antagonist, and an expression of a normal life after the problem is solved. This study presents the progression of repetition throughout series, to act as a model for comparison to other sequential novels and authors.

Introduction

The A Good *Girl's Guide to Murder* series, a set of three murder-mystery novels containing *A Good Girl's Guide to Murder* (2019), *Good Girl, Bad Blood* (2020), and *As Good As Dead* (2021). Although the overall plot and characters are slightly similar, the conflicts and themes are extremely different ranging from novel to novel.

The trilogy follows Pippa Fitz-Amobi, nicknamed Pip, who spends the last year of her high school in her hometown, Fairview, before heading off to college. The first novel, *A Good Girl's Guide to Murder*, follows Pip, a senior, as she tries to find the real culprit of the Andie Bell and Sal Singh case 5 years ago. Pip decides to reexamine the closed case as her senior project and teams up with Ravi Singh, Sal's younger brother. Pip goes around interviewing people close to Andie and Sal, and finally deduces someone had confessed in Sal's place. Pip soon begins to receive dangerous and threatening messages telling her to drop the case. However, Pip refuses to and makes another significant breakthrough by proving Sal had an alibi the night of Andie's disappearance. Pip believes Elliot Ward, a teacher at her school and father of her best friend Cara Ward, was the one who kidnapped Andie. She confronts him at the old Ward house where Elliot admits to Andie having left the house injured after a fight. Afterward, Becca Bell, Andie Bell's younger sister, was the one who murder Andie by pushing her down the stairs. Becca brings Pip to Andie's body and attempts to murder Pip as well; however Ravi and the police arrive just in time.

Beginning in the second novel, *Good Girl, Bad Blood*, Pip, with encouragement from Ravi, decides to create a podcast explaining the Andie - Sal case called *A Good Girl's Guide to Murder* (AGGGTM). Fairview decides to hold a 6-year memorial for Andie and Sal; however the next morning, Connor Reynolds, a friend of Pip, reveals his older brother, Jamie, had gone missing. The Reynoldses want Pip to take the case and find him, since the police declare him as

"low-risk". Pip mostly relies on her podcast and the internet to find evidence and track where Jamie might have gone the night she disappeared. Pip then discovers Jamie had talked a lot to a girl named Layla Mead, and she sends a concerning message to Pip on Instagram, before deleting all of her accounts on social media. From rumors on the internet, Pip discovers Stanley Forbes, who worked at the town newspaper, was Child Brunswick, son of a mass serial killer who murdered children using his son. Charlie Green, one of Pip's neighbors turns out to be Layla and he wanted revenge against Child Brunswick, since Charlie's twin sister was the last victim of Scott Brunswick. Charlie murders Stanley, and Pip, Ravi, and Connor manage to recover Jamie by breaking into Stanley's house. Finally, all characters reconnect at Stanley's funeral; however Pip begins to become mentally unstable, as support within her community dwindles.

Continuing on into the third and final novel, *As Good As Dead*, Pip continues to have nightmares about Stanley's death and takes drugs to help her sleep and be "normal". Pip believes she has a stalker, but the police don't believe her, thinking she made it up. Pip begins her investigation and she is kidnapped by Jason Bell, father of Andie and Becca Bell. Jason reveals himself to be Pip's stalker and also known as serial killer, the DT Killer. Pip manages to escape; however in a moment of rage and justice-seeking, Pip murders Jason and plans to frame Max Hastings as the murder for his drugging and raping of girls in previous novels. Pip, Ravi, Jamie, Connor, and Nat da Silva team up to frame Max, and eventually, the police arrest Max and put on trial for murdering Jason Bell. Afterwards, Pip breaks up with Ravi, trying to keep him safe, just in case Max is again declared not guilty. Pip believes the police suspect her as well for the murder, and doesn't want to rope Ravi into the mess. Soon afterwards, Pip goes to Columbia University, and is immediately texted by Ravi after Max is declared guilty, signally their inevitable reunion.

Although the main internal and external conflict of all three novels are different, there are still some messages which apply to all or the majority of the trilogy. For example, the author could have intended to emphasize a couple specific themes to make sure individuals reading their works truly understood the message the author was trying to convey. Characters might be forced into similar situations as previous, and people are able to examine how the characters reacted differently according to their added knowledge from the last instance. Some themes of the novels are constantly there, continuously acquiring more examples to support the specific message. However, the way the portrayal of the theme can vary from novel to novel, but the overarching theme is still the same for the entire trilogy. Holly Jackson's *A Good Girl's Guide to Murder* trilogy, containing *A Good Girl's Guide to Murder*, *Good Girl, Bad Blood,* and *As Good As Dead*, each has messages supported by each novel: the police are extremely restricted to what they can do, the integration of technology is pervasive, and confessions can be used to either mislead or reveal the truth.

The Perspectives of Police Effectiveness

Firstly, Holly Jackson provides many different examples of how the police can be extremely useless in high-stakes situations. Although police and law enforcement are often held

in high regard and trusted to create well-planned solutions and find justice for all, Jackson finds many instances in Pip's story where the police haven't made such brilliant decisions. The police are supposed to listen and use their best judgement to solve crimes and keep the community safe; however Jackson illustrates many times where the police refuse to listen to genuine voices of concern. Jackson illustrates the police to be lazy, gullible, extremely biased, unwilling to hear other voices, and tend towards the paths that are most convenient and easy. Throughout her trilogy, featuring *A Good Girl's Guide to Murder*, *Good Girl, Bad Blood*, and *As Good As Dead*, Jackson emphasizes how the police are extremely useless in actual situations.

In Holly Jackson's *A Good Girl's Guide to Murder*, the police falsely accuse Sal Singh of being Andie Bell's murderer. For example, when Ravi presents Pip Sal's phone which contains his "confession", Pip notices the grammar in Sal's confession text differs from his usual style. "'That maybe someone else wrote that text,' she said. 'Someone who added the punctuation themselves because that's how they were used to writing in texts,'" (Jackson 72). The obviously different texting style raises red flags from Pip and Ravi, details in which the police seem oblivious to the clear inconsistency in something extremely important, like a confession in a murder case. The significantly different grammar style the police ignored, who refused to continue to investigate before closing the case. Once the police see this "confession" and a way to quickly close the case, they easily accept Sal murdered Andie before murdering himself without even trying to dig deeper. They also fail to create a reason why Sal would murder Andie, who they had a happy relationship with. The police are so quick to just assume and support the fact Sal was a murderer because of his guilt, but they cannot see a true motive to why someone would go as far as murder another person. Jackson illustrates the police's gullibility and laziness with the ignorance to key differences and details, and the preference of a quick case without true investigation and examination. Therefore, Holly Jackson proves and highlights that the police cannot always be trusted for their inability to properly solve problems.

Further along in Holly Jackson's *A Good Girl's Guide to Murder*, Pip discovers Sal's friends suddenly changed their story which was an alibi for Sal to a new story which put Sal in a place which made him the main suspect. For example, as Pip speaks with Naomi and Max, Naomi reveals someone had blackmailed them into lying to the police and taking away Sal's alibi. "'Someone made us do it.' … 'And we had to tell [the police] that Sal actually left Max's at ten-thirty and that he'd asked us to lie before,'" (Jackson 249). The police readily accept the new statement without even trying to fact-check the new information. Since Sal's friends have already lied to the police about Sal's whereabouts, the next logical step includes identifying the truth of the new confession; however, the police make no move to even try to prove this, which expresses their laziness in the face of dangerous situations. Pip also notices Naomi expresses clear distress and guilt over Sal's death, and the police seem to make no note of her unease. A more thorough police investigation would have picked up Naomi's emotional turmoil, and interviewing Naomi even more could have led to the truth of Sal's presence for the entire night. However, since the police allow themselves to be gullible and believe every new piece of information without even attempting to rate the credibility, the police are unable to identify obvious red flags in the

situation. Further along in the novel, Elliot Ward, father of Naomi, was revealed to be the one who blackmailed Sal's friends into giving up his alibi. Elliot had read his daughter's diary and found important information to blackmail Naomi, Max, and the other friends; however the police never discovered the text Elliot sent to all of Sal's friends and never made the connection between the two. Jackson demonstrates the police's laziness and willingness to accept the most convenient story to close the case, rather than follow the clear connection of evidence to find the real truth. Therefore, Holly Jackson emphasizes the laziness of the police forces to find the easiest path, with the least resistance.

In the beginning of *Good Girl, Bad Blood*, written by Holly Jackson, the police refuse to even attempt to search for Jamie Reynolds. For example, as Pip speaks to Detective Hawkins to ask for the police's help, Hawkins refuses. "'We've got an actual high-risk case: an eight-year-old abducted from her backyard. There's nothing I can do for Jamie. It's the way it is, unfortunately,'" (Jackson 57). Blinded by their own beliefs despite Jamie's family emphasizing something is wrong, the police label Jamie as "low risk" and decide he will come back without police intervention. The police simply assume Jamie left town again, and fail to even consider the suspicions the Reynolds family and Pip bring up. When Connor, Jamie's brother, and Joanna, Jamie's mother, try to report Jamie's disappearance to the police, they completely ignore Connor and Joana's insistence of weird and strange actions and merely brush it off. The police's main classification for risk level is age, instead of real potential danger. It is later revealed in the story that the eight-year-old child was merely with her father, while Jamie was involved with extremely shady and serial killer business. The juxtaposition between what the police believed was a dangerous case and what really was a dangerous case further proves the bias of the police system towards certain people. The prioritization for the police is determined by age, instead of actual risk. Since Jamie is a 24-year-old adult with a history of disappearing for short periods of time before returning, the police ignore his situation and become oblivious to the clear suspicious and dangerous factors of Jamie's situation. The police are also shown as lazy in this case since the police do the absolute minimum to help Jamie: they state publicize his missing status. The police offer no help to the Reynolds family and sacrifice all of their resources to find a child who doesn't even need help. The police use an excuse, being Jamie's age, and therefore declare people like Jamie are allowed to "disappear" from time to time to avoid actually examining Jamie's case. If the police had actually made any investigation, then they would have quickly discovered how the suspicious and shady Jamie had gotten himself into. However, since the police's willingness to brush off cases, Jackson expresses the biased prioritization of importance by age, instead of danger. Therefore, Holly Jackson demonstrates the unfair prioritization of risk and the laziness of the police.

Another great example of how Holly Jackson explains how the police are useless in her novel, *Good Girl, Bad Blood*, is the police are unable to create a secure case against Max Hastings and are biased towards wealthier and more influential people. For example, when Pip talks with her neighbor, Charlie Green, about Max going free, Pip says, "'I practically handed Max Hastings to them, after everything came out last year,'" (Jackson 307). Pip had provided

vast amounts of information, even a confession which couldn't be used against Max Hastings; however, the police failed to create a solid case even with all of Pip's help. The police, either unable or unwilling, to conduct their own investigation, demonstrates how lazy they are. The police and justice system relies on a set of extremely strict protocols to hinder Pip's use of Max's confession. Since trial systems must have extreme requirements to what evidence can or cannot be used, many key pieces of evidence can be left out if they were gathered in ways the trial system doesn't approve of. If the police had been more competent and willing to seek justice for all people, not just the rich, then the police would have launched their own examination of the case. However, since the police are blinded by their biases towards prominent and affluent people, the police don't follow through and continue Pip's investigation. Additionally, since Max Hastings comes from a wealthy and influential family, it shields him from the consequences of his actions. The Hastings family secure a top lawyer who cleverly and slyly pushes for key evidence to be removed and undermines witness testimonies. Max's legal team manages to weasel their way out of the problem through many loopholes. The police's failures are further demonstrated since they seem to be unable to counter these tactics effectively, and soon let Max Hastings go. The police's failure to build a legally iron-clad case demonstrates their uselessness. The police express favoritism towards the Hastings family and other large and influential families, as illustrated by Max's successful bribery of another police officer. Max had used his family's influence to cover up a hit-and-run, which demonstrates his ability to corrupt the legal system with his and his family's ample resources. Jackson illustrates extreme bias towards people like Max, to demonstrate how the police are truly useless in true situations. Therefore, Holly Jackson explains the police's inability to overcome advantages certain people have, to prove the police's uselessness in delivering justice.

Holly Jackson's *As Good As Dead* demonstrates the police's dismissal of voices other than their own and their laziness. For example, when Pip receives threatening messages and suspicious situations around her, she initially goes to the police. "He didn't believe her. Even after everything, Hawkings didn't believe her… Why had she allowed herself even a shred of hope that this would go another way? Stupid, *stupid*," (Jackson 78). The police immediately assume Pip is trying to make herself a public figure, and it's for her podcast to rise in popularity. This allows the police to minimize Pip's valid concerns by telling her to blame herself for all of the shady business going around her. The police also claim Pip is hallucinating about her circumstances and because of her trauma from her previous experiences, she mentions such. Because of Pip's supposed PTSD, the police believe they can invalidate her fears and ignore her claims, treating her as emotionally unstable instead of a voice of reason. Another contributing factor to the police's uselessness is their inability to connect the fact Pip's noticings are exactly what previous victims of the DT Killer, a local serial killer, have experienced and seen. Since the police had already claimed another man as the DT Killer and closed the case, the police are unwilling to re-open the case and admit they were incorrect. Their hesitance to investigate further, although Pip eventually makes the connection, demonstrates their reluctance to listen to other voices outside the police force. By dismissing the reports from Pip and their ignorance to

other opinions, the police allow enormous dangers to continue to happen, even though the police are seen as the ultimate justice and trust seekers. Since the police dislike reinvestigation in any case, it demonstrates their laziness to do more work. Police officers and law enforcement must often dive deep into their cases to find the real truth; however the police force Pip has, only skims the top, and hopes for enough "evidence" to convict anyone they can. Jackson's illustration of their refusal to genuinely attempt any thorough examination even with voices asking them to, defines the police as lazy and unwilling to consider other opinions outside the force. Therefore, Holly Jackson demonstrates the police's refusal to listen which leads to their laziness.

Continuing on in Holly Jackson's *As Good As Dead*, she explains how the police framed convenient people, instead of generating real investigations. For example, when Lieutenant Nolan interrogates Billy Karras, Nolan feeds information to Billy so he can make his "confession". "How did you kill them, Billy?... No, Billy. That's not how they died. Come on, you know the answer. How did you kill them?" (Jackson 135). Billy was a weak individual and someone who was unfortunately right there for the police to target as their suspect. Instead of allowing Billy to present the facts he knew about the murders, Nolan takes advantage of Billy's weak state to guide him towards a confession which is then used against him. Although Billy clearly had no idea about the murders, the police push to create their confession for them, so the police don't have to continue their investigation. The constant reliance on easy paths illustrates the police's uselessness and unwillingness to find the truth. The police also use fragmented evidence against Billy, like the fact he worked at the same company which the bodies were found in. The police twist such a broad and stationary piece of evidence into something that seems irrefutable, which eventually leads to Billy's arrest. The police also discover Billy's DNA on the last victim of the serial killer, but completely ignore Billy's claims of rescue attempts, the police only use this to build up their case with an extremely weak foundation. The police also seem to ignore common patterns between the victims, such as the chalk figures and dead pigeons. Their inability to investigate further on the key topic, and instead target vulnerable individuals illustrate their uselessness. The police then quickly closed the case after Billy's "confession" without even trying to prove if it had any truth or real value. They don't attempt to examine if anyone had blackmailed or threatened Billy into confessing for them. The police just immediately close everything since it's the easiest way for them. Jackson continuously demonstrates the police's prioritization of easy case closures, over genuine justice and truth. Therefore, Holly Jackson illustrates the police's enjoyment of convenience over reality.

Towards the end of Holly Jackson's *As Good As Dead*, she expresses the police's incompetence and predictability of easy and quick decisions. As Pip and Ravi begin to manipulate the crime scene, Pip takes careful actions to create a wave of overwhelming evidence pointing in Max Hasting's direction. "Follow the trail, Hawkins. The path of least resistance was right here, he just had to follow it, as he had once followed it to Sal Singh," (Jackson 378). Pip understands the extremely flawed and corrupt police system in her town, so she uses that to her advantage. Since the system had already incorrectly charged Max not guilty of sexual assault, as

the extremely biased police prefer tidiness instead of truth. Pip targets the biased trial system, which makes it easy for Pip to manipulate the situation into her favor. The police, as expected, follow Pip's easy trail straight to the fact Max Hastings, already known as a possible rapist, could very easily be the murderer of Jason Bell. The convenient scapegoat the police constantly use is finally in Pip's advantage as she knows they won't meticulously investigate the case. Searching for a quick and easy way out, the police accept Pip's version, and ignore any inconsistencies that might have been revealed with more thorough examination. Although Detective Hawkins begins to suspect Pip is the actual murderer, he eventually drops the investigation because the corrupt system would contradict with his beliefs. The police target weak and convenient individuals, and since Pip has already provided someone who satisfies both, the police would no longer see a reason to continue any investigation in the same case. Even though Hawkins is the most competent out of the entire police force, he allows himself to be slowly corrupted by the surrounding police officers. Even people with a conscious and logical thinking can be corrupted by people and a flawed system who think a certain way. In this case, corruption from people who prioritize easy convictions over justice force Hawkins to drop his case. Jackson demonstrates the obvious pattern of the police's reliance on convenient convictions, which inevitably leads to justice when twisted the correct way. Therefore, Holly Jackson explains the often corrupt decisions the police make and the predictability of such happening.

In conclusion, Holly Jackson, author of *A Good Girl's Guide to Murder*, *Good Girl, Bad Blood*, and *As Good As Dead* intentionally portrays the police as useless and foolish. Jackson attempts to highlight the flaws and corrupt actions down during trials, which are normally seen as the deciders for justice. People have extremely mixed opinions on the police and law enforcement in general, and Jackson invites individuals to question authority and find the truth themselves. To Jackson's intentions, however, there are the benefits and harms. Jackson encourages reliance on oneself instead of government and authoritative figures, and she addresses age and economic biases to certain groups of people which should always be noticed. However, Jackson also normalizes police inactivity and builds a questionable moral message. Although there are many cases where the police haven't made good decisions, there have been many times where they have made good decisions, otherwise the whole concept of law enforcement would have been abandoned long ago. Jackson also illustrates people evading punishment for murder, and Jackson seems to support vigilante justice. Holly Jackson's *A Good Girl's Guide to Murder* trilogy indisputably expresses a side of the police restrictions and reliability debate; however, the topic can be seriously debated and questioned from both sides.

The Pervasiveness of Technology in Modern Life

Secondly, Holly Jackson provides many instances of how Pip begins to rely more and more on technology to push through with her investigations. Although technology and social media can be dangerous, it can also be used as a tool to make certain events more wide-known. Jackson incorporates many aspects of Pip being completely reliant on technology. Jackson illustrates how technology can be extremely harmful to anyone and how it can destroy someone's

morals and boundaries. Technology, which should be mostly harmless if used properly, slowly makes its way to a destructive force for even the most careful. Jackson demonstrates how technology can lead to many real life, life-threatening consequences. Throughout her trilogy, consisting of *A Good Girl's Guide to Murder*, *Good Girl, Bad Blood*, and *As Good As Dead*, Jackson emphasizes how the integration of technology is pervasive.

Beginning in Holly Jackson' *A Good Girl's Guide to Murder*, Jackson illustrates how Pip uses technology to gain a simple understanding of the murder case before digging deeper into her own investigation. For example, as Pip begins the process to acquire more information about the case, she scours the internet to see all of the resources about the murder case, "After some serious social media stalking, it looks like Andie's best friends were two girls named Chloe Burch and Emma Hutton," (Jackson 14). Pip thoroughly searches different social media sites to find clues to the murder like photos, videos, and posts to try to piece together the entire thing that happened. Pip also uses technology to gather background information about the murder case and she uses technology to deduce who are the best people to interview to gain the most information. Although Pip's in-person interviews and communication are extremely important to her process, without the usage of technology, Pip wouldn't have a single lead to even begin her research. Most of Pip's town refuses to speak about the murder, so she couldn't have gathered much information by just using her fellow townspeople as the main resource. Pip had to use websites from newspapers and police documents to acquire the most accurate information possible. She uses the public information available online to uncover details missed by the previous investigations. Pip also relies on digital methods of recording information, like text messages, typed out interviews, and project logs to organize and clearly find the pieces of evidence that relate to one another. Without modern technology, it would have been extremely tedious to handwrite everything. Deleting, copying and pasting information would have also been extremely difficult to do, so Pip relied heavily on the benefits of online note-taking instead of by hand. Jackson demonstrates how technology becomes a part of everyone's daily life. Therefore, Holly Jackson expresses how technology is prevalent in gathering information of any kind.

Holly Jackson's *A Good Girl's Guide to Murder*, illustrates the pervasiveness of technology by using how technology can be used to manipulate others. For example, when Pip contacts Andie's best friends, one blurts out that Andie loved her secrets. Pip, hoping that one of those secrets might help her reach Sal's innocence, she uses technology to manipulate the friends into spilling their secrets, "I'm going to catfish Emma, pretending to be Chloe… I can text Emma, pretending to be Chloe with a new number," (Jackson 84). Pip uses a pay-as-you-go SIM card and she uses this to manipulate Andie's friends. The usage of technology as a weapon and device of deception shows the darker side and the dangers of using technology. Pip can create an entire fake identity using technology as her shield. This would have been impossible to happen in real life, since people can see who they are really contacting. Pip exploits Emma's trust in a digital connection with her friend, to share information to Pip that wouldn't have been possible before. Without the usage of technology, Pip wouldn't have been able to gain a crucial piece of information, expressing how technology is needed to gather evidence, even if it isn't gathered in

the most ethical of ways. Although Pip had tried to avoid being forced to catfish and deceive someone for information, the situation with Andie's secrets became an extremely important part of information that was needed to find the real truth. Pip also preferred in-person communication, since she had interviewed many people in her town; however technology proved to be unavoidable, since Pip began to use technology extensively in her investigations. Jackson demonstrates how central a tool technology can be for deception and although some people may try to avoid it, it is unpreventable. Therefore, Holly Jackson illustrates how technology can be used as a weapon, but is still unavoidable.

Nearing the climax of Holly Jackson's novel, *A Good Girl's Guide to Murder*, Jackson explains how the usage of technology is inevitable. For example, Pip secretly slides her phone into the Wards car and uses a find me app to track its location, "'I'm enabling Find My Friends on our phones… Now we are sharing our locations indefinitely. And just like that… we have a tracking device,'" (Jackson 326). Pip simply sliding her phone into the Ward's car demonstrates how invasive technology can be. This new method replaces old methods such as tailing the suspect themself as less technology dependent detectives might do. Pip's adapted method for a digital age, in which many people rely on the use of technology. The commonality of a "find my device" app on smartphones and mobile devices makes these actions plausible and easy for Pip. The scene illustrates how anyone with a device can be tracked, and the normalization of such features demonstrates the invasiveness nature of technology. The introduction of more modern technology expresses how people's privacy slowly decreases, since there will always be a record of everyone's movements as technology continues to advance. The added technology also allows Pip to be in the action, while also not being in the action. Pip can see every event happening, like Elliot Ward's location; however she doesn't need to be there in order to see such situations happening. Pip can just watch the events unfold from her device, which is extremely different from traditional surveillance, which requires physical presence. The use of the new technology allows Pip to confront and obtain a confession from Elliot Ward, which wouldn't be possible without the use of technology. Without the technology, Pip might not have been able to uncover the truth quick enough, before another, more severe threat would be headed her way. Jackson expresses how technology is invasive; however can be needed for serious situations such as Pip's. Therefore, Holly Jackson demonstrates how technology removes people's privacy; however, it will always be there and will continue to advance.

Heading into *Good Girl, Bad Blood*, Holly Jackson uses social media messages to demonstrate the integration of technology is pervasive. Pip had directly messaged Layla Mead to try and figure out who she was. Layla had replied with the message saying "You're getting closer :)" (Jackson 183). Layla herself is a fictional persona created to catfish and manipulate people like Jamie Reynolds. The fact that a digital alter ego can cross the boundary from an online relationship to directly threatening Pip in the real world illustrates the extremely dangerous consequences of online deception. The instant and extremely pointed message from the person behind "Layla Mead" illustrates how they are not just observing Pip's investigation, but are also a direct and active participant. It reveals that they have been watching Pip and know who she is,

showing how personalities online can have real world consequences. Layla Mead's message transforms social media from a casual communication platform into a weaponized tool for intimidation and manipulation. The anonymous poster uses many social media platforms to communicate a direct threat, turning Pip's pursuit of truth into a terrifying game of cat and mouse. Layla's message also reveals that she had been constantly monitoring Pip and her progress, reflecting the modern day reality that most people's digital actions can be tracked and used against them. Immediately after her message, all of Layla's social media accounts vanish, demonstrating how criminals can utilize technology to operate anonymously, leaving no digital footprint. It also reinforces the feeling of constantly being under surveillance. If Layla can respond so quickly to Pip's actions, then it becomes clear that Pip's digital and real life are no longer private. Jackson illustrates how technology can be seen as harmless and casual; however social media can be used as a manipulative and dangerous tool. Therefore, Holly Jackson expresses how technology is extremely extensive, and can have dangerous influences.

Continuing along in Holly Jackson's *Good Girl, Bad Blood*, she demonstrates the pervasiveness of technology by illustrating Pip's use of Jamie's Fitbit. "The dashboard on Jamie's computer had icons for step count, heart rate, calories burned, sleep, and active minutes… She clicked on the step count icon and it brought up a new screen, with a bar chart breakdown of Jamie's steps throughout the day" (Jackson 235). Pip's usage of Jamie's Fitbit data expresses how technology has embedded itself into every part of modern life, and creating a digital footprint can be exploited for investigations. A seemingly innocent fitness tracker designed to track health becomes a crucial tool that reveals information Jamie most likely believed was private. Using Jamie's data, Pip can reconstruct Jamie's movements with an extreme level of detail that would have been impossible without technology. The Fitbit data allows Pip to determine the approximate area where Jamie took off his watch and she learns that she was running, not walking. The data also allows Pip to refine her search area and reject false assumptions and testimonies, illustrating how technology is far more accurate than human eyewitnesses. Jamie's Fitbit also records his heart rate, which significantly elevated in the minutes before his disappearance. Without the usage of technology, Pip would have most likely never discovered that Jamie was under stress or fear during those moments, meaning that she would miss out on a crucial detail in Pip's investigation. The Fitbit data turns out to be extremely important to Pip and the investigation; however it can be seen as an invasion of privacy. Jamie's data is an intimate and personal record that is exposed to others, demonstrating how technology can completely remove someone's privacy. Jamie's location, activity levels, and physical reactions were all recorded, expressing how technology means constant surveillance even without consent. Fitbits are an example of seemingly harmless and innocent pieces of technology that people integrate constantly into their lives. The device is so normalized that people wear it without second thought, making it such a powerful tool for surveillance. In an advancing world, even small, mundane personal items can be the key to uncovering a major crime. Jackson illustrates how when combined with other digital devices, the Fitbit can create an entire picture of someone's life and movements, making it impossible to achieve moments of true privacy.

Therefore, Holly Jackson demonstrates how inevitable advancing technology makes it nearly impossible to have privacy.

Leading into the climax of Holly Jackson's *Good Girl, Bad Blood*, Pip decides to impersonate Layla Mead to force Stanley Forbes to confess. "'I have another SIM card I can put in my phone, so Stanley won't recognize my number. We text him, as Layla, telling him to meet us at the farmhouse later tonight" (Jackson 345). Pip's text as Layla illustrates how pervasive technology can be used to manipulate people and expose hidden truths all from behind a screen. When Pip uses the catfishing technique to lure out Stanley, it expresses how easily technology allows anyone to engage in deceptive methods. Pip and her friends create a new fake number, mimicking Layla's usual style to contact Stanley. The ease with which a false identity can be cloned and used highlights how simple it can be to use technology to mislead others. Although to this point, Pip had tried to keep herself morally right, she realizes this situation required moral grayness. Pip recognizes that to catch a suspect who operates through deception, she must manipulate technology to her favor. Many people now realize that technology can force individuals to cross ethical boundaries in order to achieve their goals. Pip's text, which lures Stanley out of hiding proves that online actions have significant and sometimes severe real-world consequences. Stanley, who has already been deceived by false online persona, falls for it again, expressing his susceptibility to this type of manipulation. By reactivating the Layla Mead alter ego, Pip uses Stanley's past online behavior against him. His prior interactions with the fake account becomes the key to his undoing, demonstrating how people's online histories can always be leveraged, no matter how distant or insignificant they may be. Pip's entire stunt as Layla Mead illustrates how technology is able to exploit people's past desires and secrets, leading to more intimate and private details of a person's life. Jackson expresses how someone's online behavior and digital history can always be brought to light, enforcing the idea that people's digital life can be more telling that their real-life behavior. Therefore, Holly Jackson demonstrates how technology can reveal extremely personal details about people, making technology invasive and pervasive.

Continuing to the final novel in Holly Jackson's trilogy, *As Good As Dead*, Jackson uses Pip's Google research to illustrate how technology is prevalent. "There are three main mortis factors used to determine the estimated time of death, and some of these tests are performed at the crime scene itself, as soon as possible after the victim is found" (Jackson 31). Pip's Google searches express how easily online information can be used for sinister purposes. Researching such topics doesn't help Pip solve a mystery or crime, but to cover up a murder she committed herself. Information covering body decomposition is freely available to anyone through a simple search, illustrating how dangerous and horrible technology can be. In previous novels, Pip's use of technology was somewhat morally justifiable; however her digital dependency has completely eroded her ethical boundaries by the last novel. Pip's instant and constant presence on technology demonstrates how quickly and easily technology allows her and anyone to step into the role of a criminal. The events express the same digital tools that once empowered Pip to uncover truths and be just as effective at covering the truth up. Technology doesn't have a moral compass, and

can be used to provide information to anyone, regardless of intent. Pip's ability to find detailed information about murder in seconds highlights how accessible specialized knowledge has become through technology. Pip's Google search expresses a disturbing reality of the digital age: anyone with an internet connection can learn how to manipulate a crime scene without any special training. The accessibility of technology makes it extremely easy for amateurs to become extremely dangerous and learn concerning facts quickly. Jackson illustrates the extremely available and accessible world of information technology presented to everyone with access. Therefore, Holly Jackson demonstrates how pervasive technology is, by how easy it is to find dangerous information.

Heading further into Holly Jackson's *As Good As Dead*, she expresses the prevalence of technology with Jason Bell's anonymous messages to Pip in social media. Jason had stalked Pip for months on social media, posting the same message but from different anonymous email addresses. "That same message again: *Who will look for you when you're the one who disappears?* From anonymous987654321@gmail.com. A different email address again, but the exact message" (Jackson 37). Jason's use of messages to Pip serves as a chilling demonstration of pervasive technology, which highlights how digital communication can be used as a weapon for stalking and intimidation. Jason utilizes anonymous messages to establish a sense of surveillance and dread. Pip is digitally intimidated by Jason's threatening messages and images, illustrating how easily technology can be used to harassment without any direct physical confrontation. The usage of advancing technology means being able to constantly monitor someone's actions, and in this case: Pip's. The erosion of privacy with the usage of technology demonstrates how invasive it can be. Jason uses technology to force a psychological game with Pip that pushes her to her limit, which effectively changes technology from Pip's tool to her tormentor. Jason also uses personal and specific messages to Pip, expressing how technology can be used to directly target individuals heightening the physical and emotional impact. Although Pip wants to avoid all contact with Jason's messages, she is dependent on her phone for communication, investigation, and other personal reasons. Technology can be extremely helpful to many people; however it can also make many others extremely vulnerable. Jackson expresses Pip's physical abduction by Jason, demonstrating how digital interactions can directly lead to dangerous, real-world consequences. Therefore, Holly Jackson's usage of Jason's terrifying messages to Pip underscore how technology is not just a harmless tool, but a pervasive force that can jeopardize physical and mental safety.

Reaching the climax of *As Good As Dead*, Holly Jackson utilizes Pip's headphones that serve as a link to the murder scene to illustrate technology's pervasive and incriminating role. "'Explain to me, then, why your headphones, the ones you use on a daily basis, were found inside the home of a murdered man you've had no contact with in months?'" (Jackson 397). Headphones, a seemingly innocuous item, designed for entertainment and communication, becomes a piece of crucial evidence directly linking Pip to a crime she committed. The digital footprint the headphones create express how unavoidable online traces are and how they can have extremely severe consequences. Although the headphones themselves are a small and

forgetful piece of technology, they represent how every interaction with technology leaves a traceable, physical footprint. Pip's headphones are used as a source of comfort for her, and as a tool for her podcast investigations. Suddenly, they become a tangible link to the murder scene, directly connecting Pip to the location and time of the crime. Pip had put in hours of effort to establish an alibi and conceal her involvement; however the headphones contradict with her efforts, highlighting the difficulty of completely erasing digital and physical traces in the modern age. The headphones demonstrate how closely tied technology is to people's daily lives and how it can be used for personal enjoyment and criminal investigation. The discovery and investigation of the headphones represent a violation of Pip's privacy and highlight how insignificant, personal items can be used to incriminate an individual. Even if Pip had planned the murder cover up even more meticulously, her headphones still would have been lost, illustrating how effortlessly technology can create an unavoidable trail that can be used against someone. Jackson uses the headphones to demonstrate how everything on technology can be traced and tracked back, and can unravel even the most carefully constructed deceptions. Therefore, Holly Jackson uses the headphones to symbolize how pervasive and inescapable technology can be to anyone.

To conclude, the trilogy, which consists of *A Good Girl's Guide to Murder*, *Good Girl, Bad Blood*, and *As Good As Dead*, written by Holly Jackson illustrates how pervasive and invasive technology can be even in daily life. Jackson underscores how technology, although can be useful, can often spiral into extremely dangerous and sinister uses. Many people constantly have debates over the benefits and harms of technology, and Jackson has provided arguments on both sides. Earlier in the trilogy, Jackson seems to encourage the usage of technology as a tool, and justifies slightly morally compromising actions. Continuing on in the trilogy, however, Jackson begins to push for people to end their overuse of technology, through the many dangers that technology can pose to everyday life. As Jackson explores the darker sides of technology, she expresses how people can evade punishment through the usage of technology, which illustrates Jackson's overall message of staying away from technology. Technology's many terrifying usages force Jackson to advocate for less digital use. Holly Jackson's *A Good Girl's Guide to Murder* trilogy unconditionally expresses the extreme dangers of technology; however, the aspect builds strong opinions from both sides of the debate.

The Confessions That Expose the Truth

Third and lastly, Holly Jackson expresses many confessions to continue the plot. Without such admissions of the antagonist's actions, there is a loss of closure for both the readers and the characters. Jackson's novels revolving murder and crime series, must have some mysteriousness to build suspense; however without a confession at the end of the novel, both the readers and the characters are in the dark about what actually happened. Jackson demonstrates how confessions are crucial for books like hers, but there are greater lessons that can be learned from Jackson's series. Throughout her trilogy, consisting of *A Good Girl's Guide to Murder*, *Good Girl, Bad Blood*, and *As Good As Dead*, Jackson illustrates confessions highlighting the deceitfulness of authorities, the impacts of revenge, and the addictiveness of power.

For example, in *A Good Girl's Guide to Murder*, Holly Jackson demonstrates Becca Bell's and Elliot Ward's confessions to illustrate resolution and the deceitfulness of trust of authority figures. Becca had confessed that she had stood by when her sister Andie Bell fell and died. Elliot had admitted to murdering Sal Singh and kidnapping a girl similar to Andie. Both confessions provide closure for the readers and the characters, since the readers and the characters can finally understand what had actually happened instead of being in the dark about the truth. Elliot's admission to his actions illustrates the deceitful nature of authority figures, since it expressed how his flawless reputation was just a facade. "'She was seventeen!' Pip said. 'The same age as your daughter. You were a teacher!'" (Jackson 344). As Elliot was a respected teacher and supportive father figure to Pip, his position of trust and authority allowed him to manipulate events and murder Sal with minimal suspicion. Pip was unable to consider Elliot as a serious suspect because of his image as a reliable adult figure. His image was the primary tool he used to evade suspicion and allowed the town to focus on the easy narrative of Sal's guilt. Elliot's confession reveals his cold manipulation of events, from blackmailing his own daughter to staging Sal's suicide, all of which directly betray the trust placed in him by his students, family, and the wider community. Elliot's authoritative position also enabled him to influence Pip's investigation and further deceive those around him. When Pip started digging, he used his fatherly and teacherly concern to subtly discourage her from continuing further. Elliot also planted false evidence and sent threats to Pip to turn her away from the truth. His ability to insert himself into the case and direct the narrative away from his own guilt highlights how authority can pervert the truth rather than uphold it. Jackson illustrates Elliot's confession to force Pip and people to confront a terrifying reality: a person's trusted status is no guarantee of their morality. The revelation that someone who is admired could be a murderer teaches people that even the most respectable faces can hide the most sinister secrets.

Continuing into Holly Jackson's *Good Girl, Bad Blood*, she demonstrates Charlie Green's confession to express resolution and the negative impacts of a vengeful mindset. Charlie had confessed to being "Layla Mead", a completely false and online persona used to help Charlie find Childs Brunswick. Charlie's admission also provides some background information to his life and his motives. Charlie's confession provides closure for the readers and the characters, since the readers and the characters can finally process what happened and why. Charlie's disclosure of his actions illustrates the negativity of a mind set of revenge. "'But I knew that one day I would find you and I would be the one to kill you, Child Brunswick,'" (Jackson 365). Charlie's decades-long, single-minded pursuit of revenge for his sister's murder highlights how vengeance can corrupt and consume a person, which led Charlie to manipulate innocent people and commit further violence. Charlie spent years obsessively tracking Child Brunswick which led him to fabricate a persona and exploit others for his own benefit. "Layla Mead" was Charlie's online identity to catfish young men and identify a potential suspect. He also manipulated Jamie Reynolds, a completely innocent man, into confronting Stanley Forbes, intending for Jamie to kill him. Charlie's mindset solely centered on revenge turned Jamie into an unknowing accomplice, nearly ruining his future and life. Charlie's confession also demonstrates how a

morally righteous desire for justice can spiral into destruction and a cycle of violence. For vengeance, Charlie murders Stanley, highlighting how his quest for revenge has turned him into the very thing he despises. Although Stanley had spent his life trying to make amends for his past and escape his father's actions, Charlie's desire for vengeance destroyed any chance Stanley had at a normal life. His actions also traumatize Pip, another innocent person, and force him and his wife to become fugitives. Charlie's laser-focused desire for revenge leaves a trail of trauma and devastation in its wake. Ultimately, Jackson illustrates Charlie's confession to demonstrate that a life centered on vengeance is a life completely lost. His revenge forces Charlie to become a criminal himself, trading his own humanity and freedom for a single moment of retribution. Therefore, Holly Jackson highlights the extremely negative impacts of a vengeful mindset.

Finally, in Holly Jackson's final novel, *As Good As Dead*, she expresses the addictiveness of power and control. Jason Bell had kidnapped Pip and with full intentions of murdering her, confessed his identity as the Duct Tape (DT) Killer. Jason's confession creates a sense of closure, since Jason's actions bring everything that happened in the trilogy to a full circle. Jason was the reason why Andie sought out Elliot Ward, which led to her and Sal's deaths. Jason, although indirectly, was also the cause for Jamie's disappearance since he left during Andie and Sal's memorial, making the root of all of Fairview's problems Jason Bell. His hunger for authority led him to murder many other young girls he deemed "too loud".“'You're supposed to listen to me. That's all. Listen and do what you're told. How is that so hard?'" (Jackson 224). Jason's sadistic monologue reveals his motivations weren't against certain women, but a compulsion to silence anyone who defied his will. Jason felt an overwhelming satisfaction whenever he dominated and silenced women who "spoke out of turn". Jason, who meticulously planned his attacks, delighted in the process of stalking, kidnapping, and silencing his victims. He felt gratified with each murder and his ability to cover his movements and manipulate the outcome. Jason's motive wasn't revenge or necessity but a deep-seated rage and sheer thrill of asserting his power over women. His way of killing his victims was his way of reestablishing his twisted sense of order and control. Although the disappearance of Jason's daughter, Andie, caused him to pause his killing spree, the addiction remained. Jason was drawn back by Pip's podcast, which he deemed threatened his perception of control. He couldn't resist the urge to silence her, even after years of inactivity, demonstrating that his need for power was permanent and insatiable. Jason's admission is cold and detached, illustrating a complete lack of remorse or empathy for his victims, including his own daughter. This dehumanization is the ultimate result of his obsession for power and control, as he sees his victims only as objects to be manipulated and discarded. In the end, however, Jason's overconfidence, driven by his need to exert authority one final time, becomes his undoing. He is thrilled as he tells Pip about his plans and this arrogance provides her the time she needs to escape and ultimately kill him in self-defense. Jackson demonstrates many instances where Jason's desires for authority completely consume his actions and thoughts. Therefore, Holly Jackson illustrates how addictive power and control can be.

Ultimately, the *A Good Girl's Guide to Murder* trilogy which consists of *A Good Girl's Guide to Murder*, *Good Girl, Bad Blood*, and *As Good As Dead*, written by Holly Jackson

illustrates how confessions are used for plot development and highlighting many prominent issues in humanity. Jackson constantly utilizes the admissions to create closure for both the readers and the characters, so both parties know the tragedies and lies of the antagonists. Jackson also demonstrates the lack of trust in authority figures, the dangers of a mind set on revenge, and the addictiveness of power and control. The many confessions present is mostly beneficial to the development of the series, since a false confession is what sets the entire series off. It also underscores how seemingly "good" people have been driven to terrible actions by fear, guilt, and manipulation. The confessions fuels the series to continue forward; however it may seem convenient and repetitive by the last book. In real-life situations, the suspects often hold information from the investigators, so when many key characters confess, it can stretch the believability of the series. Although the confessions trope may seem repetitive, Jackson's brilliant idea of making Pip the one to lie and manipulate the law system breaks the repetitiveness completely. Holly Jackson's *A Good Girl's Guide to Murder* trilogy unconditionally expresses the necessity of confessions; however, the convenience and repetitiveness can build some negatives on the other side of the debate.

Conclusion

All things considered, the *A Good Girl's Guide to Murder* trilogy which consists of *A Good Girl's Guide to Murder*, *Good Girl, Bad Blood*, and *As Good As Dead*, written by Holly Jackson explores the usefulness of police, the pervasiveness of technology, and the usage of confessions. The series follows Pip Fitz-Amobi through her experiences through the senior year of high school all the way to her life in college. With the help of her family, friends, and community, Pip manages to correctly reinvestigate Andie Bell and Sal Singh's deaths, locate Jamie Reynolds, and evade prison for murdering Jason Bell. Jackson masterfully illustrates Pip experiences to dissect complex themes and raise questions surrounding truth, justice, and the very nature of humanity. Pip, who had served as the reader's moral compass, yet her descent into morally grey areas such as orchestrating a murder forces individuals to question how far someone can go in the pursuit of justice before becoming a criminal themselves. Jackson skillfully challenges simplistic notions of heroes and villains, pure good and pure evil, by presenting a nuanced world where good people are driven to terrible acts by systemic failures. Jackson's trilogy concludes with a permanent mark on its readers, prompting consideration of the gray areas of human morality and the uncomfortable questions of what they would do if faced with similar and impossible choices.

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High-Speed Flight Dynamics and Structural Integrity With Respect to Xb-70 By Junwoo Ryan Lee-Kim

Abstract

Structural parameters of subsonic and supersonic flight dynamics have a significant impact on the speed characteristics of an aircraft. This research paper examines the high-speed flight dynamics and structural integrity of the North American XB-70 Valkyrie which was an experimental supersonic aircraft developed in the 1960s. Emphasis is placed on the aerodynamic mechanisms that allowed the XB-70 to sustain Mach 3 cruise performance, specifically its exploitation of compression lift generated through controlled oblique shock waves. Analytical and simulation-based methods were employed using MATLAB to evaluate the relationships among shock-wave angle, flow deflection, and variable wingtip geometry. We present the effects on various parameters considering supersonic and subsonic principles. Results demonstrate that compression lift substantially enhances the lift coefficient but simultaneously decreases the aircraft's static-stability margin, increasing susceptibility to roll–yaw coupling and structural stress under dynamic flight conditions.

Introduction

Supersonic travel, which involves traveling at speeds exceeding the speed of sound (767 Miles per hour), once the pinnacle of human aerospace achievement, has recently fallen into a somewhat dormant state in research communities and some industries, with air travel predominantly conducted with subsonic regimes. The first breakthrough into supersonic flight didn't occur in the current century, but in 1947 when the experimental Bell X-1 became the first aircraft to break the sound barrier by achieving an unprecedented Mach 1.06 (*Bell X-1 Glamorous Glennis*). Nearly three decades later in 1976, the Aerospitale-BAC Concorde revolutionized commercial flight by sustaining cruise speeds of up to Mach 2.04 (*Concorde, Fox Alpha, Air France*).

Despite these landmark achievements, innovations in supersonic flight were all but halted due to a singular challenge in aerodynamics: compression waves. At higher velocities, these shock ways impose extreme pressures and thermal loads, subjecting aircraft structures to forces that approach their material engineering limits. Many supersonic designs of that era failed under these constraints as the interaction between aerodynamic shock systems and structural response frequently led to instability and structural fatigue.

But one aircraft, the North American XB-70 Valkyrie, was the exception to transform this challenge into an advantage. Designed during the Cold War as a high speed intercontinental strategic bomber capable of Mach 3 speeds, the XB-70 represented a bold experience in both aerodynamic and structural engineering feets. Despite a takeoff weight of 271 tons (nearly twice that of the Concorde), the Valkyrie could cruise three times the speed of sound and cover twice the distances compared to commercial aircrafts. Its defining innovation lay in its ability to

convert the destructive energy of compression waves into usable lift, a phenomenon known as compression lift.

This research examines how the XB-70's structural and aerodynamic configuration allowed for this transformation and how these same characteristics impacted its stability margins. Through analytical modeling and simulation, the study looks into the interdependent relationships between shockwave angle, flow deflection, and variable wingtip geometry to identify aerodynamic mechanisms that influence lift and stability. The objective is to clarify the aerodynamic rationale behind the XB-70's unique performance as well as to propose potential control-based solutions (such as fly-by-wire compensation) that could help inform future designs of super and hypersonic aircrafts.

Literature Survey

Research on supersonic and hypersonic aircrafts has consistently emphasized the challenge of achieving higher aerodynamic efficiency while not compromising stability and controllability. A research paper provides a comprehensive overview of how high speed aircraft has evolved including focus on recurring reasons for program failures (particularly propulsion inefficiency, structural stress, and noise constraints) as well as design characteristics that are common to successful vehicles (Pollock and Wild). Their review establishes that sustained supersonic cruise is technically feasible with optimized aerodynamic shaping and propulsion integration, though it does not address the XB-70's Valkyrie's unique variable geometry configuration that forms the focus of this study.

Following investigations concentrate on aerodynamic optimization under stability constraints. In a work, authors examined the shape optimization of supersonic transports while enforcing subsonic static margin limits, demonstrating that low drag, high Mach designs often require thicker wings and flap deflections that trade efficiency for stability (Seraj et al.). Similarly, in other work (Aprovitola et al.), authors used computational fluid dynamic simulations of Concorde-like configuration to analyze aerodynamic center shifts and Mach-tuck effects across subsonic, transonic, and supersonic regimes which highlights the persistent coupling between drag rise and static margin reduction. These studies represent coupling between drag rise and static margin reduction. Together, these studies also show that aerodynamic optimization and stability preservation naturally compete in high-speed flight. It's a core balance to the XB-70's design philosophy.

Control and stability modeling research provides further insight into dynamic challenges of supersonic configurations. Military standards (MIL-STD-8785C, -1797, and AGARD) are applied to evaluate longitudinal and lateral-directional stability of conceptual high-speed craft, identifying critical issues such as Dutch roll divergence and inertia coupling at higher Mach numbers (Takahashi et al.). Further, this discussion is extended in (Wu et al.) by developing a trim optimization framework for tailless aircrafts, showing that adaptive control surface deflection improves lift-to-drag performance in both sub and supersonic regimes. Both these

works reinforce the need for robust stability augmentation and control law design, directly motivating the fly-by-wire approach focused on in this paper.

Parallel studies have addressed geometric and structural correlations that govern aerodynamic efficiency. A study in (Sforza) established relationships between wetted and projected areas for a wide range of aircraft, including the XB-70 and Concorde, showing that wetted area functions can approximate aerodynamic performance across design classes. Another work available in (Daidzic)complemented this by demonstrating that global range transport efficiency requires a combination of aerodynamic, propulsion and structural optimization rather than isolated advances in each. Both studies emphasize that integrated design (combining airframe geometry, propulsion coupling, and materials) is essential to achieving long-range supersonic capability.

Finally, Gallagher presented one of the earliest digital simulations of the XB-70's mixed compression inlet which validated predicted performance against flight data and noting the need for automatic control to stabilize intense shock systems under atmospheric turbulence (Gallagher). Although this study accurately models inlet dynamics, it does not examine the aircraft's use of compression lift through wing folding geometry, which is one of the Valkyrie's defining aerodynamic concepts.

In all, these papers provide a strong foundation for understanding supersonic design tradeoffs in lift generation, drag minimization, and stability augmentation. However, few have quantitatively investigated how the XB-70's compression lift mechanism and variable wingtip deflection interact to influence both light enhancement and stability degradation. The present study addresses this gap through analytical and MATLAB-based simulations, evaluating the aerodynamic and structural dynamics of the XB-70 under Mach 3 conditions.

Difference between subsonic and supersonic physics principles

The shift from sub to supersonic flight narrows on a fundamental shift in aerodynamic behavior that is influenced by compressibility effects. At subsonic speeds, pressure disturbances are transmitted from ahead of the aircraft, which allows the airflow to adjust smoothly over the body. However, once an aircraft hits Mach 1 speeds, the aircraft outran the pressure waves it generates (Seraj et al.). Since these disturbances cannot travel forward into the oncoming flow, the air has no opportunity to adjust gradually, which leads to the formation of shock waves (thin regions of abrupt pressure, temperature, and density increase). These shock waves are the dominant factor that distinguishes supersonic to subsonic aerodynamics.

A key result is the dramatic increase in wage drag that grows rapidly with Mach numbers and can exceed all other forms of drag combined. To help prevent this, supersonic aircraft operate at very high altitudes where air is less dense. This helps reduce both skin friction and wave drag. However, flying in such thin air requires substantially higher thrust output to maintain lift and overcome the remaining drag. This creates a complex design tradeoff: optimizing an aircraft for performance in one regime typically diminishes performance in the

other (Seraj et al.). Aerodynamic configurations that are ideal for high Mach cruise often violate stability margin requirements at subsonic speeds.

Lift generation also changes within the supersonic domain. Wings optimized for subsonic speeds rely on smooth pressure distributions, while supersonic wings must minimize shock strength and are typically thin with very sharp leading edges to reduce wave drag. At subsonic speeds, these thin wings reduce lift and make taking off and landing more challenging. This tradeoff drives the use of variable geometry components. The Concorde utilized a droopable nose and leading edge devices to maintain controllability at low speeds, while aircrafts like the F-14 incorporate sweepable wings to adjust aerodynamic characteristics as its speed increases. The XB-70 took this even further through folding wingtips which not only reduced drag, but also exploited compression lift by trapping shock waves beneath the airframe. This serves as an example of how advanced geometry can leverage supersonic physics rather than simply compensating for it.

In summary, the physics related to subsonic and supersonic flight differs greatly due to compressibility effects, shock formation and wave drag. Because of this, aircrafts optimized for one regime do not perform well in the other. This is the reason aircrafts require careful aerodynamic balancing and also the use of variable geometry surfaces to balance competing design requirements in many cases.

Parameter relationship with structural components

In aerodynamics, several parameters affect the forces acting on the vehicle. Two of the most important are airfoil thickness and camber. Airfoil thickness is the maximum distance between the upper and lower surfaces of the wing, whereas camber refers to the curvature of the airfoil. Both of these strongly affect lift coefficient, which is the ratio of aerodynamic lift to dynamic pressure. Increasing either thickness or camber raises the lift coefficient and steepings the lift-curve slope, meaning that the wing generates more lift per change in degree.

Unfortunately, these benefits come at a structural and aerodynamic cost. For instance, increasing thickness increases structural stiffness and volume, but too much camber or blunt leading edge geometry increases pressure drag, which impacts overall efficiency. This is precisely the reason high speed aircraft are designed with thin, sharp, and streamlined profiles due to the fact that sharp leading edges weaken shock strength and delay drag rise, while thinner forebody shapes help maintain favorable pressure distributions along the aircraft's fuselage.

The geometry of the forebody and nose are critical in determining the center of pressure and the character of the aircraft's pitching movement. Even small changes in the nose radius or fuselage contour can shift the aerodynamic forces along the aircraft, which end up directly impacting stability margins. A higher lift coefficient usually leads to better aerodynamic efficiency, but because every geometric change alters both lift and drag (not to mention structural loading), engineers must carefully balance these competing effects. It ultimately results in a delicate balance in which aerodynamic efficiency, stability, and structural integrity must all be accounted for and satisfied.

Flight dynamics and structural XB-70

The XB-70 puts into use several, more conventional aerodynamic features such as large delta wings and forward canards, which are elements that are found in high-speed aircrafts. But its overall configuration diverges greatly from typical designs. What makes the Valkyrie unique is its deliberate use of a phenomenon of oblique shockwaves. While shock waves normally generate wave drag and create severe structural loads, the XB-70 converts part of this energy into usable lift.

This capability is achieved through its variable geometry wingtips. Each wingtip is equipped with a large, foldable panel that can be deflected downward during high Mach cruising. When positioned correctly, these panels capture and redirect the oblique shock waves generated along the underside of the aircraft. The redirected shock system increases pressure beneath the wing and produces a substantial amount of additional lift (a mechanism known as compression lift). At Mach 3 speeds, this effect contributed nearly a third of the XB-70's total lift, which enabled efficient sustained supersonic cruise despite its considerable size and weight.

Unfortunately, these advantages came with substantial tradeoffs between structure and aerodynamics. The same geometry that enhances performance at Mach 3 results in lower efficiency and handling at lower speeds. The wing configuration also introduces stability challenges. The Valkyries downward folded wingtips shift the aerodynamic center aft which alters roll-yaw coupling and reduces static stability margin. This required careful control inputs during subsonic flight.

Given the era the XB-70 was designed, it operated within the limits of 1960's material engineering. At Mach 3, the airframe experienced intense thermal and aerodynamic loads. Skin temperature exceeded 600 degrees F on leading surfaces. These conditions may have contributed to repeated mechanical failure in everything from inlet-related compressor stalls, panel delamination, to structural fatigue. The combination of extreme speed, complex shock interactions and high thermal stress can make the Valkyrie simultaneously groundbreaking and very fragile.

Shock-Wave Deflection Relationship

The relationship between the flow deflection angle (δ) and shockwave angle (β) in supersonic flow are governed by standard oblique-shock relations (Wagner, 1971). Simulation results show peak compression and lift at $\beta \approx 65°$,which is the point where lift coefficient is maximized yet minimizing the stability margin.

The relationship between flow deflection angle and shockwave angle in supersonic flow is given by:

$$tan(\theta) = 2cot(\beta)\frac{M_1^2 sin^2(\beta)-1}{M_1^2(\gamma+(n)(2\beta))+2}$$

M_1 is defined as the freestream Mach number.
γ (gamma) is given a value of 1.4

Wingtip Deflection Effects

The lift coefficient is defined as per (Lithgow): $L_{ift} = C_L \times \frac{1}{2}\rho v^2 s$

https://www.flight-training-made-simple.com/post/the-lift-formula

Here, C_L is the angle of attack, ½ρ is the density, v is the speed and S is the wing surface area. Increasing wingtip deflection raises C_L but lowers the static-stability margin, reaching as low as 2%. Asymmetric wingtip deflection produced roll moments of approximately 116,595 ftlbf and yaw moments of 16,041 ft·lbf. These are magnitudes sufficient to destabilize flight or induce structural failure.

Fly-by-Wire Compensation

A simplified FBW control model dynamically adjusted aileron (Δα) and rudder (Δψ) angles to correct asymmetry, approximated by $\Delta\alpha \approx 0.6\,\Delta\varphi$, where Δφ is wingtip asymmetry (Jinj Raj, n.d.)). This allowed up to 40° deflection compensation, restoring lateral equilibrium and demonstrating how modern FBW systems could have mitigated the Valkyrie's instability.

Simulation results and discussion

Initially, simulations are performed considering subsonic aircraft parameters to study the relationship between the Lift-to-Drag ratio/Drag and Knots Calibrated Airspeed (KCAS), as shown in Figures 1 and 2. The following parameters are used for simulations: Weight =2400 lbf, Wing reference area =174 ft², Aspect ratio=7.38, Parasite drag coefficient =0.037, and Altitude=40,000 ft. A MATLAB command, *atmoscoesa,* is used to convert altitude to meters and retrieve atmospheric properties (temperature, speed of sound, pressure, and density). Further, Knots True Airspeed (KTAS) is computed using a standard expression that minimizes the drag-to-lift ratio. After converting KTAS into KCAS, the flight path angle is calculated, and the lift coefficient and drag coefficient are determined at this condition. For all calculations in the simulations, expressions are referred to from (Anderson Jr).

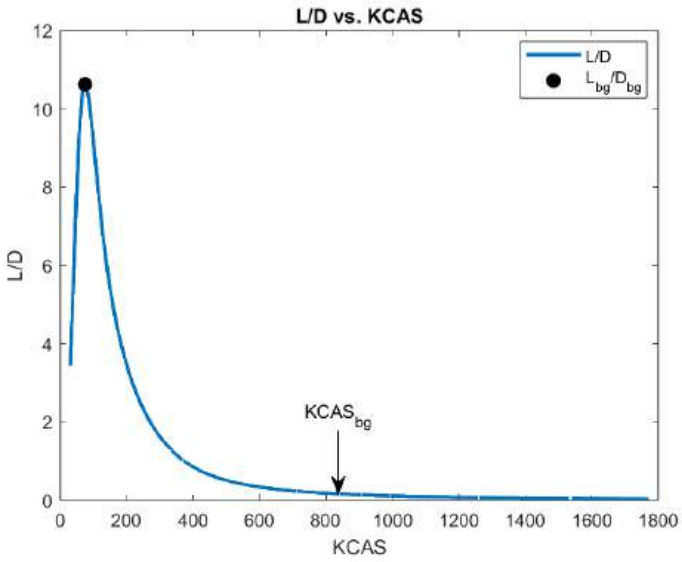


Fig 1: Lift-to-drag ratio vs KCAS for subsonic case

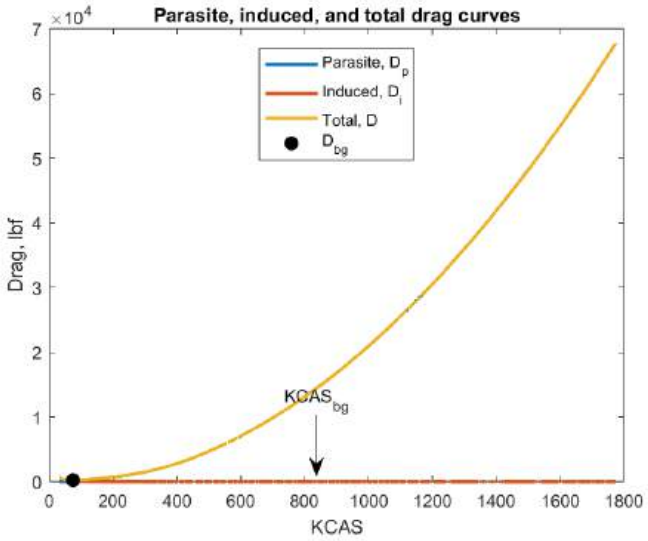


Fig 2: Drag vs KCAS for subsonic case

To analyze the supersonic behavior in the case of the XB-70, we began by observing the L/D ratio as a function of Mach number, as shown in Figure 3. Parameters for XB-70 simulations are used as follows: weight = 534700 lbf, Wing area = 6297.8 ft^2, Aspect ratio = 1.751, parasite drag coefficient = 0.0095, efficiency factor = 0.85, altitude = 73000 ft. Furthermore, the oblique shock behavior is analyzed using MATLAB, and Figure 4 illustrates the relationship between the flow deflection angle and the shock wave angle. It can be observed from the results that the flow direction angle is maximized at the shock wave angle value of 65 degrees. The power output is maximized at this value, which lifts the total lift coefficient during compression

lift. Although considering the peak point of the shock wave angle can provide high speed, it is a sensitive approach from the perspective of stability, which can result in hazardous situations.

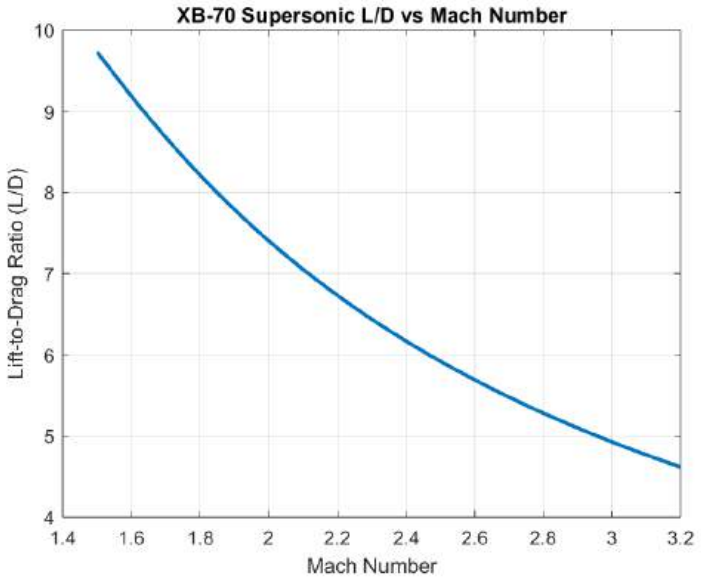


Fig 3: XB-70 Supersonic L/D vs Mach number

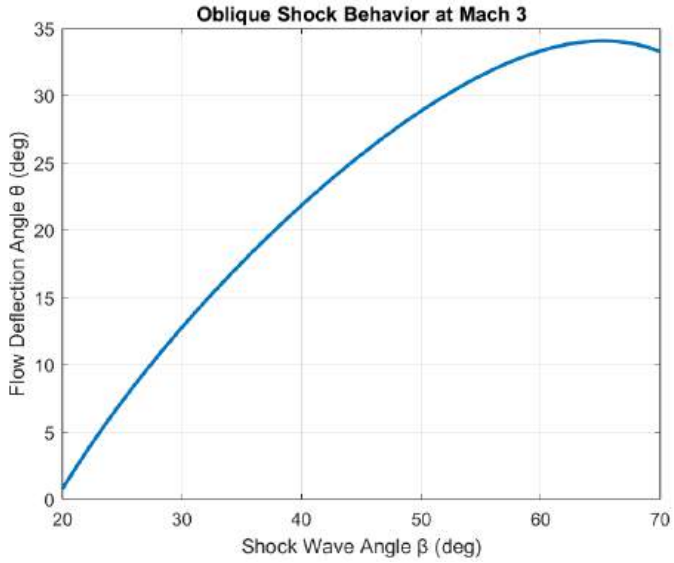


Fig 4: Flow Deflection angle with respect to Shock wave angle for supersonic aircraft XB-70

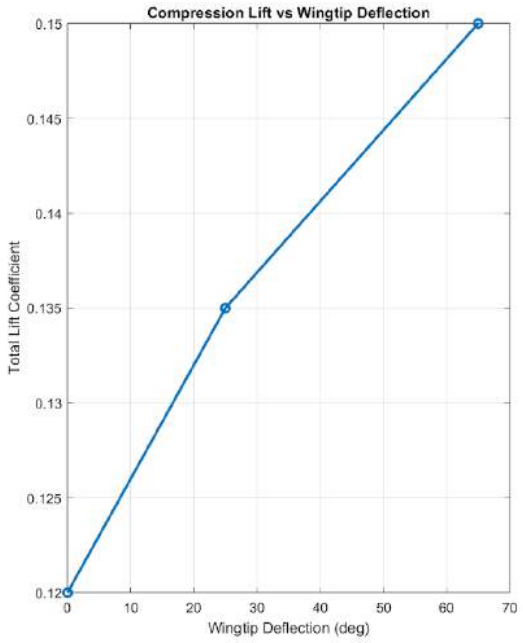


Fig 5: Total lift coefficient with respect to Shock wave angle

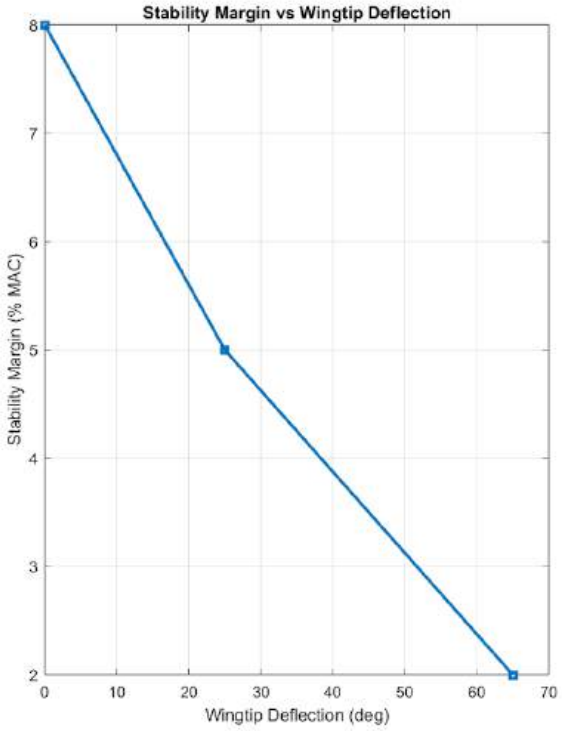


Fig 6: Stability margin w.r.t. Shock wave angle for supersonic aircraft XB-70

As part of the XB-70 design, adjustable wingtips are built into the aircraft. To account for the effect of adjustability, we have also analyzed the relationship between wing tip deflection and total lift coefficient, as shown in Figure 5. The total lift coefficient increases with an increase in wing tip deflection, resulting in a decrease in stability margin, as shown in Figure 6. This fall in the stability margin makes XB-70 prone to failure at such high speeds. It can be seen in the results that at higher speeds, the stability margin rapidly falls off, reaching as low as 2 percent, which could've been one of this aircraft's downfalls, as long-distance flights in turbulent weather could have been a challenge to resolve.

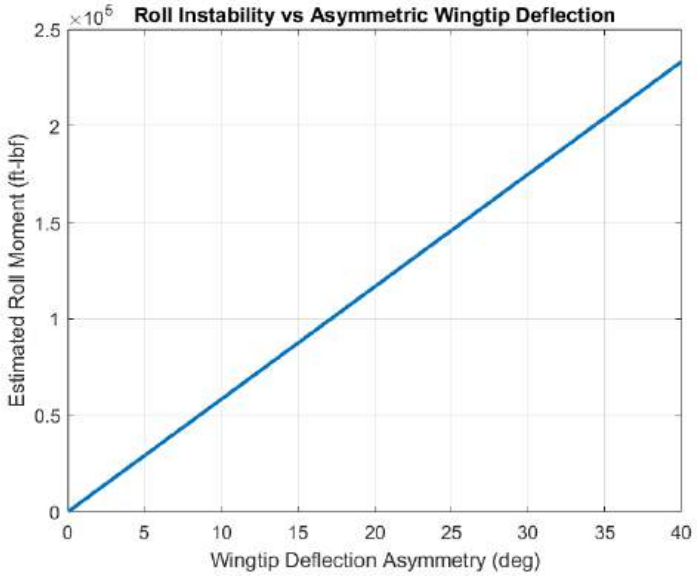


Fig 7: Roll instability vs asymmetric wingtip deflection

However, these built-in adjustable wingtips were also prone to failure, as the high speeds at which the aircraft would travel put immense stress on the part. In the case of an asymmetrical extension in wingtips, it can cause a Roll Moment of a magnitude of 116,595 ft-lbf and a Yaw Moment of a magnitude of 16,041 ft-lbf due to constant pressure change, as seen in Figure 7. These measurements could easily put the aircraft into a state of uncontrolled flight, or, in the worst case, cause enough instability to tear the aircraft apart, adding to the list of this aircraft's shortcomings.

A possible solution is FBW (fly-by-wire), which dynamically counteracts asymmetrical lift by actively adjusting the ailerons and rudder, dramatically improving stability (M. Durgut). The graph in Figure 8 displays the trend that the increase in aileron correction can effectively counteract asymmetrical wind deflection. For example, an imbalance of 35 degrees in the wingtips could be resolved by adjusting the aileron to lower its angle to 21 degrees, as seen in the graph. This system is capable of mitigating up to 40 degrees of Wing Deflection Asymmetry.

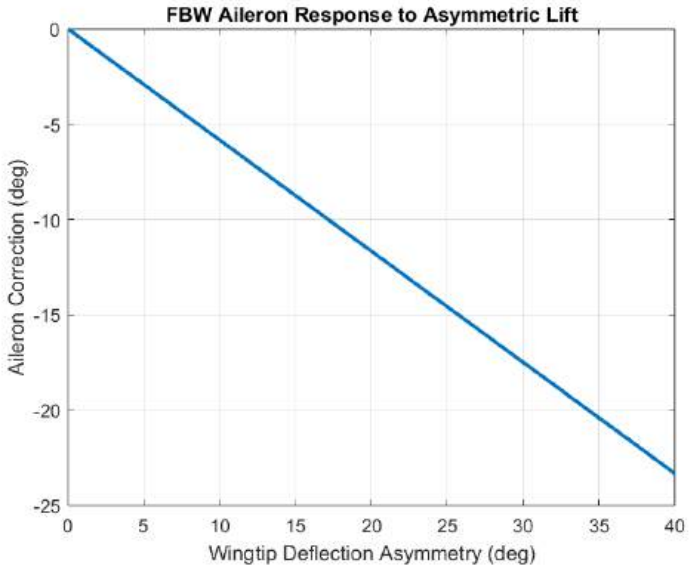


Fig 8: FBW (fly-by-wire) Aileron response to asymmetric lift

Conclusion

This study examined the high-speed flight dynamics and structural behavior of the North American XB-70 Valkyrie, with a focus on its exploitation of compression lift and variable wingtop geometry. Using MATLAB-based analytical and simulation methods, we established the relationships between flow deflection angle, shock wave angle, and lift coefficient to characterize the aerodynamic response at supersonic conditions. The results demonstrate that the controlled use of oblique shock waves can substantially enhance lift performance at Mach 3 cruise, albeit at the expense of a reduced stability margin and heightened structural stress.

Analysis of wingtip deflection effects revealed that while increased deflection amplifies total lift, it comes at the cost of decreased stability margin (in some configurations reaching as low as two percent). This instability is amplified by roll-yaw coupling, where asymmetrical wingtip behavior generates roll and yaw moments of considerable magnitude (116,595 ft/lbs and 16,041 ft/lbs, respectively). This suggests that, although the XB-70's innovative aerodynamics achieved groundbreaking performance, they also introduced several challenges related to controls inherent to supersonic flight regimes.

A simulated fly-by-wire control system was proposed as a mechanism to actively compensate for asymmetrical lift. The FBW system restored stability in the modeled environment by demonstrating effective mitigation of up to 40 degrees of wing deflection asymmetry through dynamic aileron and rudder adjustments. This illustrates the need for integrated control systems for future high-speed aircraft designs that utilize compression lift or similar aerodynamic principles.

In conclusion, the XB-70 Valkyrie stands as a trailblazing example of advanced supersonic design philosophy that balances aerodynamic innovation with the constraints of structural and dynamic stability. The insights from this study contribute to a much deeper

understanding of managing high-speed aerodynamics and offer a pathway towards developing stable, efficient, and resilient next-generation supersonic and hypersonic vehicles.

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AI By Jesse Zou

Abstract

In this study, we investigate the feasibility of predicting living wages using the most basic geographic and demographic features such as population, density, and land area. The motivation of this project is from the inefficiencies from those traditional ways of living wage calculations, which often relies on extensive surveys and economic models that are usually costly and slow. Our hypothesis is that even with minimal and universally accessible data, a model's prediction can provide accurate and reasonable estimation for general use.

To test this hypothesis, we implemented several models by increasing complexities, from basic linear regression to tree-based models and eventually deep neural networks. These models are trained with available dataset from 100 major U.S. cities. The results are assessed through mean squared error (MSE) across training, validation, and testing sets. Results show random forest achieved strong predictive performance, while neural networks initially suffered strong overfitting and underfitting due to small dataset size and hyperparameter sensitivity. The best performance is achieved by deep neural network model Model 8 that applied data normalization, dropout, and early stopping, yielding an MSE of 6.19.

This research proves that a lightweight model can effectively estimate living wages. This suggests a scalable alternative to traditional economic surveys. This study also points out the importance of preprocessing and choosing the correct parameters when dealing with small scale data. Future work could expand upon adding additional economic features to enhance model complexity and generalizability.

Introduction

The development of artificial intelligence (AI) enabled people to accomplish problems that were considered extremely difficult or even impossible. In the past, the speed and accuracy of solving problems heavily relied on human experience and manual calculation. Today, AI can analyze and process massive datasets, identify patterns, and provide results with visible numbers. For example, tasks like autonomous navigation, AI chat, and natural language learning were once considered impossible, but now these techniques are widely applied to self-driving cars and online applications. AI is not only acting as a tool for convenience, but also as a catalyst for future technology and creating new possibilities.

In this study, AI models are trained to solve socioeconomic problems, specifically about the basic estimation of individual living wages across diverse regions. This topic is important because it helps individuals to meet the minimum criteria for different expenses, such as food, housing, and healthcare. Traditional methods of calculating living wages based on massive surveys and economic modeling can be very time-consuming and possibly outdated by the time it is published. For instance, ILO's methodological review highlights the complexities of defining a wage that meets workers' basic needs, including housing, food, transportation, and healthcare (Anker, 2011). These conventional approaches are usually time consuming while

resources are intensive. If this data is outdated or inaccurate, individuals might struggle to correctly plan their income, and policymakers would not be able to plan financial aid and economic welfare on time.

This study proposed a machine learning model that predicts the living wages of an individual adult in the given country based on basic geographic and demographic features, such as population, density, and country area. These data are universally available, easy to access, and inherently up to date. These traits help avoid lengthy surveys and costs associated with them. The hypothesis is that these fundamental data are enough to predict a relatively accurate value. The expectation is that even without complex economic factors like inflation rate and consumer price indexes, the prediction value is still accurate enough for general usages. The Kaggle dataset used in this study is derived from publicly available sources, including city population and geographic data from Wikipedia and living wage estimates from the MIT Living Wage Calculator. It contains data from 100 largest US cities, including both geographic and demographic features as well as living wages from different household configurations. In addition to demographic and geographic features, the dataset provides living wage estimates for multiple family types, such as one adult with no children, one adult with one to three children, and two-adult households with different numbers of children and employment statuses. In this study, we focused primarily on individual living wages without children as a prediction target.

The meaning of this study is to prove that even using a minimal set of data can still predict a strong model. By building a model relying on those basic geographic and demographic features, the models show that costly socioeconomic surveys are not always necessary to generate meaningful estimates. This suggests a new direction of estimating living wages and other data using fast, accessible, and simple approaches. Such lightweight models can be easily updated and used by policy makers and individuals to change their economic plans.

Results

To identify the best machine learning architecture, we tested a variety of different models: from the simplest linear regression model to tree-based methods and complex neural networks. The goal of these different experiments is to find the one with the lowest prediction error on testing sets, with MSE (Mean Squared Error) as the evaluation metric.

All the models use geographic and demographic features as their input: population_2020, population_2010, land_area_sqmi, and density. The unit for the output means squared error is in dollars per hour.

MSE is commonly used to identify the average of the squared difference between predicted value and the actual value. A lower MSE indicates that the model's predictions are closer to the actual value overall. In this study, we calculated the MSE for training, validation, and testing sets.

Model	Training MSE	Validation Loss	Testing MSE	Key Configuration	Parameters

Linear Regression	4.17	-	7.35	Baseline linear fit	-
Decision Tree	0.01	-	7.26	max_depth = 10	-
Random Forest	2.90	-	6.71	10 trees, max_depth = 2	-
Model 1 (without Validation set)	11526.1194	-	74101.4140625	Neural network model with no validation set	Layers:256, 128, 64, 32, 16, 1 Epoch: 50 Optimizer: adam Activation: ReLu
Model 2	92,937	645,433.5625	4,142,996	Highly similar models with slight difference in epoch numbers and random state	Layers:256, 128, 64, 32, 16, 1 Random State: 1 Epoch: 50 Optimizer: adam Activation: ReLu Dropout: 0.2
Model 3	92,937	201,851.4688	536,523		Random State: 2
Model 4	92,937	12,120.6191	56,835.9688		Random State: 3 Alpha: 0.01
Model 5	10195.2559	76.2157	63.2798	Different parameters with a tanh activation function	Layers: 128, 64, 32, 16, 1 Alpha: 0.0005 Early stop Random state: 3

					Activation: Tanh Dropout: 0.3 Optimizer: RMSprop Epoch: 100
Model 6	51.1558	54.3024	55.1788	Similar to Model 5 with different parameters	Layers: 64, 32, 16, 1 Alpha: 0.005 Early Stop Random State: 1 Activation: tanh Dropout: 0.1 Optimizer: adam Epoch: 100
Model 7	2,295,970,560	504,144.4375	3,285,432.7500	Similar to Model 5 with different parameters	Layers: 128, 64, 32, 16, 1 Alpha: 0.005 Early stop Random state: 1 Activation: ReLu Dropout: 0.1 Epoch: 50
Model 8	0.5164	1.1931	6.1943	Applied StandardScaler to prevent overly large numbers	Layers:256, 128, 64, 32, 16, 1 Alpha: 0.001 Standard Scaler Early Stop Optimizer: adam Dropout: 0.2 Epoch: 100

In the first linear regression model, it has a mean squared error at about 7.35. This value serves as the simplest reference point for future comparison. The decision tree model then reaches a 7.17 MSE, which indicates that a nonlinear model does help capture the relationship between city characteristics and living wage. The random forest model further reduced this number to 6.83, improving the model's generalization. These three models create a clear baseline as a reference for the neural network models.

After that, we tested several neural network models to assess whether a more complex model can outperform the baseline. Model 1 is a deep network without a validation set. The model starts with 256 neurons on its first layer and runs for 50 epochs. It performed poorly with a MSE of 112,287.77. Models 2, 3, and 4 share the same neuron structure with 256 neurons on its first layer and reduce its neuron number like a funnel. These three models shared a ReLu activation with a 0.2 dropout, and it contains minor variations in random state and the use of early stopping. These models exhibited extremely large MSE values ranging from 4,142,996 (Model 2) to 56,835.97 (Model 4). This presents that the models are underfitting with unstable training.

Subsequent models introduced alternative activation functions, dropout rates, and optimizers to improve generalization. Model 5 used Tanh activation and 0.3 dropout and reduced the MSE to 63.28. Even though the MSE is relatively low compared to the previous models, it still doesn't reach the 6.83 MSE produced by the random forest.

Model 6 further reduced the MSE to 55.1788. This model has 64 neurons on its first layer with Tanh activation functions and a dropout rate of 0.1. However, this model has a problem of underfitting, where the model is overly shallow with only four connected layers, so it is worse than model 5. Model 6 lacked sufficient training and failed to find a meaningful pattern before the training halts. A similar training and testing loss indicate that the model had not fully converged. Model 7 was trained on a different parameter than model 6 with more layers of neurons. In this model, the model produced a MSE over 2.2 million, highlighting the sensitivity of deep models to hyperparameter choices on small datasets.

The best performance was achieved by Model 8, which applied StandardScaler to normalize both input features and target values prior to training. This model employed a four-layer ReLU network with 0.2 dropout and early stopping, and it produces a MSE of 6.1943. This result is nearly identical to the random forest model but with stable training and smooth convergence.

Overall, the experimental results indicate that while deep learning can produce competitive results, classical ensemble methods such as random forests are already highly effective for this dataset.

Discussion

Training Loss	Testing Loss	Interpretation

low	low	Most ideal outcome, good fit and generalization
low	high	**Overfitting**, the model memorized the training set and failed to generalize
high	high	**Underfitting**, the model is overly simple or not trained enough
high	low	May occur because of dropout or early stopping, and the model stopped before convergence

By testing a variety of traditional and neural networks, we found significant differences between different models. By comparing training and testing loss, these models provide critical insights in model behavior, particularly underfitting and overfitting.

The three classical ensemble methods: linear regression, decision tree model, and random forest model provide a reasonable result for the living wage prediction. The decision tree model produces a lower MSE than the linear regression model, while the random forest model produces an even lower MSE than the other two models. The results from all three methods are around 6 to 7, which indicates that ensemble tree methods are inherently well-suited to this problem.

In contrast, model 2 to 4 exhibits high training and testing loss simultaneously. The high value indicates that the model failed to learn a meaningful pattern. This reflects underfitting with unstable training. Similarly, model 6 also displays underfitting due to its shallow architecture and early stopping. The early termination caused the model to fail to identify a meaningful pattern.

In this study, true overfitting was less prominent since most deep models struggle to converge. A mild degree of overfitting exists in model 5, which contained a relatively higher training loss with a relatively lower test loss.

A clear improvement in performance was seen in model 8, which applied Standard Scalar to both features and predicted target value. This highlights that for small datasets, normalization and preprocessing is very important when it is applied to neural network models.

These results reinforce that even with limited data, neural networks could still be reliable if the models are preprocessed and regularized. This aligns with research by Dr. Antonello Pasini, who pointed out that neural networks were capable of good performance in small data situations in a number of areas. His research also indicates that, through proper tuning, neural models can generalize well even in the absence of large amounts of data that are usually implied by deep learning, and hence they represent an encouraging tool in areas where limited data is a limiting factor. (Pasini, 2015)

Overall, the comparison between classical models and neural networks suggests that simple ensemble models can be highly competitive for small, structured datasets. As Prof. Peter Roßbach notes, in many real-world applications, random forests outperform neural networks in both accuracy and interpretability. (Roßbach, n.d.) Future works could explore expanding the dataset with additional socioeconomic features like average housing prices, transportation indices, and local tax rate.

Some other possible questions might be asked is that would this theory still be applicable to countries rather than the top cities. If more features were introduced in the model, like medication, education level, and economic policy, would the more complex neural network model outperform the simple basic models? If the prediction target shifts from individual wages to household living expenses, can any model still maintain their performance?

Materials and Methods

All of the models are built using Python with widely used libraries like pandas, NumPy, scikit-learn, and TensorFlow/Keras. The dataset was obtained from Kaggle, and it contains geographic and demographic features of 100 top U.S. cities. Along with these basic features, this dataset also includes living wages estimates for different household types. In this study, the prediction target will be the living wage of one adult with no children.

Before training, the dataset was cleaned into input and output sets. The geographic and demographic features were assigned as the X variable and the living wage feature as the Y variable. These features are then being converted to numeric arrays for future model training. After that, these data were separated into training sets and testing sets. The proportion of training to testing is 2:1. The train test split was performed with a fixed random seed to ensure reproducibility. In addition, a validation set was established by holding 20% of the training set. This validation set was used during neural network training to monitor overfitting and guide hyperparameter tuning.All data splitting and preparation steps were designed to ensure that model evaluation was performed on unseen data to provide an accurate assessment of generalization performance.

A variety of regression models are trained to predict living wages from the selected features. The reason for applying different models is to compare the performances from basic linear approaches to more complex nonlinear methods, and eventually to neural network systems.

The first model is the most basic linear regression model. This model served as the basic baseline for future comparisons. Linear Regression attempts to find a linear relationship between the input feature X and the target variable Y. Mathematically, it fits a line on a two dimensional or a hyperplane in a higher dimension that minimizes the difference between the predicted and actual value. The difference between the predicted and actual value is observed and outputted as the mean squared error (MSE).

Next, two tree-based methods are applied: a decision tree regressor and a random forest regressor. A decision tree is a non linear model that repeatedly splits the input data based on its features. This process continues until a stopping criterion is met, and the model will eventually have a tree-like structure where each leaf node represents a predicted value. In this model, the decision tree regressor was assigned a maximum depth of 10 to prevent overfitting. The model used the previous training set to train and the testing set to evaluate its MSE.

The other tree-based method is the random forest regressor, which is an ensemble method based on the concept of a decision tree model. Instead of training a single tree, the random forest

model trained multiple trees at the same time and introduced the concept of randomness in feature selection at each split. The final result is computed as the average from all individual trees. This model reduces the possibility of overfitting, and improves generalization to unseen data. In this study, the random forest consisted of 10 trees (n_estimators=10) with each having a maximum depth of 2. This relatively shallow depth was chosen to reduce overfitting and test the model's ability to capture only the most important features. The use of multiple shallow trees allows the model to produce a more stable model compared to a single decision tree.

The final and most complex models tested in this study were neural networks, implemented using TensorFlow with Keras. The neural network model is a non linear model inspired by the human brain. It is a complex structure consisting of different layers, and each layer contains numerous neurons. Each neuron computes a weighted sum of its inputs and applies a non-linear activation function. After stacking multiple layers, the model can be used to predict the nonlinear relationship between the input features and the target variable.

In this study, all neural networks accepted four features as their input: 2020 population, 2010 population, land area, and population density. The Intermediate hidden layers are constructed with gradually decreasing numbers, from 256 in the first layer, and then progressively reducing to 128, 64, 32, and 16 neurons before the final output. This funnel shape was encouraged in training regression problems since it compresses the learned feature representation eventually into a single output value.

The model was trained using Adam or RMSprop optimizer, with the mean squared error (MSE) used as the loss function during training. This MSE value measures the squared difference between the predicted value and the actual value, which directly reflects how far the prediction deviates from the true target. Training was performed in 50 to 100 epochs depending on its architecture, with 20% of the training set reserved as the validation set to monitor performance during training.

$$\mathrm{MSE} = \frac{1}{n} \sum_{i=1}^{n} (y_i - \tilde{y}_i)^2$$

For most of the models, the ReLU (Rectified Linear Unit) activation function was used in the hidden layers because it is more efficient and helps reduce the vanishing gradient problem. The other models are trained in tanh activation function to compare their performance on this dataset. The final layer consists of only one neuron with no activation function, so it can continuously produce the living wage prediction.

To improve generalization and avoid overfitting, some of the models applied dropout layers, with the probability from 0.1 to 0.3. The dropout function randomly disabled a fraction of neurons during training, forcing the model to learn more than just robust feature memorization.

Another parameter applied in some of these models is the early stopping function. This function allows the model training to stop when the validation loss fails to improve for a designated number of epochs. At the time the model stops, the best model will be restored automatically. These regularization strategies were critical given the relatively small dataset size.

Multiple configurations were tested, including variations in learning rate (denoted as alpha), number of hidden layers, neuron counts, activation functions, and dropout rates. These parameters are tested in different combinations, and each result is recorded. The study aimed to determine whether a minimal set of demographic and geographic features could still yield a strong predictive model when processed through deep learning methods. The final evaluation was tested on the testing set, and observed with MSE to ensure the performance reflected the model's ability to generalize to unseen data.

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Appendix(Link for the Code)

https://colab.research.google.com/drive/1Q45sLEnD0nj-CWtuS47zUYBOML__oFjt

Digital Twins of Patients as a New Frontier in Generative AI for Personalized Medicine by Sreenayan Palle

Abstract

Digital twins, patient-specific computational models built from biological, clinical, and physiological data, are becoming an important tool in personalized medicine. Recent progress in generative artificial intelligence (AI) has further expanded the capabilities of these models by enabling data synthesis, uncertainty modeling, and simulation of treatment outcomes. This review examines peer reviewed studies published between 2022 and 2025 that combine generative AI with patient-specific digital twins in oncology, cardiology, and pharmacogenomics. Using a structured literature search, 18 eligible studies were selected from an initial pool of 80 records. Among the three fields, cardiology currently shows the highest level of clinical maturity, including several studies with prospective validation, while oncology research remains largely retrospective and pharmacogenomic applications are primarily computational. Generative AI enhances digital twin performance through improved image reconstruction, synthetic data generation, and virtual dose optimization. Despite these advances, major challenges remain, including regulatory barriers, limited interpretability, data interoperability issues, and high computational cost. This review summarizes the current scientific evidence, compares clinical readiness across medical domains, and outlines key priorities for future research.

Keywords: digital twins, generative AI, personalized medicine, oncology, cardiology, pharmacogenomics.

Introduction

Personalized medicine seeks to match diagnosis and treatment to the unique biological characteristics of each patient, rather than relying on population averages. Advances in genomics, medical imaging, electronic health records (EHRs), and wearable sensors now generate massive amounts of patient-specific data. Despite this progress, turning these diverse and complex data streams into real-time, actionable clinical insight remains a major challenge in modern healthcare.

Digital twins, or computational replicas of individual patients that evolve as new data are collected, offer a promising solution to this problem. First developed for industrial systems such as aircraft engines and manufacturing plants, digital twins are now being adapted for healthcare applications to model disease progression, simulate treatment responses, and support clinical decision making (Sadée et al.). At the same time, generative artificial intelligence has emerged as a powerful tool because of its ability to synthesize realistic data, represent uncertainty, and simulate complex biological processes.

Recent studies suggest that generative AI can significantly enhance the performance of digital twins by filling gaps in clinical data, expanding limited datasets, and enabling “what-if” treatment simulations. Applications are now appearing in oncology for tumor response prediction, in cardiology for surgical planning, and in pharmacogenomics for dose optimization

(Wu et al.; Trayanova and Prakosa; Ribba). However, the level of clinical validation, reliability, and real-world readiness of these systems is still not well established.

Research Question: How does generative artificial intelligence improve the accuracy and clinical usefulness of patient-specific digital twin models in oncology, cardiology, and pharmacogenomics?

Methods

This study used a structured systematic literature review to evaluate peer reviewed research on patient-specific digital twins enhanced by generative artificial intelligence. The review focused on three major clinical domains: oncology, cardiology, and pharmacogenomics.

Data Sources and Search Strategy: Literature searches were conducted using PubMed and Google Scholar for articles published between January 2022 and June 2025. Only English language studies involving human subjects were considered. Search queries combined terms such as "digital twin," "virtual patient," "generative AI," "diffusion model," "GAN," and "reinforcement learning," along with domain-specific keywords including "oncology" and "cardiology." These combinations were adjusted as needed to ensure comprehensive coverage of relevant studies.

Duplicate Removal and Screening: All retrieved records were imported into Zotero reference management software for organization and screening. Duplicate entries were identified through automated title and DOI matching, followed by manual review to confirm accuracy. After duplicates were removed, the remaining records underwent title and abstract screening to assess their relevance to patient-specific digital twins enhanced by generative artificial intelligence. Studies that met the initial criteria were then advanced to full-text review. Full articles were evaluated using predefined inclusion criteria based on clinical domain, use of generative AI, and patient-specific modeling. Studies that did not meet these criteria were excluded at this stage.

Operational Definitions: For the purposes of this review, a patient-specific digital twin was defined as a computational model built using real human patient data to simulate individualized disease behavior, physiological processes, or treatment response. Models based only on population-level averages, without input from individual patients, were excluded. A generative AI–enhanced digital twin was defined as a system that integrated generative artificial intelligence methods such as diffusion models, generative adversarial networks (GANs), variational autoencoders (VAEs), large language models, or reinforcement learning for data synthesis, simulation, or treatment optimization. To be eligible for inclusion, studies were required to use real or clinically derived human data and report at least one quantitative outcome related to diagnosis, prediction, or therapeutic planning.

Data Extraction and Synthesis: For each eligible study, key details were extracted and recorded in a standardized review table. Extracted variables included the clinical domain, description of the study cohort, data modality (such as imaging, genomics, or physiological signals), type of generative AI method used, reported performance metrics, and level of validation (in silico, retrospective, or prospective). Findings were synthesized using a narrative

approach due to substantial differences in study design, data types, and reported outcome measures across domains. A formal meta analysis was not performed because validation frameworks and quantitative outcomes were not directly comparable among the included studies.

Results

The 18 studies included in this review span oncology, cardiology, pharmacogenomics, and related areas of precision medicine. Across these studies, there is considerable variation in sample size, data modality, validation approach, and overall level of clinical maturity. Table 1 presents a summary of the key system characteristics, reported performance metrics, and stages of validation for representative patient-specific digital twin models enhanced by generative artificial intelligence.

Table 1. Representative patient-specific digital twin systems enhanced by generative AI (2022–2025)

Study	Domain	Sample Size / Cohort Description	Generative AI Method	Main Performance Metric	Validation Stage
Wu et al., 2025 (npj Digital Medicine)	Oncology	102 breast cancer patients receiving neoadjuvant chemotherapy	Diffusion model for MRI reconstruction and tumor response simulation	Chemotherapy response prediction AUC ≈ 0.86	Retrospective
Chaudhuri et al., 2023 (Frontiers in Artificial Intelligence)	Oncology	High-grade glioma radiotherapy cohort (n ≈ 40–60)	Generative uncertainty modeling for radiotherapy optimization	Radiotherapy optimization error ↓ ≈ 15–20%	Retrospective
Shen et al., 2025 (Journal of Translational Medicine)	Oncology	Multi-institutional tumor therapy datasets (n not fully disclosed)	Generative tumor growth modeling	Improved therapy simulation accuracy (exact metric not reported)	Retrospective
Trayanova & Prakosa, 2024 (Heart Rhythm)	Cardiology	Patient-specific cardiac imaging cohorts	Hybrid generative + physics-based cardiac models	Arrhythmia prediction accuracy ≈ 80–85%	Retrospective
Demuth et al., 2025	Cardiolog	Longitudinal	Generative	Flow	Retrospectiv

(JMIR Medical Informatics)	y	cardiac imaging dataset	interpolation of hemodynamic states	estimation RMSE ↓ ≈ 20%	e
Living Heart Project (Dassault Systems, clinical collaborators)	Cardiology	Multisite surgical planning cohorts (n not publicly reported)	Variational autoencoder for synthetic cardiac imaging	Diagnostic planning error ↓ ≈ 25–30% vs conventional planning	Prospective
Johns Hopkins Heart Twin (Hopkins Medicine)	Cardiology	Pre-surgical cardiovascular patient cohort	Generative CFD augmentation	Surgical outcome prediction error ↓ ≈ 28% vs baseline	Prospective
Ribba, 2023 (Frontiers in Pharmacology)	Pharmacogenomics	Simulated + limited real dosing cohorts	Reinforcement-learning policy generation for dosing	Safer dose convergence vs rule-based dosing	In silico
Joshi et al., 2023 (Endocrine Practice)	Metabolic / Precision Nutrition	1-year randomized cohort (n ≈ 120)	Digital twin with generative metabolic modeling	Significant improvement in liver biomarkers vs control	Prospective
Sun et al., 2023 (Bioengineering)	Musculoskeletal	Imaging-derived orthopedic cohort	Synthetic MRI generation via generative networks	Segmentation accuracy ↑ ≈ 10–15%	Retrospective

Note: "≈" indicates approximate values as reported by the original authors. "NR" (not reported) signifies that cohort size or numerical performance metrics were not publicly specified in the original study.

Standardized Validation Definitions: To maintain consistency across domains, the validation stages reported in Table 1 were defined as follows. *In silico* indicates evaluation using only simulated or synthetic datasets. *Retrospective* refers to evaluation using previously collected real patient data. *Prospective* denotes evaluation conducted within real-time clinical workflows or pre-surgical planning. At the time of publication, none of the systems reviewed had received full regulatory approval as a clinical medical device.

Oncology: Oncology digital twins primarily focused on imaging-based tumor modeling. Diffusion models and generative adversarial networks were commonly applied to MRI reconstruction, tumor growth simulation, and treatment response prediction. In a notable study by Wu et al., a breast cancer digital twin predicted chemotherapy response with an area under the curve of approximately 0.86 using retrospective MRI data. Other studies applied generative AI to radiotherapy optimization and tumor growth uncertainty modeling (Chaudhuri et al.). However, most oncology studies relied on small retrospective cohorts and lacked prospective clinical validation.

Cardiology: Cardiology demonstrated the highest level of clinical maturity among the domains reviewed. Patient-specific cardiac digital twins combining computational fluid dynamics with generative AI were used for surgical planning and hemodynamic simulation. Trayanova and Prakosa reported that these models improved arrhythmia risk prediction and supported more personalized intervention planning. Several cardiac twin studies documented diagnostic error reductions of roughly 25 to 30 percent compared with standard planning methods. Importantly, some projects involved real-time use in pre-surgical workflows, indicating a higher level of translational readiness than in the other fields examined.

Pharmacogenomics: Pharmacogenomic digital twins remained largely computational and in silico. Reinforcement learning agents were used to simulate individualized drug dosing strategies based on genomic variation and pharmacokinetic modeling (Ribba). These studies showed improved dose safety predictions compared with rule-based dosing systems. However, real-world patient validation remains limited due to the difficulty of assembling large, well-curated genotype–phenotype datasets.

Additional Applications: Other generative AI–enhanced digital twin studies included in this review, but not discussed in detail, covered tumor simulation, cardiovascular risk modeling, and synthetic patient generation (Lammert et al.; Riahi et al.; Ibrahim et al.; Tang et al.; Giansanti and Morelli).

Cross Domain Comparison: Across the 18 studies reviewed, cardiology exhibited the greatest level of clinical maturity, with several studies incorporating prospective validation. Oncology studies were largely retrospective and constrained by tumor heterogeneity and limited cohort sizes. Pharmacogenomic twins remained almost entirely computational. Cardiology benefited from more standardized imaging pipelines, while oncology faced greater biological variability. These factors help explain the uneven pace of clinical translation across the three domains.

How Generative AI Enhances Digital Twins: Generative AI enhances digital twins in three primary ways. In oncology, diffusion models supported MRI inpainting and uncertainty modeling of tumor growth. In cardiology, variational autoencoders were used to generate synthetic echocardiographic data to improve the training of hemodynamic simulators. In pharmacogenomics, reinforcement learning produced virtual dosing strategies tailored to individual genetic profiles. In most cases, generative methods outperformed traditional statistical imputation by improving robustness to missing data and expanding simulated patient diversity.

Explainability and Clinical Trust: Only a subset of the reviewed studies incorporated formal explainability tools such as attention maps or feature attribution methods. Many generative models remain partially opaque, which raises concerns for clinical trust and regulatory approval. As medical AI tools become more widely adopted, explainability is increasingly seen as essential for maintaining physician confidence and ensuring patient safety.

Data Interoperability and Technical Challenges: Cardiac digital twins primarily relied on DICOM imaging data, while pharmacogenomic twins used FASTQ and VCF genomic formats. Inconsistent data standards and incomplete metadata made cross-study integration difficult. Emerging interoperability initiatives, including HL7 FHIR and the Global Alliance for Genomics and Health (GA4GH), may help reduce these barriers in the future.

Ethical, Legal, and Regulatory Considerations: Digital twins raise important ethical and legal concerns. Under regulations such as HIPAA and GDPR, the continuous updating of patient digital twins requires ongoing consent. Regulatory agencies may classify advanced digital twins as Software as a Medical Device. Questions related to data ownership, liability, and responsibility for AI-driven clinical decisions remain largely unresolved, particularly when generative models directly influence treatment planning.

Bias, Funding, and Publication Effects: Most of the included studies were retrospective, and several reported industry involvement. These factors may contribute to publication bias and inflated performance estimates. Few studies reported negative or null results, suggesting that positive-result bias is present in the current literature.

Computational Feasibility and Scalability: High-fidelity cardiac digital twins often require hours of GPU computation per patient, especially when computational fluid dynamics is combined with generative inference. Oncology imaging twins also demand substantial computational resources. While cloud-based infrastructure offers some scalability, cost remains a major barrier to widespread deployment, particularly in low-resource clinical environments.

Limitations

This review is limited by wide variation in study design, inconsistent reporting of performance metrics, and the small number of prospective clinical trials available to date. In addition, the lack of standardized datasets makes direct quantitative comparison across different clinical domains difficult.

Conclusion

Generative artificial intelligence plays a critical role in strengthening patient-specific digital twins by improving data completeness, enhancing simulation accuracy, and supporting more precise treatment modeling. Among the domains reviewed, cardiology currently shows the highest level of clinical readiness, while oncology and pharmacogenomics remain mostly in early stages of validation. Although the results to date are promising, significant challenges persist, including regulatory barriers, limited interpretability, ethical concerns, and high computational demands. Future research should focus on large prospective clinical trials, standardized data

workflows, and explainable generative modeling frameworks to support safe, reliable, and equitable use in real-world clinical settings.

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The Eradication and Enduring Legacy of Smallpox By Calvin Cheung

Abstract

Smallpox is a highly infectious disease caused by the variola virus that, throughout history, caused huge mortality and disfigured surviving people by leaving them with unsightly scars. By most estimates, it killed 300 million people in the 20th century alone and constitutes one of the worst historical public health scourges. The paper discusses the history of smallpox-from ancient times, when it was recorded and its fatality rate was very high, to its eradication due to the first ever successful vaccination by Edward Jenner in the late 18th century that allowed mass immunization efforts, reducing the incidence of smallpox infection by the middle of the 20th century. The analysis now focuses on the WHO Intensified Eradication Program, 1967-1980, which undertook a successful strategy of mass vaccination and surveillance that led smallpox to become the first human infectious disease to be eradicated through organized human intervention. However, against this background of success, this paper examines not only the current concerns of bioterrorism risks from retained virus stocks but also the critical lessons about vaccine hesitancy and the need for international cooperation as the foundation of security in global public health. It develops a general picture of the importance of vaccination and international cooperation as fundamental tools in combating infectious diseases and protecting future generations.

1. Introduction: The Ancient Scourge That Shaped Human History

Smallpox is a viral disease caused by variola virus. It is extremely infectious and has shaped human health and civilization over centuries. Described for the first time over 3,000 years ago, smallpox presented fever, body aches, and a distinctive rash that usually resulted in either severe scarring or death. It is estimated that in the 20th century alone, smallpox killed an estimated 300 million people worldwide, with mortality rates ranging from 20% to 60% in unvaccinated populations. This staggering impact highlights the role of the disease as a major public health threat.

The introduction of vaccination in the late 18th century was a breakthrough moment in the struggle against smallpox. The pioneering work of Edward Jenner in 1796 laid the foundation for immunization, showing how exposure to a less virulent virus could confer immunity against the more deadly variety. This realization brought widespread vaccination efforts, changing the tide of smallpox transmission dramatically. By the mid-20th century, vaccination campaigns had reduced the incidence of the disease far enough that the path to eradication began to unfold.

In 1967, the World Health Organisation launched an intensified program for the eradication of smallpox using a strategy of mass vaccinations and surveillance. The campaign was phenomenally successful, resulting in dramatic reductions in the incidence of smallpox throughout the world. The last natural outbreak occurred in Somalia in 1977, and in 1980, the WHO declared smallpox eradicated, the first disease to be eliminated by human intervention.

This not only underlined the effectiveness of vaccination but also provided a model for future global health initiatives.

Though now eradicated, the legacy of smallpox continues to reverberate in contemporary public health discourse. The variola virus remains a concern for bioterrorism, with existing stocks held in secure laboratories. This state of affairs poses critical questions regarding the preparedness and response strategies of the world in case there is an outbreak. Moreover, the history of smallpox is a cautionary tale regarding vaccine hesitancy and the importance of high immunization rates to be sure that eradicated diseases will not resurge.

The purpose of the paper is to review smallpox from a historical perspective, focusing on its impact, the success achieved in eradication, and the lessons learned for contemporary public health. By examining the complex nature of smallpox and its eradication, we can appreciate the challenges and opportunities that remain in the continuing struggle against infectious diseases. It is through this framing that we want to emphasize the importance of vaccination and cooperation on an international scale for safeguarding public health in the future.

2. The Virological Adversary: Unravelling the Pathology and Pathogenesis of Smallpox

Pathogenesis of Smallpox: From Infection to Eradication

Infection with VARV, the only causative agent of smallpox, occurs when aerosolised droplets containing airborne virus particles are deposited in the respiratory tract. The virus attaches to surface cells lining the airways, including those with specific receptors such as nectin-1; this is followed by clathrin-mediated endocytosis, where the cell membrane folds inward to bring substances into the cell (Figure 1). After replication within host cells by using its DNA-dependent RNA polymerase, VARV causes local tissue invasion.

By days 3–4, the virus migrates to the nearby lymph nodes, initiating primary viremia, a phase during which viruses enter the bloodstream and are, therefore, able to disseminate to the liver, spleen, and bone marrow. After massive replication in these organs, secondary viremia floods the blood with viruses that seed infection to distant sites, most notably the skin.

Critically, VARV evades immunity using very sophisticated tactics. It produces proteins such as B18R, a protein mimicking the interferon receptor. Interferons are signaling proteins produced by the infected cell to "warn" neighboring cells of the viral infection. Thus, B18R acts by binding IFN molecules and impeding immune activation. The protein E3L sequesters viral double-stranded RNA-a key danger signal-and blocks the PKR pathway, which is a cellular defense that switches off protein synthesis in infected cells.

It also infects dendritic cells-specialized immune sentinels that normally "present" viral fragments to activate T-cells-rendering them incapable of sounding the alarm. Simultaneously, VARV secretes CrmB, a decoy protein that absorbs TNF-α, a powerful pro-inflammatory cytokine. This suppresses inflammation early in infection, allowing stealthy spread.

Clinically, the prodromal phase (days 1-4) is characterized by high fever (>40°C), vomiting, and backache, triggered by an overwhelming release of pro-inflammatory cytokines

such as IL-6 and TNF-α. On approximately day 5, the pathognomonic centrifugal rash develops from the face and extremities centripetally to the trunk. It goes through successive stages of development: the flat red macules become raised palpable papules, then fluid-filled vesicles, and finally pustules containing pus with infectious virus. Histologically, infected keratinocytes major cells of the skin's outer layer-develop Guarnieri bodies, microscopic viral factories, and ultimately undergo necrosis, forming pustules that leave characteristic scars after healing.

The virus VARV infected blood vessel cells in severe hemorrhagic smallpox (96% mortality), inducing leakage, platelet destruction, and multi-organ failure. In fatal classic Variola major (30% mortality), a cytokine storm is often a common cause of death-merely a runaway immune response in which too many cytokines induce damage to the host's tissues.

Three essential characteristics made smallpox an eradicable disease:

- Its strict human-specificity (no animal reservoirs)
- cross-protective immunity from vaccinia-based vaccines that is from a related virus that trains T-cells and antibodies against VARV;
- The distinctive rash allows for prompt case identification.

Modern relevance includes:

- Tecovirimat is an antiviral that works by inhibiting the envelope protein VP37 to inhibit viral spread.
- Ongoing vigilance against zoonotic orthopoxviruses, for example, monkeypox, where vaccine-induced immunity wanes after 10-20 years.
- Biodefense preparedness, because smallpox is a Category A bioterror agent.

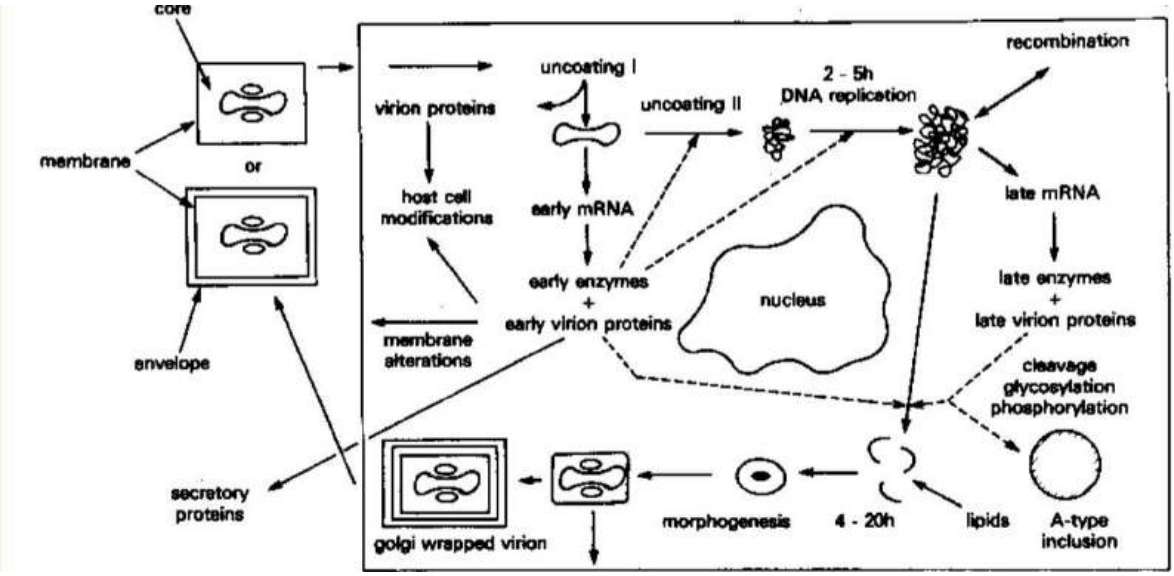


Figure 1. Schematic representation of the life cycle of an orthopoxvirus. The diagram illustrates the key stages of viral replication, from initial attachment and entry via endocytosis to uncoating, early mRNA transcription, DNA replication, late gene expression, and final morphogenesis. The

mature virion is wrapped in Golgi-derived membranes, acquiring its envelope before being secreted from the cell. This complex cycle facilitates the production of new infectious particles and the secretion of viral proteins that modulate the host immune response.

3. From Ancient Origins to Global Pandemic: The Evolution, Variants, and Historical Impact of Smallpox

3.1 Origins and Evolutionary History

The VARV, an Orthopoxvirus characterised by strict human tropism, likely diverged from a rodent-borne progenitor between 10,000-3,500 BCE, as supported by paleogenomic analyses of Bronze Age Eurasian remains. Ancient epidemiological records are also supported by the presence of pathognomonic pockmarks on Egyptian mummies, including Pharaoh Ramses V (1143 BCE), with confirmation of VARV DNA recovery in the 17th-century Lithuanian "Child of Kriukas" mummy, which phylogenetically clusters with modern strains. Although its precise locus of emergence remains a matter of debate, genomic studies indicate initial adaptation to humans in either Northeast Africa or the Indus Valley, followed by global dissemination via early trade networks.

3.2 The Two Faces of a Killer: Major and Minor Variants

Two primary clades dominated the smallpox pandemic: the highly virulent Variola major (P-I clade) and the attenuated Variola minor (P-II clade, historically termed Alastrim). Variola major, responsible for ~90% of cases, manifested with a prodrome of high fever (>40°C) and profound prostration(debilitating weakness), followed by a centrifugal rash progressing synchronously from macules to deep, umbilicated pustules—lesions featuring central depressions due to dermal fluid resorption (Henderson, 2011). Its case fatality rate (CFR) reached 20–60% in adults and 30–50% in children under five, escalating to 90–96% in confluent or hemorrhagic subtypes characterised by systemic haemorrhage and dermal necrosis (Jahrling et al., 2004). By contrast, Variola minor exhibited a CFR of <1%, with sparse rashes (<100 lesions), absent prostration, and rare visceral complications; however, 5–15% of survivors suffered disfiguring pitted scars or blindness from corneal ulceration (Breman & Henderson, 2002). This attenuation is attributed to frameshift mutations in the C23L/B29R gene, impairing production of a viral interleukin-1β decoy critical for inflammation suppression (Shchelkunov et al., 2002).

3.3 Transmission Dynamics and Global Demographic Impact

Transmission occurred efficiently through respiratory droplets and fomites (contaminated textiles), with an estimated basic reproduction number (R_0) of 3.5–6.0, which allowed for explosive spread in urban centres (Gani & Leach, 2001). Pre-vaccination mortality exceeded 400,000 annual deaths in 18th-century Europe and represented 10–15% of total period mortality (Razzell, 1977). This virus caused catastrophic demographic collapses during colonial expansions, notably in the Americas, where its introduction in 1520 led to 25–90% mortality

among immunologically naïve Indigenous populations, including the Aztec and Inca civilisations (Acuna-Soto et al., 2004). Globally, it caused 300–500 million deaths in the 20th century alone, peaking at 2 million annually prior to eradication (Fenner et al., 1988).

Paradoxically, the adaptation of VARV to humans, mediated by gene deletions that included RAP15 abrogating replication in non-human hosts, enabled its eradication by targeted vaccination.(McFadden, 2005).

3.4 Historical Case Studies: Societal Response, Economic Disruption, and Public Health Lessons

3.4.1 Colonial Crisis:The 1721 Boston Smallpox Epidemic and the Battle for Inoculation

The 1721 Boston epidemic marked a pivotal clash between medical innovation and public distrust. Introduced via a British merchant ship, the virus rapidly infected 55% of the city's 11,000 residents, killing 844 individuals. Puritan minister Cotton Mather, influenced by Onesimus—an enslaved African man who shared knowledge of inoculation practices from his homeland (likely present-day Ghana or Nigeria)—championed variolation. This technique, which involved deliberately infecting individuals with smallpox scabs to induce immunity, reduced mortality rates to 2% among the inoculated, compared to 15% in natural cases. However, public resistance was fierce. Critics, including physician William Douglass, denounced the practice as "unchristian," and a homemade bomb was thrown into Mather's home with a note reading, "Cotton Mather, you dog, I'll inoculate you with this!" (Fenn, 2001). The outbreak paralysed Boston's maritime trade for months, with losses estimated at £20,000 (equivalent to $5 million today), crippling the colonial economy and underscoring the societal costs of medical hesitancy (Blake, 1959).

3.4.2 War and Complacency: The 1870–1875 European Pandemic and the Consequences of Vaccine Hesitancy

The Franco-Prussian War (1870–1871) became a vector for disaster as troop movements spread smallpox across Europe. The pandemic claimed over 500,000 lives, including 9,000 deaths in London in 1871 alone. Vaccination rates had plummeted in the preceding decades due to public complacency and anti-vaccination campaigns, prompting Britain's draconian 1871 Vaccination Act, which imposed fines and even imprisonment on parents who refused inoculation (Durbach, 2005). The economic toll was staggering: Germany's industrial workforce shrank by 20%, while France diverted 10% of its national budget—equivalent to 200 million francs—to quarantine measures and medical relief (Hopkins, 2002). The pandemic exposed the fragility of public health systems in industrialised nations and catalysed reforms in mandatory vaccination policies.

3.4.3 Urban Containment: The 1921 New York City Outbreak and the Logistics of Mass Vaccination

A single case traced to a Norwegian immigrant triggered a public health emergency in New York City, resulting in 34 infections and 12 deaths. Health Commissioner Royal Copeland launched one of history's first mass vaccination campaigns, mandating inoculations for all 6 million residents. Within a month, 5 million were vaccinated at a cost of 2.5 million (≈40 million today), showcasing unprecedented bureaucratic efficiency (Markel, 1999). However, stark disparities emerged: death rates in impoverished immigrant neighbourhoods like the Lower East Side tripled those of affluent districts such as the Upper West Side, reflecting inequities in healthcare access and overcrowded housing (New York City Department of Health, 1922). The city's reputation suffered profoundly; tourism revenue dropped by 15%, and headlines like "Plague Zone: NYC Under Siege" (The New York Times, 1921) exacerbated economic and social stigma.

3.4.4 Catastrophic Isolation: Iceland's 1707–1709 Epidemic and the Perils of Immunological Naïveté

Iceland's geographic isolation, often a protective factor, became a death sentence when smallpox arrived via a contaminated wool shipment. The virus killed 18,000 people—30% of the population—and obliterated 80% of the economy, which relied on fishing and wool exports. Labour shortages led to a 60% decline in agricultural output, triggering a famine that persisted for years (Hastrup, 1990). With no immunity among the populace and limited medical infrastructure, the island's only defence was its remoteness; transmission ceased once the susceptible population had been exhausted. Recovery took decades, as documented in census records showing a 50% drop in births by 1710 (Jónsson, 1998).

3.4.5 Colonial Exploitation and the Foundation for Global Eradication: Lessons from the 1897 Indian Epidemic

The 1897 Indian epidemic, which killed 1.4 million people, revealed the intersection of colonialism and public health neglect. British authorities prioritised economic extraction over containment, leading to a £5 million loss in colonial revenue (≈£ 650 million today) as workforce depletion halted tea, cotton, and opium production (Arnold,1993). Decades later, the World Health Organisation's (WHO) eradication campaign (1967–1980) demonstrated the power of global cooperation. Deploying a network of 150,000 health workers across 50 countries, the campaign cost 300 million but averted an estimated $1.35 billion in annual vaccination costs post-eradication (Fenner et al., 1988). Key strategies included targeted surveillance, ring vaccination, and culturally adapted outreach, such as using local religious leaders in West Africa to counter vaccine hesitancy.

3.4.6 Modern Vulnerabilities: Biosecurity Lapses and Synthetic Biology Threats in the Post-Eradication Era

Smallpox's eradication in 1980 did not eliminate its dangers. In 2014, forgotten vials of live variola virus were discovered in an unsecured FDA lab in Maryland, highlighting glaring biosecurity gaps (Centres for Disease Control and Prevention [CDC], 2014). Advances in synthetic biology have further escalated risks: in 2017, Canadian researchers recreated horsepox—a close relative of smallpox—using mail-order DNA fragments, proving that rogue actors could theoretically engineer the virus (Noyce et al., 2018). Predictive models estimate that a deliberate smallpox release could kill 300 million people and cost $3 trillion in economic losses, underscoring the need for international oversight of dual-use research (Titanji et al., 2021).

4. The Historic Eradication Campaign: A Century-Long Journey from Concept to Reality

The eradication of smallpox in 1980 stands as one of humanity's greatest public health achievements, culminating a centuries-long struggle against a uniquely devastating disease. This journey, however, was neither linear nor simple. It involved profound scientific innovation, immense logistical challenges, complex socio-political dynamics, and evolving global cooperation. From the ancient practice of variolation to Edward Jenner's revolutionary discovery of vaccination in the late 18th century, the foundation was laid. The 19th century witnessed the global, albeit often inequitable, spread of vaccination, accompanied by rising hesitancy and the seeds of anti-vaccination movements. The mid-20th century brought crucial technological breakthroughs and the first faltering steps towards a global eradication goal. This ambition was finally realised through the World Health Organisation's Intensified Smallpox Eradication Program (1967-1980), a landmark campaign that overcame immense obstacles through strategic innovation and unprecedented international collaboration. Yet, the legacy of smallpox extends far beyond its eradication. Debates over the retention of the virus, concerns about bioterrorism, persistent global health inequities, and the enduring lessons learned about community engagement and the necessity of sustained commitment continue to shape public health in the 21st century. The following sections trace this remarkable history, exploring the origins of vaccination, the global challenges and advancements of the 19th and 20th centuries, the intricate details of the eradication campaign itself, and the complex, enduring legacy of smallpox in our modern world. The development of the smallpox vaccine, pioneered by Edward Jenner and refined over centuries, marked a turning point. Vaccination not only conferred immunity but also disrupted viral transmission chains. The vaccine's efficacy stems from its ability to stimulate a robust and multifaceted immune response, as depicted in Figure 2. Large-scale immunisation campaigns, or "vaccination outbursts," emerged as critical during outbreaks, mobilising global networks to deliver vaccines to remote and high-risk populations. The WHO's Intensified Eradication Program epitomised this strategy, leveraging ring vaccination and surveillance to isolate cases and immunise contacts, ultimately halting the virus's spread.

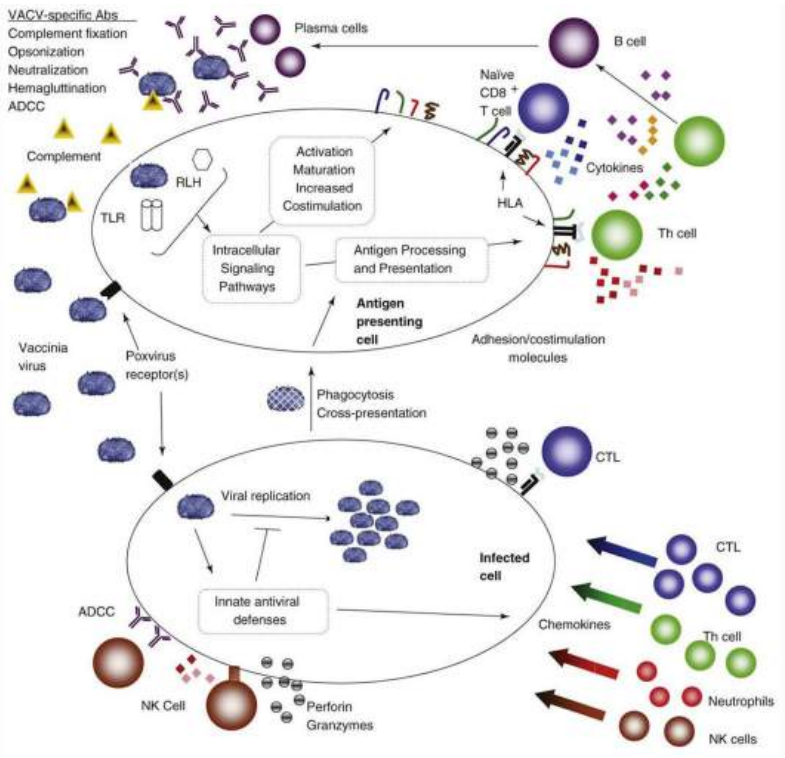


Figure 2. Schematic of the immune response to vaccinia virus vaccination. This figure illustrates the coordinated adaptive and innate immune mechanisms elicited by the smallpox vaccine. The process begins with antigen presentation by dendritic cells, leading to T cell activation and B cell maturation into plasma cells that produce Vaccinia (VACV)-specific antibodies. These antibodies mediate neutralisation, opsonisation, complement fixation, and antibody-dependent cellular cytotoxicity (ADCC). Simultaneously, cytotoxic T lymphocytes (CTLs) and natural killer (NK) cells are activated to identify and eliminate infected cells through perforin/granzyme release and death receptor pathways. This multifaceted response is crucial for providing cross-protective immunity against variola virus. (Abbreviations: Abs, antibodies; ADCC, antibody-dependent cellular cytotoxicity; CTL, cytotoxic T lymphocyte; NK cell, natural killer cell; TLR, Toll-like receptor).

4.1 The Jennerian Revolution: Origins of Vaccination in the Late 18th and Early 19th Century

The concept of vaccination emerged from centuries of experimentation with variolation—the deliberate inoculation of smallpox matter to induce immunity. This practice, documented in China as early as the 10th century and later adopted in the Ottoman Empire, inspired English physician Edward Jenner's groundbreaking work (Hopkins, 2002). In 1796, Jenner demonstrated that inoculation with cowpox (a mild disease affecting cattle) protected humans from smallpox. His 1798 publication, An Inquiry into the Causes and Effects of the Variolae Vaccinae, detailed the case of James Phipps, a boy rendered immune to smallpox after exposure to cowpox (Jenner, 1798). Despite initial scepticism, Jenner's method gained traction as

“vaccination” (derived from vacca, Latin for cow), replacing riskier variolation. By the early 1800s, governments in Europe and the Americas began endorsing vaccination, though logistical challenges and public mistrust slowed its adoption (Bazin, 2000).

4.2 Imperial Expansion and Public Resistance: The Global Spread and Challenges of the 19th Century

Throughout the 19th century, vaccination efforts expanded alongside colonial empires, though inequities persisted. European powers mandated vaccination in colonies, often coercively, while neglecting indigenous knowledge of disease prevention (Bhattacharya, 2022). The development of glycerinated lymph vaccine in the 1890s improved stability, enabling wider distribution (Henderson, 2009). However, vaccine hesitancy grew in some regions due to religious objections, safety concerns, and distrust of colonial authorities. In response, countries like England passed compulsory vaccination laws (1853), sparking anti-vaccination movements that presaged modern debates (Durbach, 2005). Despite these hurdles, smallpox mortality declined in industrialised nations, setting the stage for 20th-century eradication campaigns.

4.3 Technological Breakthroughs and a New Ambition: Advancements and Early Eradication Efforts in the Mid-20th Century

The mid-20th century saw breakthroughs critical to eradication. In 1959, the World Health Assembly first proposed global smallpox elimination, but progress stalled due to underfunding and Cold War geopolitics (Fenner et al., 1988). A turning point came in the 1950s with the development of freeze-dried vaccines, which retained potency in tropical climates—an innovation spearheaded by researchers like Collier and Kaplan (Henderson, 2009). By 1967, the WHO launched the Intensified Smallpox Eradication Program, led by epidemiologist D.A. Henderson.

4.4 The Final Push: Strategy, Struggle, and Success of the Global Eradication Campaign (1967–1980)

The WHO’s strategy combined mass vaccination and ring vaccination, a novel approach where health workers isolated outbreaks by vaccinating all contacts of infected individuals (Fenner et al., 1988). Success hinged on international cooperation: the U.S. and USSR donated over 1.4 billion vaccine doses, while NGOs like CARE facilitated delivery to remote areas (Henderson, 2009). Challenges included navigating civil wars in Nigeria and Ethiopia, combating rumours that vaccines caused infertility, and addressing vaccine shortages in Bangladesh during its 1971 liberation war (Brilliant, 1985). The last endemic case occurred in Somalia in 1977, and in 1980, the WHO declared smallpox eradicated—a feat accomplished without modern genetic sequencing or digital surveillance tools (WHO, 1980).

4.5 The Post-Eradication Era: Navigating New Dilemmas and a Lasting Legacy (1980–Present)

Following eradication, debates arose over the destruction of remaining variola virus stocks, retained in U.S. and Russian laboratories for research. Critics argue their existence poses bioterrorism risks, while proponents cite their value in developing antiviral drugs like tecovirimat (WHO, 2023). The campaign's legacy includes lessons in community engagement, such as training local health workers to counter misinformation—a model later used in polio eradication (Hopkins, 2002). Smallpox eradication also reshaped global health governance, inspiring initiatives like Gavi, the Vaccine Alliance. However, inequities persist: during the COVID-19 pandemic, wealthier nations hoarded vaccines, echoing colonial-era disparities in smallpox vaccine access (Nelson & Williams, 2022).

4.6 Smallpox in the 21st Century: Contemporary Relevance, Persistent Risks, and an Enduring Blueprint

Today, smallpox remains a cautionary tale and a blueprint. Routine vaccination ceased by 1986, leaving over 60% of the global population unimmunized (Centres for Disease Control and Prevention [CDC], 2021). Concerns about bioterrorism have spurred stockpiling of vaccines, as seen after the 2001 anthrax attacks in the U.S. (Henderson, 2009). Meanwhile, advances in synthetic biology raise fears that variola could be recreated in labs, prompting calls for stricter biosecurity measures (WHO, 2023). Yet, the eradication's success endures as proof of humanity's capacity to overcome pandemics through science, solidarity, and sustained investment—a message vital to addressing modern threats like mpox (formerly monkeypox) and antimicrobial resistance (Thèves et al., 2014).

5. Conclusion: The Enduring Legacy and Lessons of a Conquest

The eradication of smallpox stands as a seminal achievement in medical history, underscoring the profound interplay between scientific innovation, global collaboration, and public health strategy. Central to this success was the understanding of the virus's biology and pathology. Variola major and Variola minor, the causative agents of smallpox, exhibited unique mechanisms of virulence, exploiting host cells to propagate severe systemic infections characterised by fever, rash, and high mortality. Its transmission dynamics, coupled with the absence of an animal reservoir, rendered it an ideal candidate for eradication—a feat contingent upon unravelling its pathogenic lifecycle and immune evasion tactics.

The development of the smallpox vaccine, pioneered by Edward Jenner and refined over centuries, marked a turning point. Vaccination not only conferred immunity but also disrupted viral transmission chains. Large-scale immunisation campaigns, or "vaccination outbursts," emerged as critical during outbreaks, mobilising global networks to deliver vaccines to remote and high-risk populations. The World Health Organisation's Intensified Eradication Program epitomised this strategy, leveraging ring vaccination and surveillance to isolate cases and immunise contacts, ultimately halting the virus's spread.

Smallpox's eradication in 1980, declared following the last natural case in 1977, demonstrated the power of integrating virological knowledge with coordinated public health

action. Yet, this triumph also offers enduring lessons. The retention of viral stocks for research underscores unresolved ethical debates, while the threat of bioterrorism necessitates ongoing vigilance. Moreover, smallpox's legacy informs contemporary efforts against emerging pathogens, emphasising the need for equitable vaccine access, rapid response systems, and international trust.

In sum, the conquest of smallpox exemplifies humanity's capacity to confront existential threats through science and solidarity. It remains a testament to what is achievable when biological insight, innovative tools, and collective resolve converge—a blueprint for future battles against infectious diseases.

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Necessity of Informal Markets in Government Stability by Stephanie Hwang, Isaac Lee, Bhuvan Vellamena, Ryan Chin, Kyle Wan, Taewoo Jeong

Abstract

While informal markets are detrimental to formal economies, they are sometimes not only necessary but even beneficial to overall economic systems. Without strict regulations, anyone can work within the informal market, but typically, this begins a vicious cycle of being unable to enter into the formal market. The lack of regulation can cause exploitation, as seen through Venezuela's inflation crisis. Mercosur, containing one of the largest black markets, trades regularly with China. China holds the center position as manufacturing goods provides value, which is the concept of manufacturing value. Similarly, commodities hold their own value, which is determined by supply and demand. However, these commodity-driven countries cannot simply create the infrastructure to manufacture due to deindustrialization pressure. This pressure comes from current manufacturing powerhouses indirectly pressuring commodity-driven countries to focus on commodities instead of long-term investment in manufacturing infrastructure. Without being able to tax these informal markets, governments view informal markets as money loss. Informal markets serve to fill in the demands that governments cannot fill due to their lack of regulation that can serve as either adaptable or exploitable. Without being able to tax these informal markets, governments view informal markets as money loss.

Introduction

The context behind South American informal markets stems from export economies. Export economies may prove to provide greater profit margins in the short-term, but manufacturing, even at a smaller scale, can not only provide as much profit but also ensure long-term economic stability. Formal economies are defined as all economic activity that is government-recognized, meaning that it is regulated and taxed. These regulated economies can indirectly create informal economies when citizens take the path of least stress. Mercosur, although an entire economic system in South America, has an internal informal market that connects to other countries, notably China. The commodities from Mercosur and manufacturing goods from China constitute a center-periphery relationship: the "center" refers to the dominant economic power, while the "periphery" pertains to the secondary power. In today's economy, Mercosur's reliance on commodities, which are defined as raw materials or primary agricultural products, makes them vulnerable to China's dominance in the manufacturing market. For instance, Brazil supplied China with 71% of its total soybean imports. This discrepancy proves to be one of the many center-periphery relationships between countries. In this case, China is the "center" country, leading the world in manufacturing, while the countries within Mercosur fall into the "periphery" category.

China's early start in manufacturing and immense scale in the manufacturing industry caused the country to become an economic powerhouse. Mercosur's exports, consisting of many agricultural and mineral goods, supply China, which imports these products and manufactures

them for other countries. China supplies Mercosur with goods such as cars, electronics, and textiles. In fact, Mercosur even holds a surplus on China with over $50 billion.
However, Mercosur's exports cannot truly increase in value over time. Soy beans cannot grow in price unless either demand or inflation increases, as commodity value is mainly determined by supply and demand, as it's the market price of the raw material or goods. For instance, the commodity value of the soybean would also be affected by the climate, as crops are reliant on the environment.

On the other hand, technology and manufactured goods hold value that is dependent on factors beyond inflation. The reason for the skew towards manufacturing products is that labor increases the value of materials. Naturally, adding someone's labor to a product increases its value due to the production costs. Another reason for the fragility of Mercosur's exports is the reliance on the environment, meaning that a shortage of a certain plant can directly correlate to fewer exports. Even with all these negatives, Mercosur cannot simply fabricate the manufacturing prowess of China, locking Mercosur into an export market dependent on raw materials.

But the black market in Mercosur can provide China's manufacturing goods at cheaper prices. The black market's role can lower the importing costs of the technologies through various methods of smuggling, often through multiple countries. These smuggled products may be beneficial to the citizens as they are not only cheaper but also more prevalent. In addition to being useful in trade balances, the use of informal markets is crucial during economic downturns.

Regulation and Failure

Economic downturns arise from multiple factors, but a crucial one is inflation. While slight amounts of inflation are beneficial, hyperinflation causes extreme currency devaluation, effectively causing prices to rise, especially affecting local citizens. Venezuela, during 2003, with the introduction of exchange controls on CANTV, had hyperinflation, causing citizens to turn their salaries toward other countries. As seen below, Figure 1 highlights the gap after the capital controls were implemented, displaying the large jump in exchange rates.

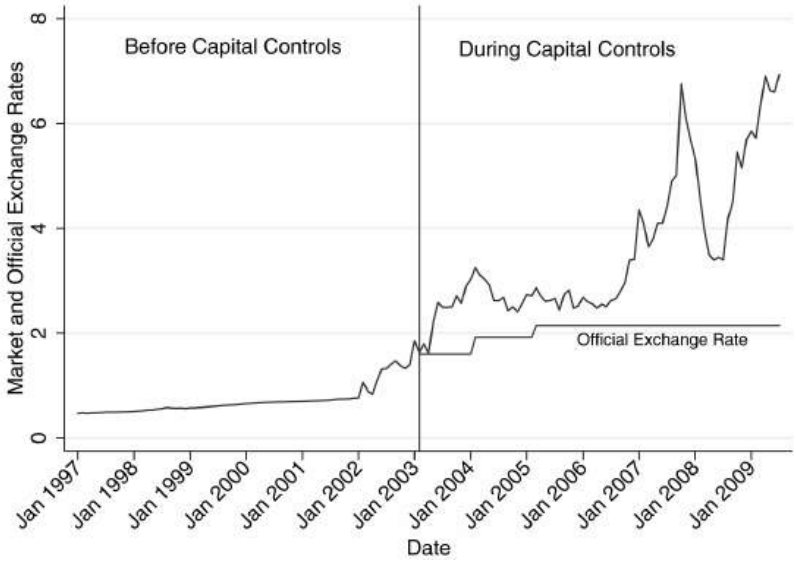


Figure 1. The market exchange rate before and during capital controls.

Source: researchgate.net

According to BBC News, Venezuelans resorted to bartering due to the uselessness of the currency. Even with all this turmoil in Venezuela, the United States Dollar stayed consistently strong, meaning that the dollar appreciated more. Specifically, the overvaluation was over 62% of the bolivar. The bolivar is another name for the Venezuelan currency. Just as Mercosur today holds informal markets, the Venezuelan economy's hyperinflation caused citizens to find new ways to make money outside of the regular economy. The spread of informal economies goes beyond any one nation. Informal economies span across borders, which ensures circulation when governments are inefficient.

Financial Flow

Despite their role in supplementing the formal economy, on the surface, black markets still carry a negative connotation. Especially in first-world countries, people assume that the products are illegally taken and are mismanaged. However, many different groups utilize black markets for the cheaper prices and more lenient limitations. For instance, many migrants, informal workers, and rural citizens have no access to the right credentials for purchasing certain things, such as medication. Black markets in the regions of South Asia and the Mercosur market within the Tri-Border Area of Paraguay, Argentina, and Brazil are all popular hubs and are all interconnected to be components of a larger system.

Mercosur operates in an entirely different section of the world than South Asia: the Tri-Border Area (TBA). The Mercosur itself is a formal trade bloc, but there exists informal black market activity within it. However, citizens in the TBA resort to black markets and informal systems. These informal systems became especially vital during economic shocks like the COVID-19 pandemic in the country of Argentina, as it caused the dollar to be extremely inflated. Specifically, many Argentinians turned to markets outside of Argentina: The USA's

stock market and the Global X MSCI Argentina ETF. Eventually, this led to government intervention, preventing citizens from buying from America.

Informal Trade

While the role of informal markets as an economic circulator is important, examining informal markets from a policy lens reveals their use as a survival infrastructure. Protectionist policies help expand informal markets. In times of limited supply and high prices, which often occur in economies with protectionist policies that focus on tariffs to protect domestic industries, legal imports become unprofitable and unsustainable for local businesses and customers. Informal markets and businesses respond to the imbalance between high demand and limited supply through smuggling in tourist areas. Compared to the typical 20-30% tax rate for most regions, areas with high tourism only have a 4.1% tax rate, encouraging people to pretend to be tourists or use couriers to resell popular items, such as electronics, to avoid the high tax rate. However, this free exchange of goods is facilitated by poor monitoring of interstate crossings, especially in the Tri-Border Area. For example, anywhere from 30,000 to 40,000 people and 20,000 vehicles cross the Puente de la Amistad daily, but less than 10% of the personal baggage and vehicle loads crossing are inspected. This lack of strict monitoring is incentivized for Paraguayan officials as Brazil's protectionist policies make it difficult for most Paraguayans to access most goods that they import, such as machinery and vehicles, which added up to $581.27M and $411.33M in imports in 2024. It is not only officials who become intertwined in the informal market system, but everyday citizens as well. During the U.S. embargo of Cuba, the government enforced strict rationing and trade restrictions that led to widespread shortages in essentials like medicine. Again, the imbalance between high demand and limited supply encouraged informal markets, especially since imports were mostly restricted to citizens who could afford to pay the high shipping fees.

Meeting Demand

This growth of informal markets has only created a reliance on them and affected the viability of economic exports and imports in countries. For countries like Paraguay, whose economy is heavily dependent on agriculture—accounting for 67.7% of total exports in 2022—access to important agricultural tools such as agrochemicals and fertilizers is foundational to economic success for farmers. In 2022, the 3,366 metric tons of agrochemicals that arrived in Paraguay represent 27% of all the country's agrochemical imports last year, according to the National Customs Directorate. Because farmers are dependent on informal markets for a steady stream of agrochemicals, their economic profits, and those of the country, become intertwined with the stability of informal markets, making strict regulation damaging rather than helpful. This informal smuggling is only strengthened by the relationship of MERCOSUR as an economic bloc, as trade between countries like Argentina, Paraguay, and Brazil is maintained by the triborder region between the cities of Foz do Iguaçu (Brazil), Puerto Iguazú (Argentina), and Ciudad del Este (Paraguay). Heightened demand for agrochemicals has also pushed informal

smugglers to more extreme actions, as seizures of agrochemicals have skyrocketed by 549% from 2021 to 2022. Although entities like *maquiladoras,* which have reduced taxes and economic regulation, are created by governments to support the agricultural business, it is not enough to meet demand and economic profit, leading many border populations and informal smugglers to see their actions as not a crime but a necessity to secure their safety. Focusing specifically on black market products, Figure 2 displays the amount of agrochemicals in kilograms seized by the Brazilian police, displaying the impact of these chemicals near the TBA.

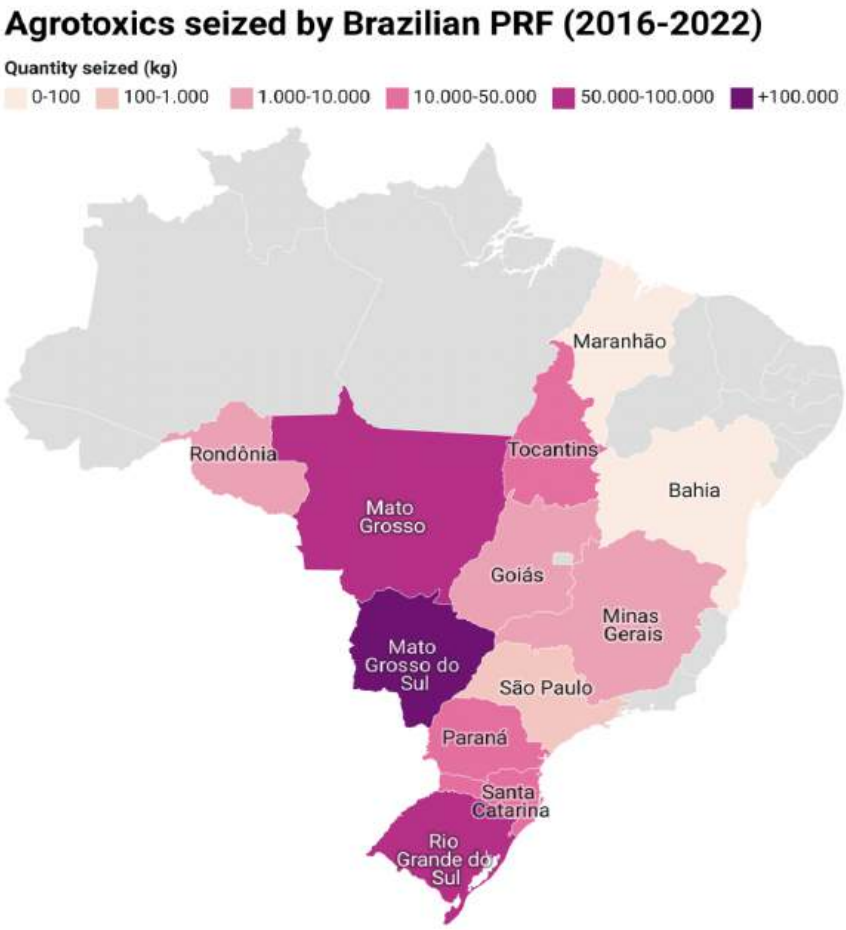


Figure 2. Agrotoxics seized by Brazilian PRF (2016 - 2022)
Source: PRF/Juan Ortiz.

Taxation and Redistribution

Supplying such a large portion of untaxed goods, it is clear that the primary function of the informal economy is to avoid taxes. Whether that be for consumers purchasing goods or employers hiring workers, direct taxes cannot be collected because economic activities are not recorded. This has two primary effects. First, it reduces government revenues. And second, it redistributes wealth across regions. These outcomes are both positive and negative, and create a cycle of taxation and growth of the informal market.

While informal economies might represent a lifeline for impoverished communities, to governments, they only represent lost revenue. Informal economic activities can detrimentally affect government revenue by reducing the taxable base, which increases tax evasion and profit losses. For example, in Sub-Saharan African (SSA) countries, regression results confirm that the shadow economy (− 0.229) significantly reduces tax revenue. Combined with other factors, SSA countries are 5% below the GDP tax collection level that is determined as sustainable. Lower GDP countries are already forced to have higher taxes to attempt to sustain themselves, except onto firms, as they are often the main source of profit for governments. But the existence of shadow economies lowers the taxable base, creating a fiscal deficit, and forces governments to increase taxes and regulations further to compensate. This creates a continuous hindrance to economic activity that applies to both businesses and consumers. These developing countries are typically filled with more informal markets. Additionally, without access to taxes, governments aren't able to benefit citizens through infrastructure. Thus, it creates a cycle where the countries with economies dominated by informal markets are unable to grow due to a lack of taxes, and can't get rid of informal markets.

Labor and Survival

Harsh legal regulations in the formal economy popularize informal labor as the main source of employment. In countries like Paraguay, limited educational opportunities and job employment restrictions prevent workers who would otherwise want to work in the formal economy, so most employment is made up of informal workers, who are made up of street vendors, according to lobbyist and politician Sebestian Acha. Opportunities for formal work are usually less accessible to low-income groups, but informal opportunities often prevent employees from achieving formal work in the future, placing them in a cycle of unreliable, informal work that does not provide enough income. Figure 3 shows how informal labor is a significant portion of employment within Paraguay. While there has been a slight decline from 74% in 2012 to nearly 70% in 2019, the rate remains notably higher than the global average, meaning that citizens are utilizing informal labor over formal labor.

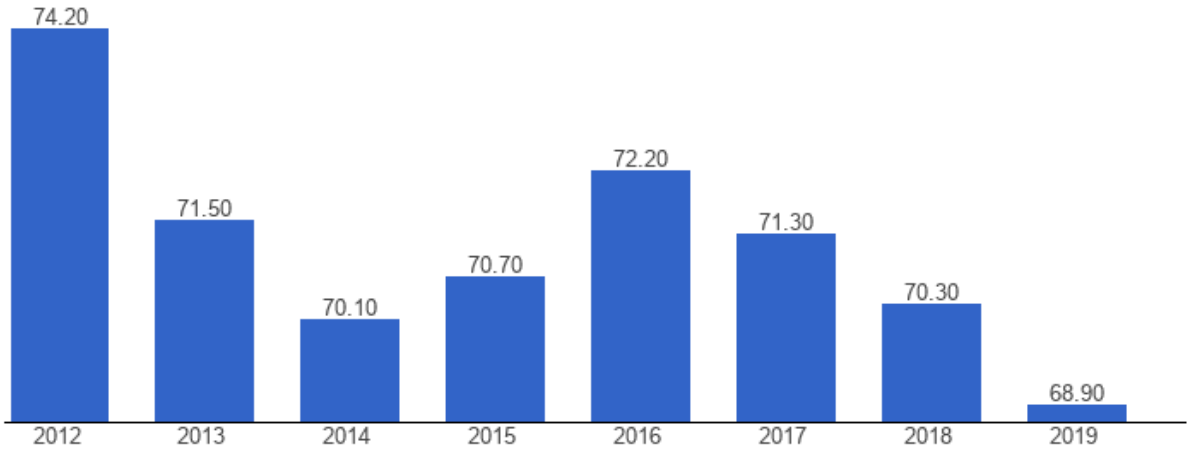


Figure 3: Informal employment, percent of total employment
Source: theglobaleconomy.com

Fragile States and Dependency

The rise of informal markets is often a response to unstable political environments or states. For example, 64.2% of Paraguay's non-agricultural workers are informally employed, reflecting how shifts between market-friendly and heavily regulated policies instituted by the political leadership create uncertainty about legality. However, harshly regulated informal work is impossible for governments as well because of how informal work brings in 34% of the revenue of Latin American countries. With 50% of workers in Latin America being employed in the informal market, the structure of socialized planned economies, which includes policies like heavy tax burdens and regulated minimum wages, incentivizes employment in the informal market to avoid these burdens that limit individuals' ability to support themselves and their families, which are often correlated with poverty levels.

Limitations

Some limitations to this research are the geographical and temporal scope of the study. This paper focuses on how informal markets affect governments, policies, and citizens within the modern era, but not on how informal markets may affect these categories in the future or their evolution from the past. Additionally, this paper primarily focuses on how informal markets have shaped the situation in South America as a whole rather than country to country. Although informal markets are globally intertwined due to the supply chain, different policies in different regions shape the types of informal markets that form and how they will be regulated by the government.

Conclusion

Although Black Markets hold a negative connotation to many, they are essential for the world's economy and stability. They fill a need for adaptability that formal markets cannot replicate, allowing citizens to purchase goods without incurring additional costs imposed by governments through taxation. Additionally, informal markets employ millions of workers supporting families as well as providing spikes in demand, especially for protectionist economies. Instead of being viewed as criminal, governments should take informal markets as indicators of what formal markets lack, such as the flow of money, especially in regions that lack formal monetary infrastructure. Thus, informal economies will continue to exist and fill gaps in formal economies, and developing countries struggling with informal economies should invest in high-level manufacturing and technological independence to fill economic gaps on legal terms.

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Impact of ADHD on Adolescent Student Athlete Mental Well-Being, Athletic Performance, and Injury Risk By Daniel Kim

Abstract

Attention-Deficit/Hyperactivity Disorder (ADHD) is a prevalent neurodevelopmental disorder affecting 6-9% of youth in the United States. However, limited research has examined the impact on professional athletic performance. Current literature was gathered on ADHD in athletes, focusing on ADHD and its influence on cognitive function, performance, and injury risk, while also examining how traits like hyperfocus can serve as athletic assets in specific sports and environments. The objective of this paper was to analyze how ADHD affects mental and physical aspects of performance, emphasizing the role of stimulant medications and different environments in turning ADHD symptoms into strengths for athletic success. Data revealed that due to ADHD characteristics like impulsivity, athletes with ADHD are more prone to injuries, such as fractures and concussions. Therefore, interventions like stimulant use, exercise, and proper techniques from parents and coaches can improve performance and attention. The findings reveal that since ADHD occurs differently in each individual, specialized treatment plans integrating tailored environmental and behavioral strategies with the correct interventions are essential for safe performance. In the future, it's important that research must prioritize athlete safety and skill development while addressing allowed stimulant use appropriately to promote a fair environment for all.

1. Introduction

Many studies have examined the prevalence and impact of Attention-Deficit/Hyperactivity Disorder (ADHD) on teenage/adolescent athletes, yet little research has focused on professional athletes (Hans et al., 2019; Pujalte et al., 2017; Gupta & Kar, 2009). Although ADHD is often framed in terms of academic and behavioral challenges, many individuals explain ADHD can be used as a strength once they find activities that fit them. This pattern is seen in the lives of several professional athletes, both current and former, who have publicly shared their ADHD diagnoses, such as gymnast Simon Biles, sprinters Noah Lyles and Justin Gatlin, swimmer Michael Phelps, and football player Zach Wilson (Pesantez, 2025).

Their reflections highlight that ADHD traits can become strengths in the correct environment. For instance, Zach Wilson has described that although inattention made schoolwork difficult, he found it considerably easy to maintain his focus when playing football. Similarly, Noah Lyles explained that ADHD made learning in the classroom hard, but later recognized that having the skills to use its symptoms for good played a positive role in his athletic performance. Michael Phelps's early experiences with ADHD provides another example of this theme. During his childhood, he struggled with inattention and restlessness, not able to sit through a class without fidgeting (Verma & Bagchi, 2020). However, he could swim for hours in the pool, and through the help of his mother's guidance, Phelps was able to turn his energy into focus during swim meets. Together, these athletes demonstrate how ADHD can impact athletes

in different ways. When paired with the right environment and customized strategies, ADHD symptoms can become strengths for athletes in their respective sports.

1.1 ADHD

ADHD is one of the most prevalent neurodevelopmental disorders, with an estimated range of 2.5% to 7.2% children diagnosed worldwide (Han et al., 2019). ADHD is characterized by excessive hyperactivity, impulsivity, mood swings, and difficulty maintaining attention. These symptoms interfere with daily functioning, impaired relationships, low self-esteem, and risky behavior in organized activities, such as sports (Feldkamp et al., 2023). Although deficits in neuropsychological testing have been observed in people with ADHD, no single profile is diagnostic for ADHD.

ADHD as a neurobehavioral condition is not fully accepted, as there is a lack of evidence for a unique cause. Research suggests a heritable factor, but it is difficult to separate genetic influences from environmental and parenting factors (Furman, 2005). Additional studies have linked ADHD to rare genetic variants as well as prematurity, lead exposure, and childhood adversity; however, none of these factors alone proves the cause, since genetic risks tend to be small and non-specific (Thapar et al., 2013). Although the impact of ADHD on motor functioning has not been extensively studied, there is some evidence that children with ADHD may experience gross and fine motor deficits, which can affect performance in physical activities (Pujalte et al., 2017). Overall, the combination of genetic, environmental, and developmental factors highlights the need for individualized approaches to understanding and treating ADHD.

1.2 ADHD Stimulant Medications

Stimulants are the most commonly prescribed medications for ADHD, working by increasing levels of the neurotransmitters dopamine and norepinephrine to improve attention, impulse control, and hyperactivity. They are considered first-line treatments for ADHD, with an effectiveness rate of 70% (Stevens & Stern, 2013). These medications are available in both short- and long-acting forms, which are best suited for individual patient needs. Common side effects include decreased appetite, weight loss, and difficulty sleeping. When initiating stimulant treatment, patients should be closely monitored by their healthcare provider to find the optimal medication and dose.

1.3 ADHD Prevalence in Sports

Research shows that ADHD prevalence in athletes varies widely, ranging from 4.2% to 15.5% depending on the study (Poysophon & Rao, 2018; Cage et al., 2023; Han et al., 2019; Pujalte et al., 2017). Studies also report greater rates among male athletes compared to females, highlighting a gender discrepancy (Poysophon & Rao, 2018). Overall, evidence suggests that ADHD may be slightly more common among athletes than in the general population (Han et al., 2019).

1.4 Purpose

This research examines how ADHD affects two main ideas: The risks and challenges associated with ADHD traits such as potential risk of injuries and cognitive performance deficits, and how symptoms from ADHD can be incorporated as athletic strengths when supported by the correct environment, coaching, and medical intervention. Overall, this paper explores the critical balance between well documented challenges of ADHD and the potential for elite performance and by examining this mind-body connection, this paper seeks to contribute to more individualized and effective approaches to athletic training that emphasize the diversity of traits of athletes with ADHD.

2. ADHD in Athletes

2.1 Diagnosis

Diagnosing and understanding ADHD in athletes presents unique considerations within youth, collegiate, and elite sports. Athletes with ADHD in professional and collegiate sports are a diverse group, as each individual may experience varying symptoms yet still meet the diagnostic criteria as outlined in the Diagnostic and Statistical Manual of Mental Disorders (DSM-5). Individuals with ADHD have a variety of symptoms of inattention and hyperactivity (American Psychiatric Association, 2022). ADHD may be more common in elite athletes than in the general population, since children with ADHD may be drawn to sports due to the rewarding and stimulating effects of physical activity (Han et al., 2019). Although males are diagnosed roughly twice as often as females, ADHD is prevalent across a variety of sports, ranging from youth to collegiate and professional players (Pujalte et al., 2017). Understanding these diagnostic differences is essential for predicting risk patterns and identifying where ADHD traits may also create performance benefits.

3. Learning, Performing, and Cognitive Function in Athletes with ADHD

3.1 Cognitive Processing

Athletes with ADHD face specific challenges in learning and performing sports skills, often exhibiting distinct cognitive and processing characteristics. These challenges can significantly impact their ability to transfer acquired skills from practice to high-pressure competitive environments. Novice and intermediate performers may initially master a skill, but often regress under pressure, returning to a lower performance level (Christensen, 2015). Children with ADHD experience a more severe decline in performance under pressure because of their cognitive and processing characteristics (Gupta & Kar, 2009). Research suggests athletes struggle with hyperactivity, attention deficit, inability to maintain long-term concentration, and high impulsivity, which could interfere with optimal motor learning (Pashabadi et al., 2021). Under stressful and pressure conditions, these traits prevent effective information processing, causing performance to regress even after improvements during practice. Athletes with ADHD

may also be over-responsive to pressure conditions, which could lead to extreme responses (Pashabadi et al., 2021).

3.2 Motor Performance

While cognitive characteristics play a major role in performance, motor skill and performance outcomes also distinguish athletes with ADHD from their peers. Neurocognitive testing reveals that athletes with ADHD often score lower on many assessments and tests than peers without ADHD. These tests include the Immediate Post-Concussion Assessment and Cognitive Test (ImPACT), Hopkins Verbal Learning Test, Controlled Oral Word Association Test, Trails Test, Stroop Test, and Symbol Digit Test (Poysophon & Rao, 2018). These results not only reflect deficits in cognitive function but can also suggest differences in motor performance.

Athletes with ADHD also reported more fatigue, worse concentration, and were likely to score worse on the postconcussion symptom inventory. Higher scores on the Post-Concussion Symptom Scale, as well as the presence of concussion-like symptoms in nonconcussed athletes further indicates a significant disadvantage in a multitude of factors, which could play a role in the motor skills and performance of an athlete.

3.3 Skill Development Advantages

Although athletes with ADHD experience difficulties in cognitive processing and motor performance, symptoms of ADHD such as preservation or hyperfocus can give certain elite athletes a slight edge in certain sport environments. ADHD is more common in elite athletes than in the general population, possibly because children with ADHD are drawn to sports due to the positive reinforcement that sports provide. Exercise has been shown to improve behavioral symptoms and cognitive functioning in individuals with ADHD, with acute exercise of moderate intensity for at least 30 minutes producing measurable gains in executive functions like inhibition, planning, and information processing (Cummings et al., 2020). One potential performance-related strength observed in some athletes with ADHD is hyperfocus, where intense focus on a task leads to blocking out distractions. When used in the context of sports, hyperfocus can be used as an asset, potentially enhancing high-level performance (Ekman et al., 2021). Additionally, ADHD can benefit athletes in activities requiring reactive decision-making and quick movements (Cummings et al., 2020). However, at the same time, athletes can exhibit risk-taking behavior that may increase susceptibility to risk of a sports-related injury. Sports offer physical activity, motivation, stimulation, and reward, all of which have been shown to have a positive influence on ADHD symptoms. Therefore, this highlights an important point: ADHD does not act as either a hindrance or enhancement to performance. Instead, its impact completely depends on the environment and the athlete's ability to use ADHD's traits productively. When matched correctly, these ADHD traits can shift from potential drawbacks to performance enhancers.

4. Stimulant Medications and Sport Performance

4.1 Medications Influencing Performance

The use of medications to treat ADHD is one of the most common practices, and stimulant medications can significantly influence factors related to athletic performance (Berezanskaya et al., 2022). However, while stimulants may enhance individual function, many are prohibited in competitive sports due to their potential performance-enhancing effects. Stimulant medications like methylphenidate and amphetamine have been shown to improve athletic metrics. Research has shown that when these medications are used, there is an increase in acceleration, knee extension strength, time to exhaustion, mean handgrip force, and power output in cycling trials. Additionally, these medications have had notable improvements on attention and overall cognitive performance. (Advokat & Scheithauer, 2013). For instance, individuals may find it easier to concentrate on complex tasks, resist distractions, or smoothly transition between different activities. In this sense, medication may help athletes with ADHD compete with athletes without ADHD by addressing leveling out functional disadvantages related to athletic performance.

However, the same advantages that medications provide which support athletic performance are the primary reason why many stimulant medications are banned (Berezanskaya et al., 2022). Additionally, not all stimulant medications prove to have positive outcomes; for example, bupropion showed mixed results, and stimulant medications also commonly create side effects such as raised heart rate, increased core temperature, decreased appetite, and sleep difficulties. Together, ADHD medication with athletes can improve physical capabilities related to sports, giving them an advantage to those who don't take any. At the same time, restrictions and possible adverse effects reinforce the idea that stimulant use introduces both benefits and risks of athletic success.

4.2 Decreasing ADHD Symptom Presentation With Exercise

Studies have shown increased performance in swimming, cycling, throwing events, and aesthetic/weight-class sports due to improved fine motor coordination, weight loss, enhanced fatigue perception, and attention. Exercise improves attention, executive function, and emotional regulation in people with ADHD, and it also enhances mood, motor skills, and overall cognitive development, leading to better coordination, learning and daily functioning (Sun et al., 2022). Exercise could also increase attention span, stimulus selection speed, and improve inhibition of unrelated stimuli. The benefits of exercise show how athletes with ADHD could improve their symptoms not only by using stimulants but also through exercise (Mickleborough & Sogard, 2022). However, high-intensity exercise may increase central fatigue and reduce performance in athletes with ADHD compared to non-ADHD athletes, potentially impairing skill execution. These findings demonstrate how exercise can mitigate risks and where it may create new ones.

Counselor ratings indicated that sports training improved skills, sportsmanship, effort, enjoyment, and reduced frustration in children with ADHD (Altszuler et al., 2019). Sports training significantly affected children's game awareness, where children in the training

condition answered twice as many attention questions correctly as did children in the recreation condition. While medication can improve sports skills, sports training also plays a significant role in improving these skills for children with ADHD, as evidenced by enhanced game awareness and reduced frustration. Therefore, an approach combining appropriate training strategies with medication can optimize athletic development in children with ADHD. This approach, which considers both pharmacological and behavioral interventions, offers a thorough plan for fostering athletic success and well-being in individuals with ADHD, ultimately contributing to a more informed understanding of the complex interplay between ADHD and sports (Kleeren et al., 2023).

5. Injuries in Athletes with ADHD

5.1 Musculoskeletal Injuries

In general, there is a significantly higher risk of injuries in children and adults with ADHD compared to those without ADHD (Goikoetxea et al., 2018). Overall, the rate of injuries was 1.55 times higher for individuals with ADHD (Merill et al., 2009). Severe injuries, such as those to the skull, neck, and trunk, and nerves, occur more often in people with ADHD. The most common injuries involved wounds of the head, neck, and trunk, or sprains and strains of joints. Intracranial injuries, or injuries within the skull, were most strongly associated with ADHD, which could help explain why concussions are particularly common in this population. Baseball athletes with ADHD experience higher rates of injuries than athletes without ADHD. Specifically, baseball players with ADHD are more likely to suffer ankle sprains due to a mix of quick acceleration, rotational force, and sliding (Feldkamp, 2023). Baseball players with ADHD face more injuries of the arm, upper limb fractures, lower limb fractures, head and neck injuries, upper and lower limb injuries, shoulder, knee, and ankle sprains, and rotator cuff injuries. This shows that athletes with ADHD are at a clear disadvantage in the likelihood of getting injured. Thorax, abdomen, and pelvis injuries are also more common in baseball athletes with ADHD than in athletes without ADHD.

5.1.1 Fractures

Individuals with ADHD have an increased risk of fractures compared to the general population, with one study showing a bone fracture rate 1.32 times higher in individuals with ADHD than those without ADHD (Zhang & Yan, 2021). Studies also suggest that stimulant medications play a role in injury risk, and while there was no major difference, individuals with ADHD who received stimulant medications experienced fracture rates lower than untreated individuals.

Fracture risk patterns also vary depending on gender and age. The increased risk of fractures in children with ADHD was most common for upper and lower limb fractures, with less noticeable risk for skull, neck, rib, and spine injuries. The incidence of fractures among girls with ADHD was 40% higher than that among girls without ADHD, compared to 30% than that among boys with and without ADHD. While there is an increased rate of injury related to ADHD, the

association between bone fractures and ADHD is uncertain, since many factors contribute to the higher injury risk. These ADHD-related injuries underscore the importance of proper care in athletic environments regardless.

5.2 Developmental Coordination Disorder

Children with Developmental Coordination Disorder (DCD) often experience higher rates of being overweight, reduced physical activity, and poor motor coordination. When DCD combines with behavioral characteristics observed in children with ADHD, these challenges can intensify and influence increased fracture risk. Research by Chou et al. (2014) highlights how the combined behavioral and motor characteristics of these conditions contribute to greater vulnerability to fractures and other sports-related injuries. For athletes, this means that difficulties in motor skill development, limited activity levels, and behavioral impairment interact in complex ways that elevate risk, emphasizing the needs for correct training and supervision within athletic environments.

5.3 Concussion

Regarding concussion, the NCAA data shows that more than 50% of athletes with ADHD reported at least one earlier concussion, compared to only 14% of athletes without ADHD (Feldkamp, 2023). Nelson et al. found that athletes with ADHD and Learning Disabilities (LD) were more prone to repeated injury, showing 2 to almost 3 times the prevalence of three or more prior concussions compared to non ADHD athletes (Nelson et al., 2016). Additionally, individuals with ADHD had higher levels of concussion-like symptoms and showed poorer performance on baseline cognitive tests. Athletes who had both ADHD and multiple concussions reported the highest symptom levels overall.

ADHD is associated with double the odds of an individual having a prior concussion before age 11 (Cook et al., 2022). While ADHD was associated with a greater history of concussion, a study by Cook et al. showed that the duration of concussion and the longest recovery time were the same for both groups, with a median of 21 days. Additionally, adolescents with ADHD returned to both school and sports just as quickly as those without ADHD (Cook et al., 2021).

5.3.1 Challenges in Baseline Concussion Analyses

However, there are challenges in diagnosis due to overlapping symptoms. In a study by Cook et al., 28.8% of boys and 47.1% of girls reported symptoms that met the criteria for post-concussional syndrome classification, even though they were uninjured athletes and were free of any recent concussions (Cook et al., 2020). This creates a challenge because many pediatric primary care providers only clear athletes when they are completely asymptomatic, which is not often in youth with ADHD. Additionally, treating concussions in patients with ADHD is difficult because they are nonspecific and not unique to concussions. Therefore, while ADHD is not proven to slow down concussion recovery, it necessitates an individualized approach to determine whether someone with ADHD can safely return to baseline.

6. ADHD and Mental Well-Being Post-Injury

6.1 Post-Concussion

ADHD and Learning Disability was independently associated with worse outcomes following sport-related concussion (SRC) in young athletes (Pullen et al., 2023). These included a decrease in confidence and lower likelihood of achieving symptom resolution. Additionally, athletes had more than three times higher odds of changing sports behavior to a safer style of play or even retiring from the sport. These findings suggest that injuries may augment pre-existing vulnerabilities in attention and emotional regulation, influencing how athletes with ADHD respond to their recovery processes.

6.2 Sports Engagement Supports Mental Well-Being for Athletes with ADHD

However, while ADHD may worsen post-injury difficulties, engaging in sports can have a protective effect on overall functioning. Ekman Et al. (2021) compared student athlete scores using the Adult Self-Report Scale (ASRS) during school and sport activities. The study demonstrated that athletes with ADHD had higher ADHD symptom presentations in school environments, aligning with attentional difficulties in class, yet showed reduced symptoms while participating in sports. This suggests that ADHD symptom expression is environment-dependent and organized physical activity may act as a natural remedy to enhance overall health. Therefore, while injury may introduce new challenges, continued sport participation can support better focus and motivation.

7. Coach and Parent Support for Athletes with ADHD

Individuals with ADHD may find it hard to stay focused or follow instructions. To provide the best learning environment, educators should have clear classroom rules, routines, and procedures (DuPaul & Stoner, 2014). Similarly, coaches can establish clear training rules, routines, and procedures during training sessions (Vargas et al., 2012). Coaches should also create low-distraction environments to maximize attention on specific tasks (Campbell & Stonebridge, 2021). Strategies to create these environments include using only necessary equipment, maintaining eye contact, and ensuring close distance towards athletes. Possessing the ability to implement these techniques to real practice can allow athletes with ADHD to thrive.

In addition to coaches, parents can play an integral role in positively supporting their children. A Parental Friendship Coaching (PFC) intervention suggested that parents should create social opportunities for their child and provide constructive feedback on their social interactions (Tarver et al., 2014). As previously explained above, individuals have different levels of health indicators for when they are able to return to play after a concussion. Therefore, instead of relying on a single, generic parenting program, the most effective approach to adhering to needs of children with ADHD may be an approach where clinicians and parents should take parts from multiple behavioral interventions to create an individualized treatment plan.

8. Conclusion

The findings of this paper highlight the relationship between ADHD and athletic performance, showing that ADHD cannot be characterized solely as an obstacle to sports. Although traits such as hyperactivity, impulsivity, and mood swings can contribute to increased risks of fractures, concussion, and cognitive performance deficits, these same characteristics can also create increased motivation and stimulation in athletic contexts. Research highlights that treatments like stimulant medication and behavioral strategies can help improve cognitive function and motor skill performance. However, athletes with ADHD are more prone to injuries, especially fractures and concussion-related injuries. This plays an important role in monitoring and adjusting based on individualized symptoms. Parents and coaches are also extremely integral in the management of youth with ADHD in sports. Coaches can help athletes by creating effective environments that reduce distraction and are clearly structured practices. Parents can also support their children by finding the right clinician to effectively treat their child's needs and symptoms. By doing this, parents and coaches can ensure that athletes with ADHD can perform fully. Ultimately, ADHD should be known not as a disadvantage but as a multitude of traits that can contribute uniquely to each athlete's development. With proper understanding and informed training practices of how characteristics interact with physical performance, ADHD can positively contribute to athletic achievement. Future research should continue to improve strategies that support athlete performance and prevent injury, allowing effective support and an equal playing field for athletes with ADHD.

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Agro-Bharat: Development of a Product With Fertilizer Function Formulated From Indian Neem Properties by Monica Grenadier Macaesa, Laura Franchini Placidoa, Juliana Izidoroa

Abstract

Nature-Based Solutions (NBS) focus on solving environmental problems. Among these problems, the search for alternative fertilizers that do not pollute the environment stands out. This study sought to select and apply natural compounds that could reduce or replace the use of commercially available agribusiness products. The plant commonly known as Indian Neem (*Azadirachta indica*) has been shown to be a good potential fertilizer candidate. Thus, the objective of this study was to develop a new product capable of providing the nutrients necessary for bell pepper growth and development, as well as acting as an agricultural pesticide. To this end, the methodology was divided into 5 stages: extraction of the respective Neem compounds; preparation of the formulations; analysis of the formulation; application of the product to bell pepper seedlings and collection and statistical analysis of the data. The active ingredients of neem were extracted and applied to the plants. Analysis of the data has shown that the growth of the group treated with Neem was significantly more robust than that of the control group. The plants treated with Neem have grown faster than those in the control group. Thin-layer chromatography (TLC), performed in a partner laboratory, showed that the neem extract has a greater number of compounds and is therefore more complex than common fertilizers. Therefore, it can be concluded that this study could contribute to the development of a new, more sustainable product.

Keywords: Fertilizers; Crop Protection Products; Indian Neem; Bell Pepper; Agricultural Engineering.

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1. INTRODUCTION

Brazil has plentiful potential for agribusiness due to its extensive territorial area, soil quality, climatic conditions, among other reasons. Commodities generate significant revenues due to their exports (1). The planting of peppers, as well as other crops, involves the use of chemical compounds with potential risks to the environment.

1.1 Fertilizers

Fertilizers provide key nutrients and promote plant growth. They contain both macronutrients and micronutrients essential for plant development. Commonly marketed fertilizers, such as NPK, supply crucial macronutrients (N, P, K, Ca, Mg, and S). Nitrogen, for instance, is not directly assimilated by plants. While the nitrogen cycle naturally synthesizes amine and amide groups through ammonia, the Haber-Bosch process (2) enables artificial nitrogen production, considerably boosting agricultural productivity. However, this improvement has also introduced new risks, such as leaching, CO2 emissions, and ammonia volatilization in the soil.

Micronutrients such as B, Zn, Cu, Fe, Mo, Cl, and Mn influence plant growth. In this sense, the yield of organic cultivation - that is, without the addition of industrial compounds - can achieve the same performance of plantations in which NPK is already applied (3). In addition, the recent Micro Carbon Technology MCT® methodology (4), which can boost the

encapsulation of organic matter, has the potential to revolutionize agriculture. By employing reticles made of polymers and colloids, encapsulated nutrients can remain in the medium and mitigate photodegradation by heat, ion oxidation, and UV rays (5).

Nanofertilizers contain materials rich in humic substances added to the soil, which can infiltrate the earth, supplementing the metabolism of plants (6). In conclusion, nature-based solutions are relevant in Agricultural Sciences because of their economic and environmental implications.

1.2 Nature-based solutions and alternative agricultural methods

All the factors already mentioned, among others, have led to the growing consumption of organic products and the investment in producing new biotechnologies to support agricultural development (7). An example of biotechnological practice is the use of genetically modified seeds that can naturally resist attacks because they have in their composition the addition of a substance considered toxic to predators.

Other alternatives that may be helpful in agricultural production are so-called nature-based solutions, also known as NBS. This term has been used internationally and denotes the conservation, restoration, and management of ecosystems sustainably. It encompasses ways of understanding issues related to the ecological protection of the natural environment (8). NBS can encompass various environmental initiatives and forms of ecosystem-based climate change adaptation, ecological restoration, and protection of conservation areas. These actions can occur in different environments and in diverse ways (8). In this context, medicinal plants, their seeds, leaves, etc., can function as raw materials for active ingredient extraction. Also, it is an alternative to circumvent the contamination problem related to synthetic compounds used as pesticides and fertilizers. Some plant types may contain active ingredients capable of performing the function of a fertilizer, as is the case of the Indian Neem, or even have substances capable of acting as pesticides, as some plant oils (3). The following section describes Neem characteristics.

1.3 Indian Neem

Indian Neem is an Asian plant known and utilized in India for over two thousand years. It has a wide range of applications, including fertilizer, medicine, and in the production of cosmetics, among many others. Currently, this plant's cultivation - also known as Amargosa - is central in countries of Central America, Africa, the United States, and Australia (9). Figure 01 shows the plant's appearance.



Figure 01 - Example of the Indian Neem plant, with its evident fruits and leaves.
Neem's scientific name is *Azadirachta indica*. It is a large tree of the order Sapindales and family Meliaceae (9). By isolating and obtaining a derivative of the tree, Azadirachtin, it is possible to explore its unique properties. This compound is non-flammable, non-corrosive, and formulated as an emulsifiable concentrate. Additionally, it acts systemically without posing significant environmental risks.

Azadirachtin is the main compound found in *Azadirachta indica* extracts. However, azadirachtin goes through the bio-elimination process, degrading when exposed to light. After 24 hours, although there are still remnants of the compound, they solely affect invertebrates. Thus, over time, before being consumed by humans, azadirachtin undergoes photodegradation and is diluted in water, being found at a concentration of 12 μg/mL, lower than the maximum concentration recommended by the Brazilian Health Regulatory Agency (ANVISA) 2016 technical standard. The ingested dose only becomes harmful above 1600 mg/kg/day (10). Neem was introduced in Brazil approximately 30 years ago. According to LIMA (11), Neem's uses range from oils and products derived from its leaves to the tree's bark. Planting Neem requires careful steps and precautions to ensure the supply of nutrients and satisfactory ecological maintenance. (9) (12) Furthermore, the plant also has medicinal effects, presenting hypolipidemic, antifertility, microbicides, antidiabetic, hepatoprotective, antipyretic, insecticide, nematicides, anti-ulcers, antioxidants, neuroprotective, cardioprotective, and antileishmanial functions (13).

Significantly, with the plurality of possible effects of Neem, the plant undergoes purity tests to ensure that its dosage provides the maximum benefits. In addition to not posing a health threat, the product presents low toxicity risk and can be inhaled by humans. In addition, neem is safe in contact with the skin since it has dermatological properties. It can also be ingested in the form of herbal teas and is present in the composition of common hygiene products (14). Other compounds present in the plant are Nimbin, Nimbidin, Salanine, and Quercetin. Accordingly, these components are associated with repellent properties and may be involved in combating diseases and infestations.

Figure 02 shows two examples of molecules in Neem, Salanine, and Nimbin, present mainly in its leaves (15). In addition, the presence of, among other particles, organic contents that affect the properties of Neem stands out: carboxylic acids such as glutamic acid, aspartic acid, margaric acid, and several other long-chain fatty acids. Neem also contains the amino acids alanine and tyrosine, which contribute to the functional structuring that enables their oxidation-reduction with their oxygen atoms in the middle of their chains - heteroatoms - as indicated by Figure 02 (16).

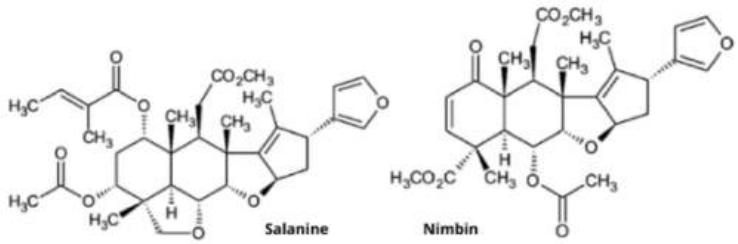


Figure 02 - Chemical formula of the main active principles of Indian neem, being represented by limonoids.

In addition to the compounds mentioned above, there are limonoids - limonene derivatives characterized by the presence of several organic aromatic rings - and other triterpenes in Neem, which can act as an insecticide (17). This action is also due to the presence of Nimbin, a limonoid that potentializes adverse effects on pests - influencing their growth and reproduction and causing muscle weakening and dysphagia (18), thereby increasing agricultural productivity. Neem also has secondary metabolites that can be identified using high-performance liquid chromatography (HPLC) and gas chromatography (GC) to locate the properties of its extracts and subsequently isolate and concentrate compounds. Mass spectrometry and nuclear magnetic resonance (NMR) are part of the analysis to identify the active components (19).These compounds have the potential to function as beneficial health products, acting as antioxidants through their high total content of phenolic compounds and flavonoids - which are polyphenolic compounds with two aromatic rings linked to three carbons in a chain. Figure 03 represents the general structure of flavonoids that make up the plant, in which the organic formula could vary depending on the amounts of phytopharmaceuticals involved and the polyphenolic content (18).

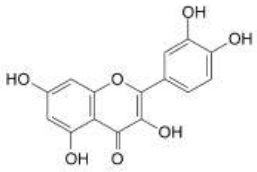


Figure 03 - Organic formula of a flavonoid molecule.

Complementing the aforementioned point, studies in academic literature feature the diversity of compounds in the different derivatives of the neem plant: oil, bark, roots, seeds, leaves, fruits, and flowers. Figure 04 was adapted from BATRA (20). These plant units reveal unique nutritional aspects depending on each branch of the Neem tree. On another level, the species has variable nutritional content across its various plant types, showing the quality of seedlings produced with macronutrient treatment (N, P, K, Ca, Mg, and S) and micronutrients (B, Cu, Fe, Mn, and Zn). (21)

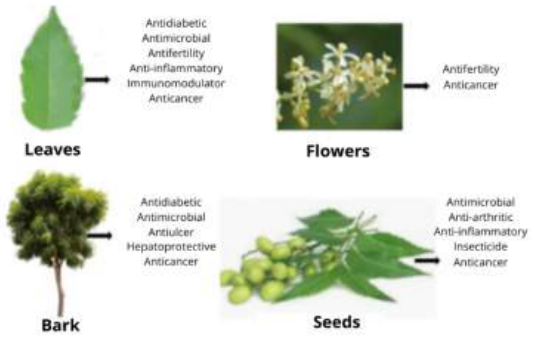


Figure 04 - Organization and systematization of functions of each part of the Neem tree. Referring, respectively, to the purpose of the leaf extract; of the properties of the flowers, of the trunk and its bark, and of the fruit and its seeds.

Neem leaves also contain several organic compounds. Neem retains key nutrients such as nitrogen, phosphorus, potassium, calcium, and magnesium (22), which can act as natural fertilizers. In addition to proving the benefits of using oil from its seed, extracted by cold pressing, the use of neem and its derivatives as fertilizer remains poorly explored. After obtaining the oil from the kernel of the seed, the seed mash – crushed material from the seed shell – can be used as an organic fertilizer. Therefore, its fertilizing potential, even though it is less potent compared to Aloe Vera, for example, is still quite significant, as the leaves of the plant have a high protein content (7.1%), carbohydrates (22.9%), minerals, calcium, phosphorus, vitamin C, carotene and amino acids, such as glutamic acid, tyrosine, alanine, aspartic acid, glutamine, cysteine and also fatty acids, which makes it suitable for the performance of purification processes that isolate active ingredients (17).

Compared to the NPK-based compounds seen previously, the structure of Neem can give rise to nano fertilizers and nano pesticides that are alternative solutions that sustainably enhance its properties in agriculture, which can prevent the leaching of excess nutrients from synthetic compounds and reduce the effects of eutrophication on plant cultures (23). These characteristics indicate the possibility of using Neem in the nascent technology of nanoparticles to perform an agricultural treatment on a microscopic scale. By improving over time, encapsulation techniques have achieved greater efficiency (3).

1.4 Bell pepper production in Brazil

Bell pepper is a species of vegetable crop that has significant value in the cuisine of tropical countries. The development of the plant to its average fruiting state encounters obstacles in nutritional requirements, sensitivity, and agricultural care (24). Its consumption is usually ‘in natura’, which subjects the fragile crop to agrarian losses and the difficulty of following standards related to the exposure to pesticides tolerated by health inspection agencies (25). The main concentration of the crops is in the state of São Paulo, with a more significant number of cultivable hectares compared to the other Brazilian states.

The vegetable has a shorter ripening time compared to other herbaceous plants, providing a favorable financial return for commercialization in Brazil, notably green bell peppers. The color of this vegetable varies as it advances in its state of maturation; thus, it can be green, red, yellow, orange, cream, and purple (26). Among the main species that attack pepper agriculture are aphids, mites, cows, and lizards. In this context, one of the pest species that most affects the crop is *Icerya purchasi*, known as the white aphid. Furthermore, other variations of arthropod pests are considered threats, as they are prone to contaminating plants and their leaves by spreading diseases that reduce productivity (27).

Plants of the genus *Capsicum*, in particular, are known for the burning sensation they produce when consumed, as they contain Capsaicin. In addition to being natural sources of flavonoids (as discussed in Section 1.5), bell peppers can have carotenoids and are an essential source of vitamin C (28) but are not as spicy as peppers since they contain comparatively less Capsaicin. The place where the bell pepper grows can affect its quality and the color of its leaves. The acidity of the culture substrates – or basicity – is a parameter that drives soil volatilization to affect the nutritional composition and the soil's pH (29). The evaluation of bell pepper's quality considers the dose of vitamins that remained in its culture media, in addition to the final biomass obtained, and residues that were absorbed from pesticides by the vegetable, as can be seen in Figure 05, stressing that pepper surpasses the 90% mark of the highest residual of pesticides that are grown in Brazil.

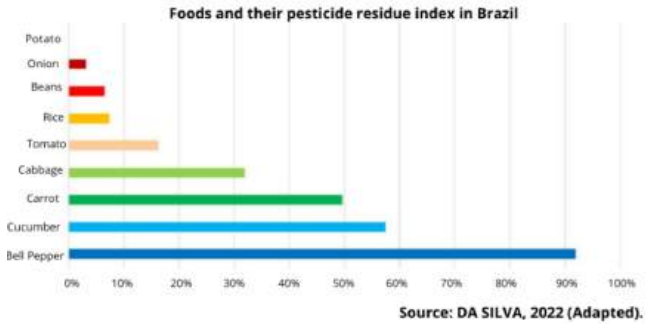


Figure 05 - Foods with the highest residual of pesticides that are grown in Brazil.

Relevant research shows that the pepper grown in Brazil has a concentration of 4.31 kg/ha of pesticides (30). The country has large arable areas compared to other countries that are agricultural exporters. Overall, this number is considered high. Climatic conditions such as humidity and temperature can significantly affect plant development, influencing pest activity to varying extents (31). In turn, these factors contribute to differences in nutritional and mineral dosages in each region of the world and in Brazil, both due to the influence of luminosity, temperature, soil composition, and relative humidity, which can result in a higher planting yield.

2 HYPOTHESIS

According to LIMA (11), Neem, a plant native to Asia, has medicinal and herbal properties, insecticidal effects, and, above all, contains several nutrients, making it a potential fertilizer. Thus, this work aims to develop a formulation of a product that can act as a fertilizer. This product will have Indian Neem as a raw material. We hypothesize that the nutrients present in the Neem extract may assist in the growth and development of a plant. Bell peppers were chosen for cultivation in the present study because they are among the ten most important vegetables in terms of economic value in Brazil and are considered one of the products that consume the most pesticides in the country. (31)

3. MATERIALS AND METHODS

3.1 Extraction of the active ingredients of Neem

The extraction of Indian Neem (whose active ingredient – mainly azadirachtin – is present in the *Azadirachta indica* plant) used an adapted methodology (32). Briefly, the soluble compounds from the leaves were obtained using ethyl alcohol, according to the steps detailed below. The location was the chemistry laboratory of *Colégio Dante Alighieri.* The neem leaves were weighed and dried until a uniform mass was obtained. The brand of neem obtained was *Grupo Rocha Saúde*® (Figure 06).



Figure 06 - Sample of commercial Indian neem used for the extraction of the active ingredients.

In the study, we measured the capsule's mass used in the drying stage. Subsequently, 50g of neem leaves were placed in an oven at 85ºC for 8 hours (Figure 07). This temperature was chosen (33) so that the azadirachtin half-life of 12 hours at 90°C does not affect its concentration. The moisture content present in the leaves was determined by the gravimetric method (measurement of the mass of the material before and after the drying stage). The drying stage was repeated three times until the test material felt dry to the touch. The dried material was placed in a desiccator to prevent moisture reabsorption.



Figure 07 - Experimental steps related to the extraction of the main compounds present in Indian neem, carried out in the chemistry laboratory of Colégio Dante Alighieri.

A volume of 200 mL of PA ethyl alcohol *(Itajá® - 99ºGL)* was added to the dried material. No water was used in the process, as it reduces the solubility of the compounds of interest at the extraction time (32). In this process, 50g of dried leaves were blended with the ethyl alcohol solution for 4 minutes using a *Britania® Diamante* blender, model 800, 900W (Joinville, Brazil). After blending, the suspension underwent filtration, which, in turn, was divided into two stages: first, filtration using the sieve, and second, filtration using laboratory filter paper. The final stage consisted of drying the filtered material at 38ºC using a *FANEM®* oven, model 515 (Guarulhos, Brazil). This temperature prevents the degradation of the compounds. Finally, Figure 08 illustrates the experimental steps of the neem extraction method.



Figure 08 - Extraction steps of Indian Neem carried out in the chemistry laboratory of Colégio Dante Alighieri: a) Sieving of the extract + neem leaves; b) Filtration with filter paper; c)

Appearance of the extract obtained (dark green).

Figure 09 shows the appearance of the neem extract placed in a capsule and submitted to the greenhouse. The solid material obtained after drying had a mass of 0.1977 g (Figure 10).



Figure 09 - Appearance of Indian Neem extract after ethanol



Figure 10 - Weighing of neem extract. Chemistry laboratory of Colégio Dante Alighieri.

3.2 Preparation of formulations

The solid samples of neem (with a mass of 0.1977 g) were diluted in 50 mL of water. Subsequently, the solution containing neem extract had a final volume of 200 mL (after adding water). Solution 2, containing just water, was given to the control group. Table 01 shows a summary of these formulations.

Table 01 - Formulations used in this study from the extracts of Neem and Control.

Solution Number	Formulation composition
1	Neem Extract with Water
2	Water

Source: Authorship.

3.3 Application of products obtained on bell pepper

Initially, the bell pepper (*Capsicum Annuum*) seeds were planted in the biotechnology lab of Colegio Dante Alighieri school and separated into 2 experimental groups – the test and control groups (Figure 11).



Figure 11 - Preparation of the pepper pots at the Laboratory of Biotechnology

The solution application on each bell pepper seedling started in March and extended throughout April and June, adding up to a total of 10 weeks. The next step consisted of performing the following procedures: watering each seedling daily and conducting the application of the two experimental groups with aliquots of 1 mL of the respective products directly on the root of each seedling. Each experimental group contained 2 (two) bell pepper seedlings in its pot. It is worth noting that the seedlings were not watered on Sundays and during a holiday, as the school was closed on those days and the lab is a locked and secure room.

4. RESULTS AND DISCUSSION

4.1 Obtaining the Neem extract

The study's first stage, as mentioned in a previous section, consisted of drying Neem leaves until a uniform mass precipitate was obtained. The results of this step are in Table 02.

Table 02 - Results of the Neem drying stage performed in the chemistry laboratory

Drying stage	Capsule Mass	Weight before drying	Weight after drying
1	302.46 g	50.0 g	42.59 g
2	302.46 g	42.59 g	42.57 g
3	302.46 g	42.57 g	42.36 g

Source: Authorship.

The mass loss of neem leaves can be between 20% to 75% (34). In this study, the total mass loss was 15.28%, lower than expected.

The Neem solution contains a volume of 190 mL, which will be applied later in the bell peppers. The next session will detail the experimental groups.

4.2 Planning of experimental groups

The names of the experimental groups assembled, the composition of the test and control dosages applied, and their identification for this study are summarized in Table 03.

Table 03 - Experimental groups planned for the experiment to evaluate Neem and Control extracts in pepper seedlings.

Experimental Groups	**Composition**	**Acronym**
Control Group	Water	COG
Nim Group	Neem dissolved in water	NGR

Source: Authorship.

The data-gathering process occurred weekly, according to pre-established parameter plant height.

4.3 Analysis of the formulation

4.3.1 Thin layer chromatography

The Neem extract obtained in the laboratory was evaluated in a partner laboratory, with the assistance of researchers in the field of natural products, Dr. Anelize Bauermeister and Dr. Massuo Jorge Kato, from the Institute of Chemistry at the University of São Paulo (IQ-USP). For this evaluation, methanol was used as a solvent in the experimental procedures, instead of ethyl alcohol. Since methanol has a high toxicity, it cannot be used in a high-school setting. Methanol extracts present some differences compared to ethanol. Methanol evaporates faster and is slightly more polar than ethanol. Methanol may be better for the extraction of highly polar compounds (such as flavonoids, phenolics, and glycosides). Ethanol can dissolve moderately polar to nonpolar constituents (such as terpenoids, alkaloids, and aglycones). Methanol extracts often have higher antioxidant activity. However, ethanol's performance is also effective, usually being close to that of methanol, albeit usually lower in terms of phenolic and flavonoid yield. (34) After grinding the plants and adding methanol, the sample contained in the Erlenmeyer flask was subjected to ultrasound equipment to homogenize the sample more efficiently. Finally, the extract was subjected to thin-layer chromatography (TLC) analysis to verify the plurality of compounds present in the plant extract sample. The TLC analysis used a silica gel sample as the stationary phase, which is a porous material with high capillarity, capable of attracting the mobile phase (35). Thus, the stationary phase (SiO_2) can attract the compounds present in the extract, according to the solvent used, which was methanol, mixed in a ratio of 1:2 with ethyl acetate. Each silica plate was placed in a dark chamber with a power of 110V, containing lamps that emit radiation at 2 different wavelengths, 254nm and 365 nm.

Figure 12 shows the results of the thin layer chromatography analysis of the extracts using methanol solvent placed in a dark chamber with different wavelengths. As indicated by the plates photographed at 254 nm (left) and 365 nm (right), neem extracts included the presence of

flavonoids, evidenced by a pink glow under UV light. According to Souza (2023), compounds with low molecular weight, such as terpenes and flavonoids, are found in higher concentrations and may be related to the CCD profile found. According to Vani (2016), neem is a plant with several constituent varieties, among which the measured tetranortriterpenoids, including nimbin, nimbinin, nimbidinin, nimbolide and nimbidic acid, ascorbic acid, amino acids, and azadirachtin. It is noteworthy, however, that the flavonoid group represents, within the described proportion, a more significant portion when compared to other listed organic compounds. Flavonoids can act as antioxidants, whose free radicals decrease interaction with oxygen, and this factor may have influenced the results.

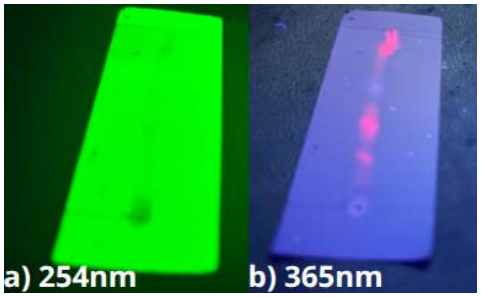


Figure 12 - TLC analysis of Neem on methanol a) 254nm; b) 365nm.

4.4 Data Collection

The seeds were planted on March 28, 2025, and data collection was conducted every week, for 10 weeks, starting on April 4. Thus, data collection happened on the following dates: April 4, April 12, April 19, April 26, May 3, May 10, May 17, May 24, May 31 and June 7. The experiment was run at the Biotechnology Laboratory of Colegio Dante Alighieri, in São Paulo, Brazil (exact location: 23° 33' 1.872" S and 46° 37' 59.9124" W). Ten vases, numbered 1 to 10 in each group after the seeds started to germinate (a few seeds did not germinate, as expected, as warned by the supplier), were used to grow the plants. The plants were measured (stem length) with a standard ruler with units in centimeters at the end of each week. An important fact to be considered was that the school closes on Sundays, and the lab, being a secure facility inside the school, was not available, and the plants could not be watered on those days. Also, Good Friday (April 18) is a national holiday in Brazil, which also prevents watering on that day.
The summary of the data is displayed in Tables 04 and 05, which show the sizes reached (in cm) by the plants in both the Neem and Control groups during the data collection period. In addition, Figure 13 shows the plants after 10 weeks of growth.



Figure 13 - Results of a) Neem and b) Control Group over the 10 weeks

Table 04 - Size of plants in centimeters per bell pepper vase for the Control group (COG) each week.

Control Group (COG) size (cm)										
Vase	***Week 1***	***Week 2***	***Week 3***	***Week 4***	***Week 5***	***Week 6***	***Week 7***	***Week 8***	***Week 9***	***Week 10***
1	0.60	0.80	1.30	1.80	2.20	2.90	3.50	3.90	4.60	5.20
2	1.20	1.60	2.00	2.60	2.90	3.00	3.40	3.80	4.40	5.10
3	0.80	1.10	1.60	3.00	2.80	3.10	3.60	4.10	4.50	5.10
4	0.70	0.90	1.20	1.50	1.90	2.60	3.00	3.40	3.80	4.20
5	1.40	2.50	2.90	3.10	3.40	3.70	4.00	4.20	4.80	5.40
6	0.90	1.40	1.70	2.00	2.40	2.70	3.20	3.80	4.30	4.50
7	0.60	1.00	2.00	2.30	2.50	2.80	3.00	3.20	3.50	3.90
8	1.80	2.30	2.50	2.70	3.60	4.10	4.30	4.40	4.90	5.20
9	1.60	2.10	2.40	2.60	3.00	3.50	3.70	3.90	4.30	4.50
10	1.20	1.40	1.70	1.80	1.90	2.10	2.40	3.10	3.40	3.70

Source: Authorship

Table 05 - Size of plants in centimeters per bell pepper vase for the Control group (COG) each week.

Neem Group (NGR) size (cm)										
Vase	***Week 1***	***Week 2***	***Week 3***	***Week 4***	***Week 5***	***Week 6***	***Week 7***	***Week 8***	***Week 9***	***Week 10***
1	1.50	1.70	2.50	3.00	4.70	5.70	5.90	6.00	6.20	6.40
2	1.90	2.10	2.70	3.40	4.00	4.80	5.00	5.40	5.50	5.60
3	0.60	0.90	1.20	2.40	2.80	3.40	4.30	5.20	5.30	5.50
4	0.80	1.30	1.30	1.50	1.70	1.90	2.40	2.90	3.60	4.10
5	1.10	1.70	2.40	2.70	3.00	3.60	4.40	4.80	5.10	5.40
6	1.60	2.40	3.20	4.00	4.70	5.30	5.60	5.70	6.00	6.20
7	0.80	1.50	2.30	2.70	3.00	3.40	3.80	4.40	4.90	5.30
8	1.10	1.30	2.10	2.40	2.90	3.00	3.50	3.60	3.90	4.60
9	1.90	2.40	2.90	3.70	4.30	4.70	5.00	5.80	6.30	6.60
10	2.00	2.60	3.20	3.50	3.70	4.10	4.40	4.50	4.90	5.10

Source: Authorship

4.5 Statistical Analysis

The data presented in tables 04 and 05 allowed a 2-way ANOVA analysis with repeated measures to be performed. Initially, the mean, variance, and standard deviation were obtained, as well as other relevant information, as shown in Table 06. The mean for each group during the experimental period is also shown in the bar graph in Figure 14.

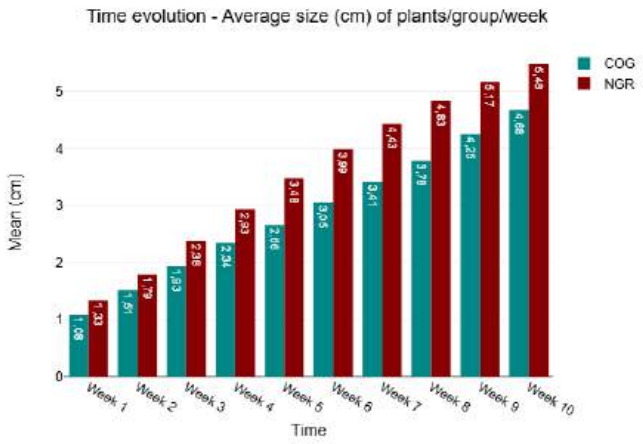


Figure 14 - Bar graph showing time evolution of plant size (cm) per group

Table 06 - Descriptive statistics of weekly plant height in COG and NGR groups

Week	**Group**	**Frequency**	**Mean**	**Std. Deviation**	**Variance**	**Minimum**	**Maximum**	**Range**	**95% Confidence interval for mean**
Week 1	COG	10	1.08	0.43	0.18	0.6	1.8	1.2	0.78 - 1.38
	NGR	10	1.33	0.52	0.27	0.6	2	1.4	0.96 - 1.7
Week 2	COG	10	1.51	0.6	0.37	0.8	2.5	1.7	1.08 - 1.94
	NGR	10	1.79	0.56	0.32	0.9	2.6	1.7	1.39 - 2.19
Week 3	COG	10	1.93	0.54	0.29	1.2	2.9	1.7	1.54 - 2.32
	NGR	10	2.38	0.7	0.49	1.2	3.2	2	1.88 - 2.88
Week 4	COG	10	2.34	0.55	0.3	1.5	3.1	1.6	1.95 - 2.73
	NGR	10	2.93	0.75	0.56	1.5	4	2.5	2.4 - 3.46
Week 5	COG	10	2.66	0.59	0.34	1.9	3.6	1.7	2.24 - 3.08
	NGR	10	3.48	0.97	0.93	1.7	4.7	3	2.79 - 4.17
Week 6	COG	10	3.05	0.58	0.34	2.1	4.1	2	2.63 - 3.47
	NGR	10	3.99	1.16	1.33	1.9	5.7	3.8	3.16 - 4.82
Week 7	COG	10	3.41	0.54	0.3	2.4	4.3	1.9	3.02 - 3.8
	NGR	10	4.43	1.03	1.06	2.4	5.9	3.5	3.69 - 5.17
Week 8	COG	10	3.78	0.43	0.18	3.1	4.4	1.3	3.48 - 4.08
	NGR	10	4.83	1	1.01	2.9	6	3.1	4.11 - 5.55
Week 9	COG	10	4.25	0.52	0.27	3.4	4.9	1.5	3.88 - 4.62
	NGR	10	5.17	0.91	0.82	3.6	6.3	2.7	4.52 - 5.82
Week 10	COG	10	4.68	0.6	0.36	3.7	5.4	1.7	4.25 - 5.11
	NGR	10	5.48	0.78	0.61	4.1	6.6	2.5	4.92 - 6.04

The statistical analysis has shown that plants treated with Neem extract presented a mean stem length significantly longer than those in the Control group during the whole experimental period. A mixed model ANOVA incorporating both groups and analyzing repeated measures on the same plants was performed to test whether there was a significant difference between the groups along 10 weeks in relation to the dependent variable, a significant difference between the groups in relation to the dependent variable, and whether there was an interaction between the two factors (time and treatment group) in relation to the dependent variable. The results of the ANOVA are shown in Table 07.

Table 07 - ANOVA

	Sum of squares	df	Mean Square	F	p	η^2	η_p^2
Week 1, Week 2, Week 3, Week 4, Week 5, Week 6, Week 7, Week 8, Week 9, Week 10	309.21	9	34.36	259.09	<.001	0.72	0.94
Group	25.35	1	25.35	6.38	0.021	0.06	0.26
RM Factor x Group	4.04	9	0.45	3.38	0.001	0.01	0.16
Residuals (Between Subjects)	71.47	18	3.97				
Residuals (Within Subjects)	21.48	162	0.13				

The analysis has shown that plant sizes have grown significantly over the 10-week period. Thus, the first null hypothesis, that there is no difference across these weeks, was rejected with a p-value <0.001. The very small p-value raises a question. Is this value a reflection only of the natural phenomenon of plant growth (if water, sunlight and nutrients are available) – or does it also reflect a contribution of the experimental setup, beyond the natural baseline? The p-value does not distinguish between these factors, and the ANOVA merely tests whether the repeated measurements show variability in size, without isolating natural growth from other factors. In fact, a “no-growth” control group would be necessary to isolate the factors, which is unfeasible. The experimental setup likely provided favorable conditions for plant growth and for the performance of a controlled experiment (same light and water schedule). Thus, what can be said is that the controlled environment was important for the experiment’s success, allowing for the comparison between the experimental groups.

The second null hypothesis analyzed was that there is no significant difference between the Neem and control groups in relation to plant size. This hypothesis was also rejected, with a p-value of 0.021. There was a noticeable difference in the average size of plants between the group grown with water only and the group treated with Neem extract when looking at all weeks

taken together. The Neem plants were generally larger.The third null hypothesis was that there was no interaction effect between the time factor (Weeks 1 to 10) and the two experimental groups. This hypothesis was also rejected, since the way the plants grew over time was different between the two experimental groups. The p-value for “repeated measures versus group” interaction is 0.001. Not only did the Neem group start bigger and stayed that way, but also it grew faster compared to the Control group. The average growth rate for the control group was ~0.390 cm per week, whereas the Neem treatment added ~0.0839 cm per week compared to the Control group, resulting in an average growth rate of 0.474 cm/week. Figure 15 shows each plant’s individual growth, as well as the average growth rate for each experimental group and the spread of the data, in orange for the Control group and blue for the Neem-treated group.

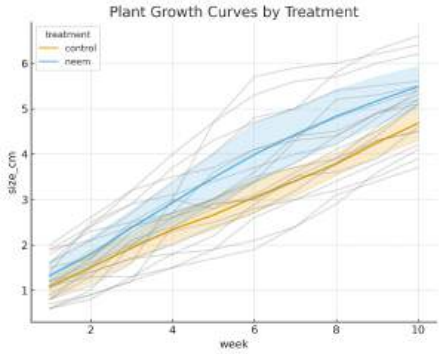


Figure 15 - Plant Growth Curves by Treatment.

5. CONCLUSION AND DISCUSSION

This study has sought to test the effectiveness of a candidate “nature-based” fertilizer, the Indian Neem. As discussed above, this plant contains compounds with fertilizer and pesticide properties and has the potential to supplement the usage of NPK fertilizers, which can pollute the water supply due to misuse. The present data investigated only the potential effects of Neem as a fertilizer, not as a pesticide, which would involve the use of agricultural pests and would complicate the experimental design.

As demonstrated in the Statistical Analysis session, the ANOVA suggests that treatment with the Neem extract may influence plant size beyond just providing water, as happened in the control group. The data shows that by week 10, the average size in the Neem group was ~5.48 cm compared to ~4.68 cm in the Control group. This overall difference suggests that Neem treatment had a beneficial impact on plant growth. It could mean that the extract helped the plants start bigger, grow more consistently, or both. However, the analysis does not specify when or how the difference developed. Finally, the partial eta-squared ($\eta p^2 = 0.26$) indicates that approximately 26% of the variability in plant size between the Neem group and the Control group can be explained by whether the plants received Neem or not. Thus, the effect was moderate, indicating that the difference is likely not caused only by the addition of the Neem extract and other factors might have contributed to the observed result.

The analysis also indicated that the pattern of growth over the 10 weeks was not the same for the Control and Neem groups. In other words, the Neem plants did not just start larger and

stay that larger: they grew differently or faster over time compared to the Control plants. Thus, the effect of Neem may build or change as the experiment progresses. This finding suggests that the Neem treatment does not provide a one-time boost but actively changes how the plants develop over time. As shown by the data, the gap in size between the groups widened from ~0.25 in week 1 to 0.80 cm by week 10, indicating that Neem might accelerate growth or sustain it better. This interaction suggests that Neem has a dynamic effect, not just a static one. The partial eta-squared ($\eta p^2 = 0.16$) means that approximately 16% of the variability in growth patterns can be attributed to the interaction between Neem treatment and time. This is also a moderate effect but reinforces that the difference in growth trajectories is noticeable (Figure 15). In addition, the TLC technique performed in a partner laboratory showed that Indian Neem leaves have a wide range of compounds, observed by the distinct variation in colors in the dark chamber, i.e., they have molecules with different absorption energies, which alters the visible color of a complex plant, since each spot color is a compound. The pink spots (which are in the majority) showed signs of being flavonoids, which absorb photons around 350 to 400 nm, which may explain their significant fluorescence at 365 nm. Flavonoids act as pigments, protect against UV rays, insects, fungi, and other harmful agents, and can neutralize free radicals, which can help prevent various diseases.As discussed in the Introduction, the role of artificial fertilizers in increasing the productivity of agro-industry crops is well established but presents environmental problems. Therefore, the Indian Neem was selected to test and/or develop a new product, "AGRO-BHARAT", with the potential to provide the necessary nutrients for the growth and development of bell pepper plants (selected because of their widespread use and their sensitivity to artificial fertilizers and pesticides), enhancing agricultural productivity. Taken together, the present results indicate that the Neem extract was better than just watering the plants and changed how the plants grew over time, warranting the development of further studies to investigate Neem as a candidate for boosting plant development.

Though promising, the scalability of neem-based products as fertilizers for global vegetable production is constrained by current cultivation, logistics, and competing demands (37). According to FAO, global vegetable harvested area reached approximately 131 million acres in 2024, underscoring the immense scale needed for widespread adoption to supplant synthetics. Neem is currently cultivated across an estimated 1.73 million acres worldwide, with India accounting for ~1.48 million acres. Mature neem plantations yield an average of 0.8 tons of seeds per acre annually, translating to a theoretical global production of 1.4 million metric tons of seeds per year. For vegetable applications, a conservative estimate requires approximately 10 kg/acre on average, yielding a total demand of 1.3 million tons if Neem were to fully supplant conventional inputs across all vegetable acreage. However, agriculture currently consumes only 50–60% of neem output, with the remainder allocated to cosmetics and pharmaceuticals/food additives. This leaves an effective agricultural supply of approximately 770,000 tons—covering just 59% of the hypothetical full-scale vegetable demand and highlighting a potential shortfall of 530,000 tons that could intensify due to competing demand. In the short term, full global coverage remains unrealistic, necessitating targeted implementation, such as prioritizing

high-value organic vegetables or hybrid systems blending neem with synthetics (38). Long-term viability supports expansion: Neem's low-input, drought-tolerant nature allows rapid scaling (maturity in 5–7 years), with Indian initiatives like the National Medicinal Plants Board already adding 300,000 acres annually, potentially doubling global area to 3.5 million acres and yielding 2.8 million tons to meet competing demands. Enhanced yields via improved varieties, as well as local cultivation in places such as subtropical South America (where neem adapts well) could increase output by 20–30% (39) (40). Ultimately, while current supplies fall short for universal vegetable application, strategic investments in cultivation and processing could render neem economically viable within 5–10 years, supporting global sustainability goals.

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Pubertal Hormones and Depression in Adolescence: Concurrent and Longitudinal Association By Ryan Han

Abstract

Puberty is a critical time period during life where all the brain development happens with hormones influencing them. Just as important, it can shape long-term mental health. Understanding how these hormonal shifts influence depression can help identify early warning signs in adolescence and later life mental health. To address this gap in the literature, the current paper examined how pubertal hormones during adolescence influence concurrent and future depressive symptoms. This project used a literature review, drawing from existing journal articles in psychology and neuroscience. Sources were analyzed to identify patterns, findings, and gaps related to the relationship between pubertal hormone changes and the development of depressive symptoms from adolescence to adulthood. Results revealed that most studies show that pubertal hormones have little to no impact on both concurrent and future depressive symptoms. The discussion focuses on the importance of moderating factors like cortisol and mood, as well as explores methodological biases to further contextualize mixed findings. Understanding the complex interactions among pubertal hormones, cortisol, and mood on mental health not just during adolescence but even later in life helps us identify early risk factors for depression and informs strategies to support mental health.

150-Character Summary

Performed a literature review on how pubertal hormones influence concurrent and future depressive symptoms with a PhD mentor.

Introduction

Puberty

Adolescence is a critical developmental period when puberty reshapes the brain, body, and emotions, shaping trajectories of mental health and risk for psychopathology. Puberty is a defining part of adolescence, an exciting stage of growth and change that marks the transition to adulthood. However, this biological process can also bring several mental health challenges. Various psychosocial models explain how pubertal physical changes can contribute to mental health challenges. Studies show that the maturational-deviance hypothesis suggests that too early or late development can potentially increase stress and emotional difficulties. The developmental readiness and risky social context theories propose that early-maturing adolescents may be unprepared for new social pressures or exposed to risky environments. Finally, maturational compression demonstrates that rapid physical progression through puberty can overwhelm emotional and cognitive adjustment, leaving more vulnerability to psychopathology (Pfeifer and Allen).

However, could the same hormones that help us develop also increase risk for depression? Puberty is defined as a series of hormone-driven changes at around ages ten and

fourteen in females and between ages twelve and sixteen in males, leading to changes in the shape, size, and composition of our bodies (Kabotyanski and Somerville). There is a huge difference in the physical and hormonal changes each sex goes through during puberty. For instance, males develop deeper voices, facial hair, increased muscle mass, and growth spurts (Kabotyanski and Somerville). On the other hand, females develop wider hips, larger breasts, and begin menstruation (Kabotyanski and Somerville). Just like how both sexes have different physical features as they mature toward sexual maturity, the type of hormones produced during puberty also differs by sex. For instance, females experience a significant rise in the estrogen hormone estradiol. On the other hand, in males, a sharp rise in androgen hormones such as testosterone and dehydroepiandrosterone (DHEA) can be noticed (Patton and Viner).

One thing to note here is that males and females do not have completely different hormones, but instead different dominant hormone levels. Females usually have higher levels of estradiol to develop female characteristics, while males usually have higher testosterone levels to develop male characteristics. These changes are triggered by a cascade of endocrine changes that lead to sexual maturation and reproductive capability, as a previously inactive neuroendocrine network becomes reactivated. Beyond these bodily transitions, gonadal hormones affect a wide range of neuronal processes: neurogenesis, dendritic growth, synapse formation and elimination, and sensitivity of neurotransmitter receptors, contributing to continued brain development and the emergence of sex differences in neural structure. Altogether, puberty can therefore be considered as an interconnected suite of changes that integrate physical growth, hormonal regulation, and neural maturation to prepare the body and brain for adult function.

Depression

Puberty-related changes in hormones, bodies, and brains increase depression risk, particularly in females who start early, and can be linked to factors like brain chemistry, genetics, stressful life events, medical conditions, and medication (Pfeifer and Allen). Depression is a common mental health disease that is affecting more than 16% of the U.S. population and a substantial proportion of adolescents alone (Cleveland Clinic). Depression is a mental health condition that is characterized by chronic feelings of sadness that can impair how one thinks, sleeps, eats, and acts. While sadness is an acute mood symptom, a short-term emotional feeling that fades away with time, depression is a chronic mood symptom, a persistent feeling of sadness and hopelessness that affects daily life. Depression is a mental disease that does not fade away with just time but needs early identification and treatment.

During adolescence, females' risk for depression rises to about twice that of males—a gap that peaks in mid-to-late adolescence and endures into adulthood (Salk, Hyde, and Abramson). Understanding how hormone changes during puberty contribute to this disparity is critical for explaining who is most at risk and why. Our research seeks to address two gaps in the literature. First, although there is a link between pubertal hormones in adolescence and depressive symptoms, less is known about whether it has a stronger impact on current or future depression and how it differs between males and females. Second, the research remains mixed on

the relative contributions of different types of hormones (DHEA, testosterone, estradiol) on depression risk, and how that association differs by sex and over time. Thus, our literature review paper will examine how various pubertal hormones during adolescence influence concurrent and future depressive symptoms.

Methods

The aim of this paper is to examine how pubertal hormones during adolescence influence concurrent and future depressive symptoms. We conducted a literature review drawing from articles in the neuroscience and psychology field using Google Scholar and PubMed. We selected papers that focused on pubertal hormones occurring around adolescence ages 10-16 and depressive symptoms either during adolescence (ages 10-18, termed "concurrent depression") or during adulthood (ages 18+, termed "future depression"). Papers focused on at least one of the following pubertal hormones: testosterone, estradiol, and DHEA.

Results: Effect of Pubertal Hormones on Concurrent Depression

Females

Both Luo et al. and Chronister et al. showed a consistent finding that most of the pubertal hormones have no effect on concurrent depressive symptoms among female adolescents. This was contrary to hypotheses that higher estradiol levels would be associated with greater depressive symptoms in adolescents. The systematic review by Luo et al. suggests that a majority of studies found no effect of estradiol on depressive symptoms among adolescent females. However, there were some exceptions to this null effect as a small number of studies showed that higher estradiol levels in adolescent females were significantly associated with higher risks of depression diagnosis. Remaining studies were longitudinal research and will be summarized in the next section. Evidence of a null effect of pubertal hormones on depression in adolescent females seemed to be true for other hormones including testosterone and DHEA/DHEA-S, where the majority of studies fell into the p-value > 0.05 category with some exceptions falling into the positive (p-value ≤ 0.05) category. These results ultimately suggest there is no consistent direct correlation between any of the pubertal hormones and concurrent depressive symptoms.

In another study, Chronister et al. show unique aspects that address gaps and bias between studies. This study also suggested that the correlation between pubertal hormones and depressive symptoms depended on the level of cortisol, a steroid hormone involved in stress. When cortisol levels were higher, the associations of depression with both DHEA and testosterone became stronger. At low cortisol levels, DHEA and testosterone were not associated with depression in females. These results suggest higher cortisol can increase the effect of some hormones, changing vulnerability to depression in females, whereas low cortisol levels may be protective. Overall, both articles align in showing no consistent direct effect of pubertal hormones on depression in females, but Chronister et al. add nuance by demonstrating that cortisol may change these relationships.

Males

Among male adolescents, three studies by Luo et al., Chronister et al., and Culbert et al. consistently showed that most of the pubertal hormones (testosterone, estradiol, and DHEA) have no effect on concurrent depressive symptoms. However, there were some exceptions. Just like females, Luo et al. suggested that out of many studies, most reported p-values greater than 0.05, where the remaining study was not even about depression but other possible mental health issues. This seemed to be pretty consistent with other hormones (estradiol and DHEA) too, where most of the existing studies report there is no major correlation. Chronister et al. similarly reported no direct correlation between pubertal hormones and depression in males, but their analysis suggested a possible impact of cortisol and how that could also change the relationship between pubertal hormones and depressive symptoms. Male adolescents with higher cortisol levels showed a stronger positive relationship between estradiol and depression, an effect not found at lower cortisol levels. On the other hand, cortisol seemed to have no impact on DHEA and testosterone, where unlike estradiol, higher cortisol levels did not strengthen correlations between depressive symptoms and those two hormones. These results suggest that while testosterone, estradiol, and DHEA showed little direct effect on depression in adolescent males, cortisol acts as a modifier that could amplify or change the associations of pubertal hormones with concurrent depressive symptoms.

Effect of Pubertal Hormones on Future Depression

Females

After careful full-text readings from a variety of sources, there are limitations on how pubertal hormone level affects or predicts possible future depressive symptoms. Most of the studies were only able to predict within one year at maximum; hence, it was not possible to predict future depressive symptoms in the sense of depression diagnoses at age eighteen or older. With that being concluded, there are some key findings across these articles.

In a school-based cohort, Chafkin et al. found that interactions between estradiol, basal cortisol, and pubertal timing predicted spring ninth- and tenth-grade self-reported depression scores. Specifically, higher estradiol was linked to more depressive symptoms at the end of ninth grade in females with high cortisol and who had a late puberty. By tenth grade, the test was done in the same way and it appeared to predict depressive symptoms; however, this association did not remain statistically reliable once the researchers corrected for multiple comparisons, meaning it may have arisen by chance given the large number of tests conducted. Beyond hormonal impact, females who hit puberty earlier than their peers in ninth grade were more likely to report higher depressive symptoms one year later in tenth grade. This suggests that early puberty itself, regardless of hormone levels, is a meaningful risk factor for later depression.

Old longitudinal work by Susman et al. also demonstrated predictive links. For females, internalizing problems and the interaction of negative emotions with low basal cortisol were associated with higher depression scores one year later. This illustrates that it is not just baseline

mood or hormone levels alone, but the combination of high negative mood with stress hormone functioning that most strongly signals future risk of depression.

Another literature review paper by Luo et al. reviewed fourteen longitudinal designs and noted that most studies found no strong predictive effects of sex hormones. However, two analyses in females showed that baseline estradiol predicted higher depressive symptoms at eight-month and one-year follow-up, though effects did not extend to longer follow-up (twenty months). Similarly, two studies suggested that higher baseline or accumulated testosterone predicted more depressive symptoms at one year, though these findings were inconsistent.

Finally, Chronister et al. highlighted evidence that higher baseline cortisol in nine- to fourteen-year-old females predicted the onset of depression at age eighteen, reinforcing that a girl's normal stress hormone levels (basal cortisol) can be an early warning sign of who is more likely to develop depression years later. Overall, the most reliable prospective signals in females are that (a) early pubertal timing increases vulnerability to future depressive symptoms, (b) estradiol and testosterone at baseline sometimes forecast higher symptoms within the next year, and (c) cortisol levels, especially when interacting with estradiol and timing, are a consistent predictor of later depression. Still, findings are inconsistent across studies, and effects often diminish at longer follow-ups.

Males

Across longitudinal studies, links between pubertal hormones and future depressive symptoms in males are relatively weak and often overshadowed by the initial mood problems. Baseline mood (negative affect or internalizing) is the strongest and most consistent predictor of future depression, indicating that initial "sad" mood will carry on for a year and that is most likely a pathway toward depression. However, hormones like DHEA sometimes add a signal, but only in certain cases and usually just for one-year follow-up (Susman et al.). For depression specifically, males with higher baseline mood scores or internalizing scores and higher baseline DHEA showed higher depression symptom scores one year later. For a broader perspective, in the internalizing score pattern across a year, males' higher baseline internalizing combined with lower LH and lower cortisol predicted higher internalizing one year later. This suggests that males with certain hormone patterns (low LH and low cortisol) were more likely to continue showing high internalizing scores one year later, pointing to a broader emotional vulnerability that goes beyond depression alone (Luo et al.).

Another population-based systematic review aligns with this pattern: for testosterone in males, most relationships with internalizing, depression, or anxiety are nonsignificant, and the few positives are cross-sectional studies rather than prospective studies; by contrast, there is longitudinal evidence that higher baseline DHEA (but not DHEA-S) predicts higher one-year depression and anxiety even after accounting for how depressed or anxious participants already were at the start. Overall, males' negative mood at the start was such a strong predictor of their mood a year later that hormones by themselves added very little. Because negative emotions tend

to remain stable over time, there was not much room left for hormones to explain additional differences, which helps explain why the hormone effects in males were limited and inconsistent.

Table 1: Summary of the results

Hormone	Male - Concurrent	Male - Future	Female – Concurrent	Female – Future
Testosterone (T)	No clear effect	No strong effect (baseline mood stronger)	No consistent effect	Sometimes predicts higher symptoms within 1 year (weak/inconsistent)
Estradiol (E2)	Mixed; mostly no effect, possible under high cortisol	No strong evidence	Mixed; some are true, some are null	Sometimes predicts higher depression short-term (8–12 months), but inconsistent long-term
DHEA / DHEA-S	Mostly no effect	Occasionally predicts higher depression/anxiety 1 year later	Mostly no effect	One study showed higher DHEA-S → lower later depression, but inconsistent

Discussion

The current study examined whether pubertal hormones have any relationship to concurrent and future depressive symptoms. We initially hypothesized that higher levels of testosterone (T), estradiol (E2), and DHEA would be protective against depression. Across population-based studies reviewed in the current literature review, the pattern did not support that hypothesis for concurrent symptoms. Most associations between pubertal hormones and adolescent depression were null, with studies showing both positive and negative associations between hormones and adolescent depression. The most thorough review so far also found that the evidence linking pubertal hormones to mental health is weak and inconsistent, mainly because of confounding factors and issues in how hormone levels were measured.Prospectively, the longitudinal studies also fail to demonstrate the protective effect of pubertal hormones on

later depressive symptoms; again, the systematic review characterizes the overall longitudinal evidence as limited and at high risk of bias.

Interestingly, there were some exceptions during the literature review where levels of cortisol could change the relationship between pubertal hormones and depressive symptoms. When the cortisol level was high, the research from Chronister et al. (2021) suggested that higher the level of estradiol could positively affect depressive symptoms, however this is only for males. Thus,the moderating role of cortisol may be one explanation to explain the gap between why some studies of estradiol, testosterone, and DHEA demonstrate no correlation with depression, while other studies do. In addition, Chronister et al. did not measure estradiol in females due to menstrual cycle variation, indicating that all the studies on estradiol level and depressive symptoms could be under high risk of bias.

There were limitations on the paper however. First, our review is just a snapshot, not a comprehensive or systemic review. The best available systematic review flags widespread high risk of bias across studies. For example, many studies relied on only one saliva sample, without considering natural daily changes in hormone levels or, for females, variations across the menstrual cycle. Second, methodological differences matter. For example, estradiol was not measured in females in the Chronister study because of menstrual variability, which limits sex comparisons. This also shows how important it is for studies to consider menstrual cycle timing when measuring hormones like estradiol, since ignoring it can lead to inaccurate conclusions about its link to mood in adolescent females . Finally, most research has focused mainly on depression, even though puberty-related biological changes might influence other areas of mental health such as anxiety, externalizing behaviors, or eating-related issues. The systematic review also found results in these areas to be inconsistent, likely for the same methodological reasons.

In conclusion, these results indicate that simply a higher level of hormones does not provide the benefits of protection against concurrent or later depression. If anything, specific patterns (e.g., higher E2 with higher internalizing in mid-adolescent males when cortisol is elevated show that context and timing might have an impact but hormone levels alone can't decide its effect. Future research should aim to analyze the interactions between pubertal hormones and stress-related systems. Studies should include both hormonal and environmental factors, such as cortisol levels, social stress, and lifestyle influences, to clarify how these elements work together to shape mood changes during adolescence. In addition, hormone levels should be tested multiple times instead of only once, to come up with an average level of hormone level since hormone levels can fluctuate during the day and night due to environmental factors. A broader focus could reveal whether pubertal hormones affect these areas more strongly and help create a more complete picture of adolescent psychological development. Ultimately, these research findings from the current paper underscore the importance of looking beyond hormone levels to consider the combined influence of stress, pubertal timing, and social context on adolescent mental health. Understanding the complex interactions among pubertal hormones, cortisol, and mood on mental health not just during adolescence but even later in life helps us identify early risk factors for depression and informs strategies to support mental health.

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Cutting Conversations: Rhythmic Editing in The Social Network By Shivum Saha

Abstract

The Social Network demonstrates how editing shapes the rhythm and flow of a film. Editors Kirk Baxter and Angus Wall, working with director David Fincher, used techniques like rapid cutting, prelaps, montages, and intercutting to match Aaron Sorkin's fast, character-driven dialogue. This paper analyzes how these choices control pacing, emphasize emotional beats, and define power dynamics between characters. Using interviews, articles, and critical analyses, the research answers the essential question: How do the editing choices portray the rhythm of the dialogue and character driven script of The Social Network? Key sources include interviews with the editors, director, and screenwriter, as well as articles on the film that provided further insight into specific techniques. The study shows that rhythm in film is created through deliberate technical choices that influence how audiences perceive story and character, and that the role of the editor is central to shaping the final film. Because these decisions often go unnoticed when watching a movie as a whole, this analysis highlights the deeper intent behind the cuts, transitions, and pacing that give the film its shape.

Introduction

Film editing is the process of cutting and assembling film footage to tell a coherent and compelling story. Editors oversee the assembly of the film from beginning to end and work with the director(s) and producers to create a final cut that depicts the vision of the filmmakers. As three-time Academy Award winning editor Thelma Schoonmaker, best known for working with director Martin Scorsese, explained, editing is "…like sculpture. You get a big lump of clay, and you have to form it – raw, unedited, very long footage."

One film that exemplifies the power of editing in storytelling is The Social Network (2010), a biographical drama based on Ben Mezrich's book, The Accidental Billionaires. Written by Aaron Sorkin and directed by David Fincher, the film earned eight Academy Award nominations and won three, including Best Film Editing for Kirk Baxter and Angus Wall. Sorkin's screenplay is widely praised for its sharp, rhythmic dialogue and character driven storytelling. Through editing choices such as Prelaps, montages, rapid cutting, and intercutting, Baxter and Wall shape the rhythm of the script and enhance its narrative tension.

Background & Significance

Rhythm in art is often linked to music; how the pattern of sounds and silences, organized in time, evoke a sense of movement by arranging musical notes and rests in a way that creates a rhythmic structure. It is a fundamental element that shapes the overall character and feel of a piece of music as the beats, measures, and tempo are critical to building a great song and engaging listeners. Rhythm in film editing works the same way. In the early days of cinema, editing was as simple as cutting between one scene and the next, which is the perception of the majority of the general audience even now. In the early 20th century, pioneering filmmakers like

D.W. Griffith and Sergei Eisenstein started using editing not just for continuity but for a narrative effect, exploring techniques like close-up, eyeline matching, and insert shots (Shah), making the job of film editing much more complicated.

A majority of scenes are shot with coverage, footage taken from multiple camera angles of the same scene, and then the editor decides the duration and arrangement of each shot (Deguzman). A basic approach would be to cut to whoever is talking in the scene, but that method prioritizes the dialogue over everything else, disregarding opportunities to turn a simple scene into something special. For example, the editor can decide to show a reaction shot of Character A while Character B is talking, or just have the shot be on Character A throughout the entire scene or cutting to a random object while the two characters are conversing in the background. Each iteration tells a different story with entirely different moods and rhythms. Most of the time, rhythmic editing in a film can be less obvious than editing in movie trailers or musicals as they usually synchronize the pace of the music with the shots, but it can still have a huge impact on how the audience emotionally engages with the film.

The average shot duration in a film is four to six seconds, for example, in a conversation scene, the shot might be on Character A for four seconds and then cut to a shot of Character B for five seconds and etc. The editor can cut the shots shorter to increase the intensity of a scene or cut them longer to create a sense of calm. The shower scene from “Psycho” is often considered to be the greatest accomplishments in terms of film editing due to the way it uses rhythm (Tindell). In the sequence, Janet Leigh’s character takes a shower at a motel, and then she is brutally murdered by an assailant. It consists of three different sections: before the attack, the attack itself, and after the attack. Before the attack consisted of slower cuts to set up a sense of calm right before the chaos, and then the attack itself consisted of rapid cuts with each shot being less than a second, and after the attack, it returns to slower cuts to leave a lasting impression on the audience. If the editor chose to do rapid cuts before the attack, it would diminish the terrifying effect encapsulated by the attack scene, and if the editor chose to do slower cuts during the attack, it would not mirror the brutality of the murder and while it would not necessarily make the scene bad or ineffective, it would create a much different effect than what the director, Alfred Hitchcock, intended.

Film editing is not always as jarring as Psycho but can also be very subtle and still effective, and rhythmic editing is not just focused on calm scenes with slow cuts or tense scenes with rapid cuts. And while Psycho is not a dialogue-heavy film, the scene illustrates how rhythmic editing can dramatically affect tension, pacing, and character impact. The same principle applies to dialogue-driven films like The Social Network, characterized by its fast-paced, precise cutting, synchronized with Aaron Sorkin’s rapid-fire dialogue and Trent Reznor and Atticus Ross’s score, creating an engaging narrative emphasizing emotional beats and character development. This rhythmic approach is achieved with the use of techniques like montages, intercutting, and reaction shots. Understanding how these techniques are used in The Social Network offers insight into the editors’ role in defining the script’s rhythm and character development.

Literature Review

Much of the existing research on The Social Network highlights the role of Aaron Sorkin's script and David Fincher's direction. Scholars and critics often point to the screenplay's rhythm and the precision of Fincher's style as central to the film's impact. Ducker, for example, describes Fincher as a perfectionist, citing his reputation for numerous takes and control over detail (Ducker). Barfield adds that Fincher's demand for multiple takes left editors with an unusual amount of material to shape (Barfield). Angus Wall himself has spoken about the pressure of cutting down the opening scene over three weeks to find the exact rhythm. These sources emphasize Fincher's control and the quality of Sorkin's dialogue, but they often stop short of analyzing the editors' specific role in shaping rhythm and do not go into detail on how Kirk Baxter and Angus Wall use certain editing techniques to create a rhythm in the final film. This paper not only builds on existing research and analysis but also analyzes the editors' role in shaping dialogue, character interactions, and rhythmic pacing.

Research Methods

The methodology involves exploring how the editing choices of The Social Network portray the rhythm of the dialogue and character-driven script. This is primarily done by diving deep into the role of the film editor, analyzing the emotional beats of the film, absorbing interviews and commentary from the film's editors, director, and writer, as well as critical analyses and academic discussions of the film. This establishes a comprehensive foundation for understanding the significance of film editing and how it shapes the narrative of The Social Network.

Findings

6.1 Vision of the Filmmakers

On paper, The Social Network may seem to be simply about the creation of Facebook and how it led to Mark Zuckerberg facing several legal battles. But that was never the main focus of the film. The screenwriter, Aaron Sorkin (West Wing, Moneyball, A Few Good Men), mentioned in an interview that "It really didn't have much at all to do with Facebook itself… But the story itself! There are elements of it that are as old as storytelling: friendship and loyalty, class, jealousy, betrayal" (Grossman) He wanted to tell a story about a socially awkward Harvard sophomore who threw his friendship away due to his ambition, ego, and insecurities rather than it just fundamentally being about the creation of a popular social networking site.

Esteemed director David Fincher (Fight Club, Seven, Zodiac) showed interest in bringing Sorkin's vision to life and wanted to create a modern-day Citizen Kane by exploring themes of ambition, power, friendship, and betrayal in the context of Facebook's creation (Buffery). He aimed to explore Mark's arc as someone driven by a desire for social status, and how that drive came at a personal cost, amplified by the sudden societal shift caused by Facebook.

Fincher was decisive about the film having a certain rhythmic pacing to match Sorkin's fast-paced dialogue. One page of a screenplay is generally equivalent to one minute on screen, so

Sony initially believed the film would be almost three hours long, since the script was 162 pages. But Fincher had a clear vision. To test the pacing, he brought a tape recorder and timed Sorkin reading the screenplay out loud - it took exactly 1 hour and 59 minutes (Buffery). This convinced Fincher that, if planned carefully and paced deliberately, the dialogue-heavy script could be shaped into a 2-hour film, which became the runtime of the final product.

In the end, it wasn't about Facebook at all. It was about ambition, status, and betrayal - timeless human conflicts - told through the lens of the digital age, reflected by the rhythmic pacing which was achieved through the editing process.

6.2 Aaron Sorkin and the use of Dialogue

Sorkin made several choices in his screenplay to make it both dialogue- and character-driven while maintaining a distinct rhythmic structure. One key decision was using a non-linear narrative: the film jumps between present-day depositions and key moments from the past. This structure allows the audience to see how the characters' (especially Mark's) actions shaped their present legal battles and personal relationships. It also enables the exploration of multiple perspectives and conflicting narratives. Rather than presenting a single, definitive account of Facebook's origin, Sorkin dramatizes the different versions told by various individuals involved, highlighting the subjectivity of truth and the intricacies of perspective and memory. He avoids telling the audience what to think about the characters, instead presenting their viewpoints so viewers can form their own opinions and judgments.

Sorkin's parents often took him to plays from a very young age, sometimes to productions he was too young to fully understand, such as Who's Afraid of Virginia Woolf? Yet he always loved the sound of the dialogue, which to him resembled music. Growing up, when writing for stage and screen, he sought to imitate that musicality (Sorkin).Fast-paced, witty dialogue and rapid-fire exchanges became hallmarks of Sorkin's style. He uses dialogue not only to convey information but also to reveal character, build tension, and create a sense of momentum.

Editing choices made by Kirk Baxter and Angus Wall amplify the rhythmic flow that Sorkin built into the screenplay, with techniques like Prelaps, intercutting, montages, etc. In film, the definition of Prelaps is essentially hearing the audio of the upcoming scene before you see it. Baxter and Wall use it in The Social Network to smooth out scene transitions by creating seamless transitions between scenes, especially given the non-linear narrative that jumps between different timelines and locations. This smooth transition style contributes to a faster pace and maintains the audience's engagement with the story and allows the film to move quickly between events and flashbacks without feeling abrupt. Additionally, Prelaps generally create a sense of suspense or anticipation for what is about to be revealed in the next scene, keeping the audience curious. The use of Prelaps emphasize on the dialogue and character emotions in Sorkin's script as well since it highlights significant pieces of dialogue, and this can also be used to emphasize a character's internal struggles or emotions, further connecting the audience to their journey.

6.3 Montages

Montage is a film editing technique where brief, thematically related clips are strung together often used to show a passage in time, character development, or a change in mood. Early Soviet Filmmakers like Eisenstein, Vertov, and Kuleshov explored the power of montages to evoke strong emotions. Eisenstein famously used this technique in his 1925 film Battleship Potemkin to convey the chaos and brutality of the Tsarist regime's actions (Hellerman). These early montages often involved rapid cutting, rhythmic pacing, and contrasting imagery. Around the 1930s, Hollywood studios adopted montage sequences often to show a passage of time, typically using fades and dissolves to show a sense of progression (fionapleasance). The 1976 hit film Rocky is a classic example of a sports montage, intended to show Rocky Balboa's training. Today, filmmakers continue to utilize this editing technique for diverse purposes like evoking strong emotions as done in the opening montage of Pixar's Up, where it's used to portray the love story between Carl and Ellie.

The Social Network employs a variety of montages, either to depict events concisely - such as the rowing race scene - or to interweave character arcs and show how they collide, as in the "Intriguing Possibilities" montage. That sequence follows three parallel threads: Mark getting further in Facebook's development, his best friend and co-founder of Facebook Eduardo pursuing entry into the Phoenix club, and the Winklevoss twins (with Divya) falling prey to Mark's stalling tactics. Each thread shapes the others in ways that drive the film's plot.

Mark's progress with Facebook hurts his friendship with Eduardo, as he increasingly makes decisions without Eduardo's input, keeping him at arm's length under the belief that he knows better. Eduardo's pursuit of the Phoenix club, meanwhile, fuels Mark's sense of jealousy and inadequacy, since Mark himself wants to be in a final club – which was established in his opening banter with Erica. This dynamic contributes to Mark's eventual decision to dilute Eduardo's ownership of the company from 34% to 0.3%, causing Eduardo to sue Mark.

At the same time, Mark's deception of the Winklevoss twins and Divya adds another layer. They had pitched him an idea, Harvard Connection, strikingly similar to Facebook, hoping to collaborate with him. Instead, he kept them waiting, stringing them along while secretly building his own site. Whether or not Mark did steal their idea, the similarities led to their lawsuit against him. The twins' role as crew rowers also ties back thematically: as the opening scene establishes, rowing is another thing that Mark wishes to do, much like the final clubs - feeding his ambition to rise above.

Ultimately, montages like the Intriguing Possibilities are used in the film to not just move the story forward, but to deepen each character's arcs, and highlights the film's central themes of ambition, jealousy, and betrayal, and how they drive the characters forward.

6.4 Intercutting

Also known as cross-cutting or parallel editing, intercutting is a foundational editing technique where the editor alternates between two or more scenes, often to show parallel actions, events happening simultaneously, or to build tension.

Historically, it's been used to create suspense by showing simultaneous action, for example, in a chase scene, intercutting between the pursuer and the pursued escalates stakes (MasterClass). D.W. Griffith popularized this technique in films like "The Girl and Her Trust" (1912) by cutting back and forth between a heroine in danger and a hero rushing to help. It's also been used to show multiple narrative threads leading to a single outcome, used several times in Christopher Nolan's "Inception" (2010). Intercutting has also been used to juxtapose thematic elements, like the iconic baptism scene intercut with brutal assassinations in The Godfather (1972).

Intercutting has been used in a variety of ways, but The Social Network utilizes this editing technique in order to jump back and forth between the present-day depositions and flashbacks to Harvard, showing the developments of Facebook alongside Mark's legal battles. Baxter and Wall edited it in a way to display a continuous conversation between Mark's past to people in those two boardrooms in the present, creating a sense of urgency and allowing for smooth transitions between different timelines, which maintains its pacing without breaking the rhythmic flow (Kon).

One example in the film is when Eduardo finds a letter in Mark's room about the Winklevoss Twins making legal claims against Mark and how they can sue him – the film cuts between their conversation and the twins' lawyer reading the same letter during the legal case in the boardroom in present-day which fluidly connects the past (Mark and Eduardo Discussing) with the present (the lawyer reading).

6.5 The Opening Conversation

Black screen. Cue 'Ball and Biscuit' by The White Stripes. Then, Mark Zuckerberg's voice cuts through: 'Did you know there are more people with genius IQs living in China than there are people of any kind living in the United States?' Fade in.

The Social Network begins with a fast-paced conversation between Mark and Erika which eventually escalates to Erika breaking up with Mark when things heat up in a matter of 10 minutes. This scene is often considered a masterclass in screenwriting and film editing due to its brilliant pacing.

Editing plays an important role in shaping the tension of this scene. Kirk Baxter and Angus Wall use rapid cutting to match Sorkin's quick, overlapping dialogue. Rapid cutting is a fast-paced technique involving consecutive shots of very short duration, often just a few seconds or less. Also known as fast cutting, this technique involves carefully choreographed rhythmic transitions that flow smoothly. Professional film editors maintain a consistent flow of motion, keep the main subjects centered, and use close-up shots to ensure the rapid cuts do not overwhelm but rather engage the audience. Rather than keeping longer takes that could soften the rhythm, Baxter and Wall keep each cut short, creating a sense of verbal sparring, and by doing this, they make the audience experience the tension and emotions like the characters rather than simply viewing it as a conversation, making the audience subconsciously feel the same disorientation and frustration that Erica does.

It begins with a two-shot (refer to Figure 1) and cuts to individual medium shots (see Figures 2 and 3) where the two talk rapidly, often interrupting each other and giving the impression that they are talking at each other rather than listening to each other, until the close-up shots (as shown in Figures 4 and 5) "Or you can get into final club" – the two pause over here and acknowledge each other, which distinguishes from the overlapping banter and letting the audience know that this is now the main topic of conversation, and the editors switch back to a two-shot (see Figure 6). Each cut here represents a shift in power, and whenever neither character is no longer in control, a close-up shot is no longer used, and a two-shot is employed. But Erica does not want that and changes the subject, so they cut back to a close-up shot of her as she takes control of the conversation.

This power struggle throughout the scene is less about Erica wanting control and more about Mark's desire for it – he views conversations and relationships as competitions he must win. Erica's decision to break up with Mark is the result of his constant need to prove his superiority, which exhausts her – as she tells Mark, "Dating you is like dating a Stairmaster." (Fincher 4:24)

This is not only enhanced by the use of rapid cutting, but also a fundamental film technique: reaction shots. A reaction shot is a camera shot that cuts away from the main action to show a character's facial expression or body language in response to an event, dialogue, or another character. For example, the editors frequently cut to Mark sipping his beer whenever he feels pressured or uncomfortable, a subtle visual cue that reflects his inner discomfort during the conversation. Furthermore, in this scene, Erica has a total of 2 minutes and 28 seconds of screentime, while Mark only gets 2 minutes and 19 seconds (CuttingConcepts). It is about the same, but Erica is clearly given more screentime through reaction shots despite Mark having more dialogue; for instance, even when the scene opens with Mark speaking, the editors choose to cut to Erica right after the two-shot, positioning her as the audience's anchor. This allows the audience to mainly experience this conversation from Erica's perspective because Mark is not necessarily meant to be liked. In the scene, Erica often loses track of the conversation because of how fast Mark speaks and changes subjects, and siding with Erica makes it easier to empathize with Eduardo Saverin later on when he sues Mark.

Ultimately, this opening repartee not only establishes Mark's character but also demonstrates how editing can dictate the rhythm, perspective, and emotional weight of a conversation. Through rapid cutting, close-ups, two-shots, and reaction shots, Baxter and Wall turn what could have been a simple breakup into a back-and-forth power struggle that feels tense and draining. The audience is naturally pulled into Erica's perspective, dealing with Mark's constant need for control, and by the time she leaves, we don't just understand her decision, but we also see how this moment sets up Mark's larger story of ambition, conflict, and ultimately, isolation.

Discussion

Angus Wall and Kirk Baxter make specific editing choices in The Social Network to show the rhythm of Aaron Sorkin's dialogue and character-driven script. Sorkin is known for writing his dialogue like music: fast, sharp, overlapping, with a natural cadence, and characters often talk at each other rather than with each other, making some of the conversations akin to verbal sparring. His script in the end was 162 pages long, which would normally equal 162 minutes of film, but when Fincher timed Sorkin reading it aloud, it lasted exactly 1 hour and 59 minutes, demonstrating that rhythm was built into the script itself: fast dialogue compresses time, often turning three pages into two minutes on screen.

Wall and Baxter carry this rhythm into the editing. They use rapid cutting in key scenes such as the opening breakup to keep exchanges short, like beats in a measure. They use prelaps, hearing the next scene before seeing it, to create smooth transitions and keep the flow moving. Intercutting links the depositions with flashbacks, keeping the film's pace steady across timelines. Montages like "Intriguing Possibilities" push several threads forward at once (Mark coding, Eduardo seeking status, the Winklevoss twins plotting) so the audience feels a build-up rather than separate events. Rhythm also comes from power shifts in conversations. Close-ups, two-shots, and reaction shots break up the dialogue like syncopated beats in music and these shifts let the audience feel the back-and-forth of dominance between characters.

This rhythm also reflects David Fincher's working style. Baxter and Wall have collaborated with director David Fincher several times in movies like "The Girl with the Dragon Tattoo", "The Curious Case of Benjamin Button", etc. David Fincher can be a real perfectionist when directing a film, as Fincher's first assistant director from the early 1990s, Michael Alan Kahn, described: "[Fincher] would spend five hours and 57 minutes dressing the fuselage, dressing the background, moving the background around, putting the bottle right in place, finessing the light so it felt like you were in flight…" Every aspect has to be perfect in the eyes of Fincher, and he has gained a reputation as a demanding director who is always intense and never satisfied (Ducker). He would take around 65 takes of a scene on average, which is triple what most directors do, and then it is the editors' job to figure out which is the best (Barfield). Angus Wall took three weeks to edit just the opening scene of The Social Network, and no matter how tiring his process may be, he described how it allows him "to sleep at night knowing that I had a mechanism in place, so I knew I was getting all the best stuff." (Wall). While Fincher's mastery as filmmaker is undeniable, Baxter and Wall's contributions are equally significant, often underappreciated, for bringing Fincher's complex vision to life.

Comparing The Social Network to other films involving the same creative team shows how editing adapts to different narrative styles. In The Curious Case of Benjamin Button, also edited by Baxter and Wall under Fincher's direction, the editors shape a very different rhythm. The film follows the story of Benjamin Button, played by Brad Pitt, a man born old who ages in reverse, exploring themes of mortality and love. The rhythm here moves slower. Baxter and Wall hold on longer shots and let quiet moments breathe, which gives the film its reflective tone. Scenes between Benjamin and Daisy often stay with the characters' faces instead of cutting quickly, letting the emotion build on its own. Cross-cutting works differently as well. Instead of

creating tension, it links together memories and moments across time, underlining the film's focus on aging and loss. The editing matches the story's theme of time moving forward even as Benjamin moves backward. This contrast with The Social Network shows that the choices made by Baxter and Wall are not fixed signatures, but rather responses to the needs of the story.

Conclusion

The editing of The Social Network creates rhythm through deliberate choices in pacing, structure, and shot selection. Editors Baxter and Wall use techniques like rapid cutting, prelaps, montages, and intercutting to bring out the cadence of Sorkin's dialogue and to highlight power shifts between characters. Rhythm in this film is central to how this story is told and how the audience experiences character, tension, and emotion.

The value of this study is essentially to bring light into the work of a film editor. Rhythm, in not just film but all forms of art, is often felt but goes unnoticed even though it plays a huge role in engaging with the audience. Academically, this analysis adds to film studies by highlighting the film editor's role in rhythm, rather than focusing only on the writer, director, or actors. Each editing choice was not simply to stitch a film together but was important to help portray what Sorkin and Fincher wanted the audience to feel or understand.

Future work could expand this kind of analysis to other dialogue-heavy films, or even to genres like action or documentary, where rhythm takes different forms. By looking deeper at editing, we gain a fuller understanding of how films communicate. In the case of The Social Network, the rhythm created by Baxter and Wall is what makes the story of Facebook's creation feel urgent, tense, and, above all, human.



Figure 1: Opening "Two-Shot" (0:27)



Figure 2: Medium Shot of Jesse Eisenberg as Mark Zuckerberg (0:34)



Figure 3: Medium Shot of Rooney Mara as Erica Albright (0:39)



Figure 4: "Or you can get into a Final Club" - Close-up shot (0:41)



Figure 5: "Or I can get into a Final Club" - Close-up shot (0:44)



Figure 6: Two-shot (1:20) - In Fig. 1, they lean in to converse; now, they sit pushed back

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Optimizing AI Systems through Backpropagation By Warren Stading

Abstract

Artificial Intelligence (AI) systems often require human feedback to correct errors, a process that can be slow and limited by human availability. This project explores a novel approach for accelerating AI improvement by having one AI teach another, using a continuous backpropagation-like feedback loop. Backpropagation is a common technique in AI where errors are sent backwards through a system so it can learn from mistakes. In a self-driving car simulation (F1Tenth autonomous racing environment), a "coding" AI agent drove a virtual racecar and logged crash data, which a second AI agent analyzed to suggest code improvements. Iteratively, the driving algorithm was updated based on AI-generated feedback without human intervention. The results show that this two-AI backpropagation design dramatically outperformed both a human-coded baseline and a single AI with no feedback. For instance, averaged across multiple trials, the dual-AI system was able to complete an entire track (234 m) without crashing, compared to only 120 m using a single AI and 91 m with no AI assistance. Optimal performance was achieved with a moderate amount of context window data (10 steps before each crash); too little or too much context reduced effectiveness. The two-AI trained driver also generalized partially to a new, unseen course, traveling 350% farther than an untrained model. However, the AI could not yet beat the simulator's most advanced human-designed driving algorithm on complex courses. Implications of this study suggest that AI-to-AI with continuous feedback training can significantly speed up learning in autonomous systems by removing the human bottleneck. This approach may pave the way for AI systems that self-improve in real time in fields like robotics and coding. Future work will explore enhancing the feedback loop for more complex scenarios and integrating reinforcement learning to further boost performance.

Background

AI plays an increasingly important role in daily life, yet even advanced AI systems can make mistakes that require human intervention to identify and correct. This process is often time-consuming and depends on human expertise, which may not always be available. Leveraging AI's capabilities to analyze and improve other AI systems could fundamentally change how AI learns and evolves. Such an approach offers key advantages: AI systems can operate continuously without human scheduling constraints, and they can process vast amounts of data at speeds far beyond human capacity. In other words, if an AI could teach another AI, the cycle of improvement might accelerate dramatically.

One area to test this idea is self-driving cars, where safety and learning from mistakes are critical. Modern self-driving algorithms typically improve either through human engineers tweaking code or through machine learning on large datasets. For example, deep reinforcement learning has been used to train autonomous driving agents in simulation. Chen *et al.* (2019) demonstrated that a deep recurrent reinforcement learning network can solve simulated

self-driving tasks by learning through trial and error, rather than relying on a fixed dataset [1]. However, pure reinforcement learning often requires many training episodes. It also lacks transparency, because it is hard to see how the model improves its decisions. On the other hand, human engineers can analyze specific failure cases (like a crash) and adjust the algorithm, but this manual process is slow.

This project investigates a different paradigm: using one AI to provide feedback to another AI in order to optimize performance, inspired by the concept of backpropagation in neural networks. Recently, researchers have proposed frameworks for *"automatic differentiation via text,"* in which language models feed textual feedback into an AI system to improve another AI system [2]. Yuksekgonul *et al.* (2024) call this approach "TextGrad," essentially backpropagating feedback from a language model to refine components of another AI [2]. Our work applies a similar idea in a physical context – a self-driving car simulation – by having one AI agent analyze driving mistakes and suggest code improvements to another.

Crucially, unlike straightforward question-answering tasks handled by generative AI, autonomous driving is a continuous learning environment where there may not be a single correct answer for every situation. The system must learn a policy (how to drive) through experience. By modeling AI feedback on the backpropagation principle, the aim is to enable the driving AI to *learn from its own mistakes* without a human in the loop. If successful, this method could reduce errors faster and more efficiently than traditional human-guided debugging, pointing to new ways AI can self-optimize in real-world tasks.

Hypothesis

It was hypothesized that using two AI systems in a feedback loop (an "AI-teaching-AI" design) would improve the performance of a self-driving car algorithm beyond what is achieved by either a human-coded algorithm or a single AI running alone. In particular, the backpropagation-style training with dual AIs was expected to significantly increase the distance the autonomous car could drive without crashing, and to do so more quickly than human-driven improvements. In other words, if one AI analyzes crashes and instructs another AI how to adjust its driving code, the autonomous car's performance should surpass both the original human-written driver and a conventional AI lacking such feedback.

Materials

Simulation Environment: All experiments were conducted using the F1Tenth autonomous racing simulator, an open-source 1/10th scale self-driving car environment. This platform provides realistic racecourse simulations with sensor data (such as LIDAR scans and telemetry) for a virtual car [3]. The simulator was configured via OpenAI Gym interfaces, allowing custom tracks and programmatic control of the car's driving algorithm. Several track layouts of varying difficulty were used, including simple oval tracks and more complex courses with sharp turns and obstacles (for example, an "Sochi Obstacles" track modeled after a real racing circuit).

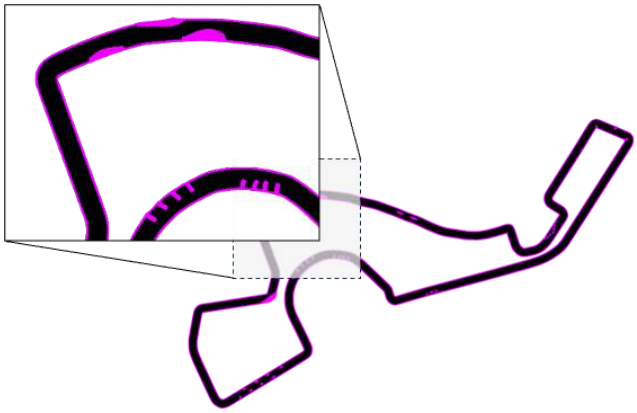


Figure 1. "Sochi Obstacles" course used in testing. This track contains narrow sections and sharp turns that challenge the baseline driving algorithm.

Driving Algorithms: Three levels of driving algorithms were available to serve as baselines: a Basic driver (simple default code), an Intermediate driver (moderately optimized), and an Advanced driver (a highly optimized human-coded algorithm). These baseline algorithms, provided by the simulator or written beforehand, attempt to navigate the car around the track using traditional coding approaches (no machine learning). They were used to compare how much improvement the AI feedback loop could achieve at different starting skill levels.

AI Agents: Two large language model (LLM) based AI agents were employed (using OpenAI 4o and Anthropic Sonnet 3.5):

- A "Coding AI" agent maintained and executed the driving algorithm. It could take code suggestions and integrate them into the driving program.
- "Feedback AI" agent analyzed crash data and recommended improvements in plain English and pseudo-code. (In some trials, these roles were swapped or both agents were tested in the feedback role to compare their effectiveness.)

Both AI agents were accessed via their APIs and prompted programmatically. They use advanced natural language understanding to interpret logs and generate code. Notably, these models have a limited *context window* (amount of recent information they can consider), which became a factor in how much crash history could be fed back effectively.

Crash Logging System: A custom logging mechanism was built into the driving code to record critical data leading up to each crash. This system captured:

- Sensor data: LIDAR readings (distances to track boundaries/obstacles) in the moments before the crash.
- Telemetry: vehicle speed, steering angles, and position coordinates for the last several time steps.
- Environment context: descriptions of track features (e.g. upcoming turn, obstacle proximity) when available.

The logging system was adjustable to include a variable number of steps prior to the crash (e.g. 0, 10, or 20 steps of history). These logs were saved as structured text and formed the

basis of the feedback AI's analysis.

Hardware/Software: The simulation and AI interactions were run on a standard PC. The code was written in Python, leveraging the OpenAI Gym interface for F1Tenth and API calls to the OpenAI and Anthropic models for AI responses. No specialized hardware (like GPUs) was required beyond a normal computer to run the simulations and AI queries. The code and data from all trials were saved and later uploaded to an open-source repository for verification and further research.

Procedure

1. Establish Baseline Performance: First, the F1Tenth simulation was set up with a basic driving algorithm (the "Basic" driver) to obtain an initial performance baseline. The car was run on a simple track to see how far it could go and how it behaved. Key metrics recorded were:

- Distance traveled before a crash or off-track event (in meters).
- Lap completion: whether the car could finish a full lap without crashing.
- Time to complete a lap (or time until crash if it didn't finish).
- Average speed (m/s) during the attempt.

These baseline tests were repeated on a variety of courses: from easy (wide turns, few obstacles) to hard (sharp turns, narrow passages, obstacles). For each run, it was noted if the car crashed and where. This established a performance reference for "no AI feedback" and also for different difficulty tracks. For example, with no AI assistance, the Basic driver might crash very early on a complex track (as observed, about 91 m traveled on one course before crashing with no AI).

2. Implement Crash Logging: The driving code was then instrumented with the crash logging system. For every run, if the car crashed, the program would output a log containing the recent history of sensor readings and actions. Different logging window sizes were tested:

- *0-step log:* (no history, only the moment of crash) – essentially provides the conditions exactly at the crash.
- *10-step log:* the sequence of states and actions for roughly the last 10 time steps (a few seconds) before the crash.
- *20-step log:* a longer history leading up to the crash.

The hypothesis was that a certain amount of context would be ideal: too little might not tell *why* the crash occurred, while too much could include irrelevant data that confuses the AI. These logs were saved in a readable format (including numeric values and some plain-language description of events).

3. AI Feedback Loop (Backpropagation Simulation): Next, the two-AI feedback loop was initiated (Figure 2). After each simulated drive (lap attempt):

- If the car crashed, the log file was fed into the feedback AI (Anthropic or OpenAI). The feedback AI was prompted to act as a driving instructor or code reviewer: it received a description of the driving algorithm and the crash log, and was asked to analyze the cause of the crash and suggest conditions the code AI should consider for

future changes. The AI's response was captured, which typically included an explanation of the mistake and a recommended code snippet or logic tweak.

- The coding AI then took the feedback and applied it to the driving algorithm's code. This allowed the coding AI to update the algorithm autonomously without human intervention.

This process emulates backpropagation: instead of a mathematical gradient, we use the *textual feedback from one AI as the "error gradient"* to update the other AI's behavior. After applying the change, the simulator was re-run with the modified algorithm to see if performance improved.

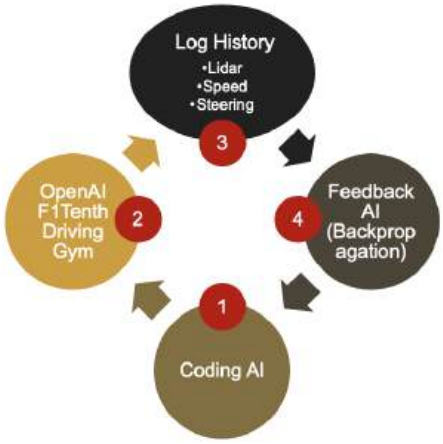


Figure 2. Diagram of the AI-to-AI Backpropagation feedback loop using the log history.

4. Iterative Training: The above feedback cycle was repeated for multiple generations. Up to five iterations of AI-to-AI feedback were conducted for each scenario. In each iteration, the car would (hopefully) crash a bit later or maybe complete the lap, and new logs would drive further refinements. This was to observe cumulative improvements and whether there were diminishing returns or overfitting. If the car completed a lap without crashing, that algorithm version was considered a success for that track. We noted at which iteration the most significant gains occurred.

5. Comparative Testing: After training the AI-improved driver on the basic track, we challenged it with new scenarios:

- The improved algorithm was tested on a different track (of medium difficulty) that it had never seen, to assess *transference*. This tested whether the lessons learned on one course (e.g., how to handle turns or obstacles) would generalize to another course. Performance (distance traveled before crash, etc.) on the new track was compared between the AI-trained driver and an untrained baseline driver.
- The AI feedback process was also applied to the Intermediate and Advanced algorithms as starting points. For these cases, the baseline performance was much better (especially for the Advanced algorithm), so we wanted to see if the AI

feedback still provided gains or if it struggled to improve an already competent driver. Each was run through the same multi-iteration feedback training on courses of matching difficulty (Intermediate algorithm on intermediate-level track, Advanced on an advanced-level track).

- The role of the logging window was formally tested: runs were conducted where the crash log length was varied (0 vs 10 vs 20 steps) to see which led to the best improvements after a fixed number of iterations.
- A head-to-head comparison between the two AI models (OpenAI's vs Anthropic's) was performed. In separate trials, GPT 4o was used as the feedback agent for a set of runs, and Sonnet 3.5 for another identical set of runs (starting with the same baseline and track). Both were given the same initial conditions and number of iterations. We then compared which AI's feedback produced better driving outcomes (distance, crashes avoided, etc.). This was done to identify if one model was more effective or insightful in improving the driving code.

Throughout all tests, careful records were kept of each lap attempt's outcome, the AI suggestions, and the resulting performance changes. After completing the experiments, the data was analyzed across all these variables to evaluate the hypothesis.

Trial Count Summary

Category	Condition	Trials	Iterations	AI Model	Logging Window
Baseline	No AI	5	N/A	None	0
Single AI	Coding AI Only	5	N/A	OpenAI / Anthropic	0
Two AIs	Backpropagation AI-to-AI	5	1–5	OpenAI / Anthropic	10
Course Type	Basic	10	1–5	Both	0 / 10 / 20
Course Type	Intermediate	10	1–5	Both	0 / 10 / 20
Course Type	Advanced	10	1–5	Both	10
Driver Alg.	Basic	10	1–5	Both	0 / 10 / 20
Driver Alg.	Intermediate	10	1–5	Both	10
Driver Alg.	Advanced	5	1–5	Both	10
Transfer Test	Unseen Track (Medium)	5	N/A	Both	10
Total	All Configs	60	1–5	Both	Varies

Table 1. Summary of all trial configurations and counts used in this study.

Results

The AI-to-AI backpropagation training produced clear improvements in the self-driving performance. Key findings from the experiments are outlined below:

- Two AIs vs. One AI vs. No AI: Backpropagation with two cooperating AIs significantly outperformed both a single AI and no AI at all. Starting with the Basic driving algorithm on a challenging track, the average distance traveled with no AI assistance was approximately 91 meters of travel before crashing (essentially failing very early). Adding a single AI (where the AI could suggest changes *once* but without iterative feedback) improved the average distance to 120 m before crash. However, using the dual-AI iterative feedback loop, the car was able to complete the entire track (234 m) without crashing. This suggests the backpropagation design took a car that initially could not finish a lap and enabled it to finish with ease. This is a significant improvement – almost 3 times farther than the no-AI case. Figure 3 illustrates the average distances traveled under these three conditions, showing the two-AI system reaching nearly 2 times the distance of a single AI and vastly more than no AI. Qualitatively, the AI-guided improvements included better steering into turns and more cautious speed control, which prevented the early crashes that plagued the baseline runs.

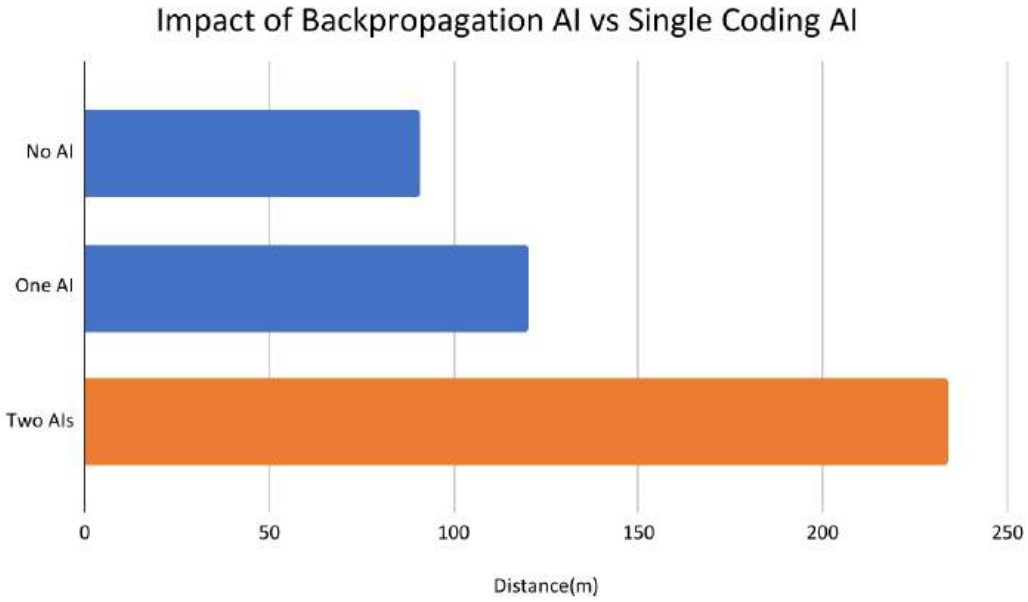


Figure 3. Average distance traveled across multiple trials for three conditions: no AI assistance, a single coding AI, and a dual-AI backpropagation system. The dual-AI approach achieved the highest average distance and was the only condition to complete the track across averaged trials.

- Effect of Crash Log Window Size: There was a “sweet spot” in how much crash history to feed to the feedback AI. With no prior steps (0-step log), the feedback AI struggled to identify the cause of crashes beyond generic advice, yielding limited improvement (similar to the single AI distance approximately 27 m). When providing a

moderate context of 10 steps before the crash, the AI got enough information about the lead-up (such as noticing a sharp turn was missed) and suggested effective fixes – this was the condition that produced the 234 m full-lap success mentioned above. Interestingly, using an even larger context of 20 steps led to worse outcomes than 10 steps. The 20-step log runs achieved an average of 38.7 m before crashing, only slightly better than giving no context (Figure 4). We observed that with too much data, the AI sometimes gave overly broad or irrelevant suggestions (it "over-thought" the problem). In summary, a concise log focusing on the immediate moments before the crash proved most useful for feedback. (This may relate to the AI's fixed context window—Claude and ChatGPT could lose focus or run out of effective memory with very long prompts.)

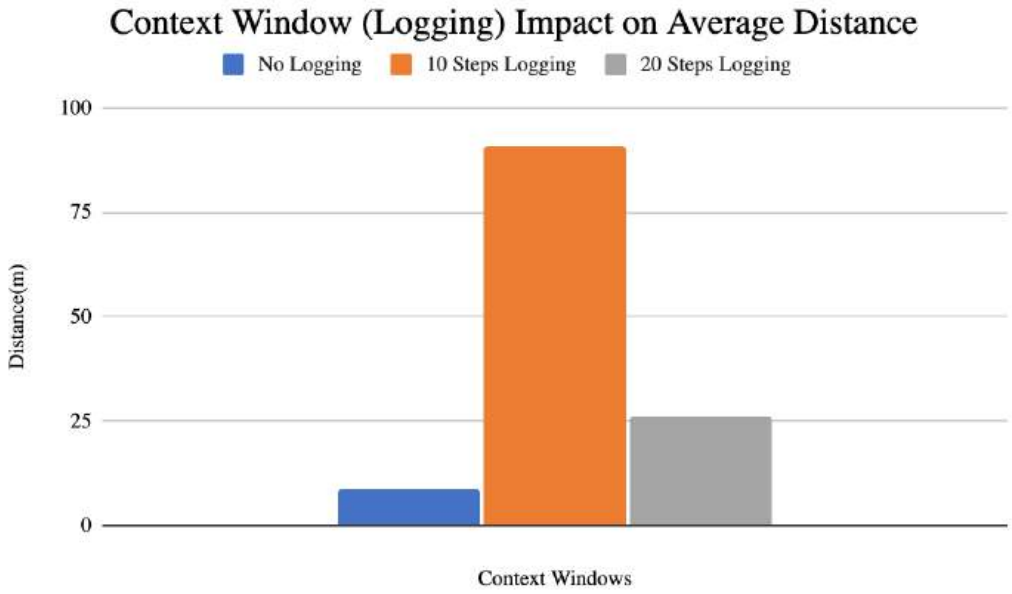


Figure 4. Effect of crash-log context window size on average performance across trials. A 10-step context window produced the highest average distance, while 0-step and 20-step windows resulted in significantly lower average performance.

- Basic vs. Intermediate vs. Advanced Algorithms: The magnitude of improvement from the AI feedback loop depended on the initial skill of the driving algorithm:
    - For a Basic driver (very poor initial performance), the improvement was enormous – from about 91 m to 234 m on the test track, as noted. The AI effectively taught the novice driver how to handle the course entirely.
    - For an Intermediate driver, which occasionally completed laps (baseline approximately 174 m on the test track used), the AI feedback still helped but less dramatically. After AI training, the intermediate algorithm's best distance increased to 205 m on that track, a modest improvement. Some crashes were

prevented, but many baseline capabilities were already near optimal for that level of difficulty.

    - For the Advanced algorithm, which was a highly tuned human-written driver, the AI interventions did not yield an improvement. In fact, performance slightly *decreased* in efficiency: the AI-altered advanced driver went roughly the *same distance* as the original (no significant distance gain), but took 74% longer to finish, meaning it drove much more slowly. Essentially, the AI suggestions for the advanced driver made it overly cautious, which eliminated any crashes but at the cost of speed. Additionally, some fine-tuned behaviors of the expert algorithm might have been disrupted by the AI's generic suggestions. This result was notable: the AI could not outperform a human expert's coding for the hardest scenario, highlighting a current limitation. The advanced human algorithm remained the best on complex courses, although the AI version was safer (no crashes, just slower).

- OpenAI vs. Anthropic AI Performance: Both large language models used for feedback (OpenAI's GPT-4o and Anthropic's Sonnet 3.5) contributed significant improvements, but Sonnet had a slight edge in performance. Across multiple trials, the car guided by Sonnet feedback traveled further on average than with GPT-4o feedback. Specifically, using Sonnet as the feedback agent resulted in an average distance of approximately 269 m before crash across test scenarios, whereas GPT-4o feedback averaged approximately 219 m. Both vastly outperformed the non-AI baseline distances (Figure 5), except in the advanced algorithm case as noted. The Anthropic model's advantage (approximately 23% further distance on average) could be due to how it interpreted the logs or the style of its code suggestions. We observed Sonnet's recommendations were sometimes more detailed in context (perhaps leveraging a slightly larger context window), which might have better addressed the edge cases. However, both AI agents were effective overall, and the differences, while consistent, were not extreme. It suggests that the concept of AI feedback is robust across different AI systems, though the specific model can influence the degree of improvement.

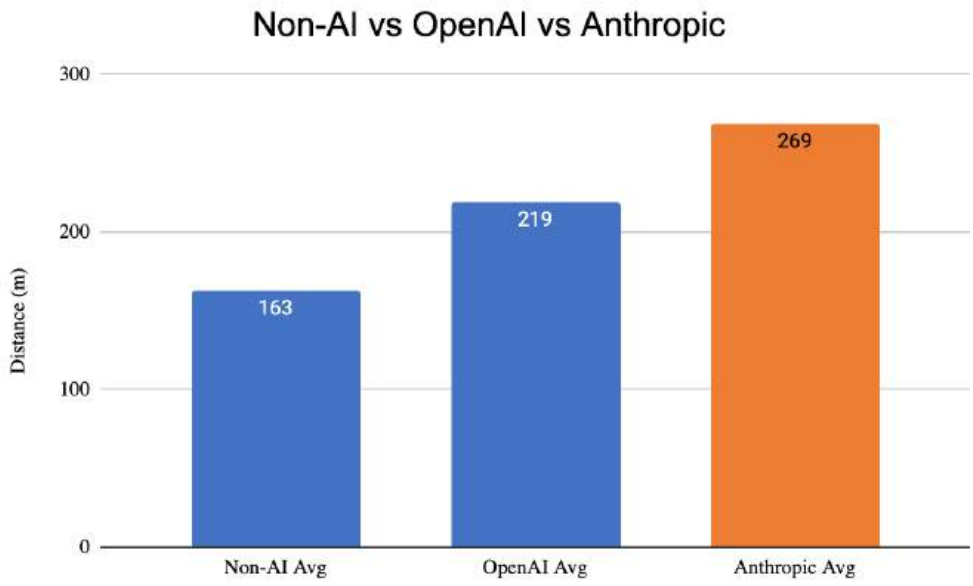


Figure 5. Comparison of average distance traveled using either GPT-4o or Sonnet 3.5 as the feedback agent. Sonnet achieved higher average distance across repeated trials.

- Transference to New Courses: After training on one track, the AI-improved driver was tested on a different medium-difficulty track to see if the learned skills would carry over. The new track proved challenging – the model that drove flawlessly on the basic track could only complete about 28% of the new track before crashing. This shows that the AI's improvements were somewhat specialized to the training course. However, when compared to the original baseline on the new track, the trained AI driver still did much better: it went approximately 350% further (an extra 68 m) than the untrained version on that same unfamiliar course. In practice, the trained AI driver navigated through several turns successfully on the new track before encountering a scenario it hadn't seen and crashing, whereas the untrained driver failed almost immediately. This indicates that while the AI training was not enough to master a new course entirely, it did impart more generalized driving skill that provided a substantial benefit. In short, some learning transferred to a different environment, but not enough to avoid all new mistakes. Future training across multiple tracks or more diverse data might improve generalization.
- Performance Over Training Iterations: The effect of multiple AI feedback iterations was examined. We found that most of the benefit was achieved within the first few rounds, based on average distance metrics across repeated trials of back-and-forth training. In early iterations (1st and 2nd), the performance sometimes decreased or fluctuated as the AI experimented with changes – analogous to an initial learning phase where the system hasn't yet found good adjustments (Figure 6). By the 3rd iteration, the AI-enhanced driver began to consistently outperform the original human-coded

algorithms (at least for basic and intermediate cases). The 4th iteration often produced the best performance model on average, as the AI had accumulated enough feedback to handle most trouble spots on the track. By the 5th iteration, we observed a slight degradation in performance in several cases. This could be a sign of overfitting or the AI overshooting optimal adjustments – the driving code became too tailored to the specific scenarios it encountered and started to do worse on average, possibly making it less adaptable. Therefore, there appears to be an optimal number of AI feedback rounds (around 3–4 in our tests) beyond which additional feedback did not help and sometimes hurt.



Figure 6. Average performance across five backpropagation training iterations, averaged across multiple trials. Improvements peaked around iterations 3–4, with declines in iteration 5.

- Speed vs. Safety Trade-off: An interesting side effect noted was that the AI-optimized drivers were slower on average than the human-coded ones. The baseline (non-AI) algorithms typically drove at higher speeds, averaging nearly 4 m/s on straightaways, whereas the backpropagation-trained AI drivers averaged around 2 m/s, roughly half the speed (Figure 7). Consequently, even when the AI driver completed a lap without crashing, its lap time was longer than the human driver's time. The AI essentially chose to go slower to avoid crashing – prioritizing safety over speed. This makes sense, as our feedback loop's goal was purely to minimize crashes and maximize distance, and the AI was not explicitly told to optimize time. It highlights a common issue in autonomous driving: driving very cautiously can reduce accidents but might not be efficient. In this project, this outcome was expected and acceptable because the hypothesis focused on reducing crashes rather than improving lap time. However, it

suggests that in real-world applications, a balance between safety and efficiency would need to be struck, perhaps by incorporating speed goals into the AI's objectives in future iterations.

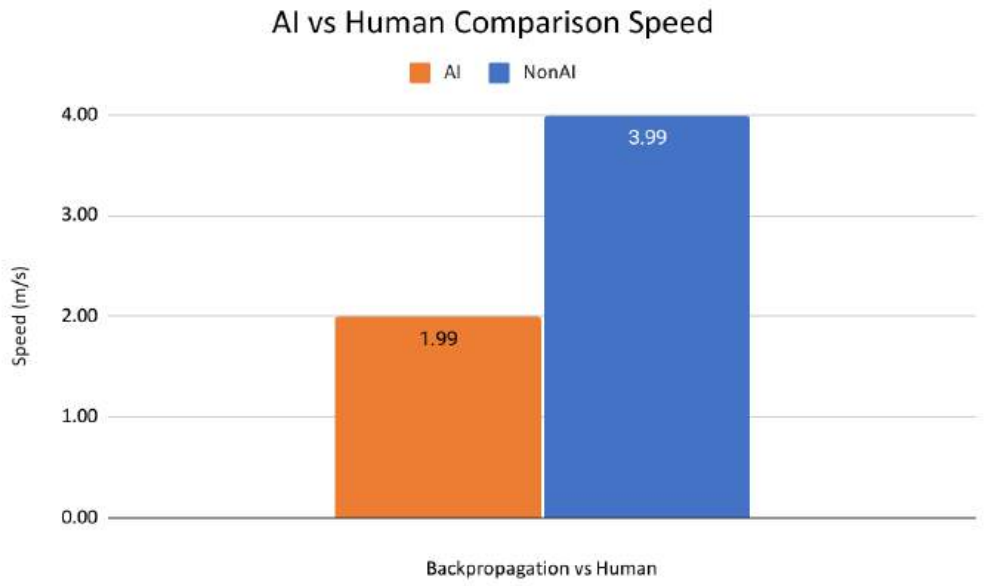


Figure 7. Comparison of average vehicle speed for human-coded algorithms vs. AI-optimized drivers. AI-trained drivers prioritized safety, resulting in slower but more crash-free laps.

Overall, these results strongly support the hypothesis that an AI-to-AI backpropagation approach can improve an autonomous system's performance. The dual-AI system learned to drive significantly better than a solo AI or the unassisted algorithms in most cases. The limitations (such as struggling with an already expert algorithm or new environments) provide valuable insights for further refinement.

Discussion

The success of the two-AI feedback loop in improving the self-driving car's performance demonstrates the feasibility of AI-driven optimization for AI systems. In essence, the experiment showed that an AI can play the role of a human expert (diagnosing failures and suggesting fixes) and do so rapidly and iteratively. This confirms the hypothesis that backpropagation-style AI-to-AI training can yield superior results to one-off AI assistance or human-only development, at least in constrained environments.

One of the most significant findings was that the AI feedback loop quickly taught the car to avoid crashes on a track that initially confused the basic algorithm. By the third or fourth iteration of training, the AI-enhanced driver had internalized solutions to the major failure modes (e.g., slowing down before sharp turns, correcting steering when obstacles are detected). This rapid learning is similar to how standard backpropagation in neural networks reduces error over successive training epochs. Here, instead of a mathematical gradient, the gradient was *conceptual*

and delivered in natural language: Sonnet 3.5 or GPT-4o essentially said "if X caused a crash, do Y instead." This approach aligns with the concept introduced by Yuksekgonul *et al.* that textual feedback can serve to improve AI components in a pipeline [2]. Our results apply this idea in a practical robotics scenario, suggesting that language models can indeed be used to fine-tune the behavior of another AI agent in real-time.

The outcome where the AI could not improve the Advanced human-written algorithm is also enlightening. It indicates that there are still scenarios where human expertise embed qualities in the algorithm that the AI feedback cannot easily replicate or enhance. The advanced driver was likely near a performance ceiling for that track (in terms of an aggressive yet successful driving style). The AI's tendency was to make it more cautious to ensure no crashes, which in a way *reduced* the performance metric we hadn't optimized for (speed). This highlights an important consideration: defining the right objective. Our training implicitly optimized "don't crash" above all. A human programmer for the advanced driver presumably balanced competing goals (fast lap vs. low risk). Thus, the AI did what we asked (no crashes) but at the expense of another metric. In future work, a multi-objective reward (e.g., minimize crashes *and* lap time) or a more nuanced feedback process could potentially allow AI to also tackle advanced performance tuning. It's worth noting that current language models lack true long-term planning and only know what they are explicitly told or have seen in their training data. A human expert's intuition and holistic view of the driving task gave the advanced algorithm an edge that the AI, working purely from crash logs, did not overcome. This points to a limitation in the scope of AI feedback – it excels at addressing known failure patterns, but might struggle to invent entirely new strategies that a creative human might.

Another discussion point is the optimal amount of information for feedback. The experiments with log window size showed that more data isn't always better for a language model's analysis. With 0 steps, the feedback AI lacked context; with 20 steps, it seemed overwhelmed or distracted by extraneous details. At 10 steps, it had the critical recent events that caused the crash and could focus on those. This finding could inform how we design prompts for AI trainers: focused, relevant data yields the best guidance. It also suggests that current AI models effectively operate within a limited context window and can lose track of relevant details if the prompt is too long. This is consistent with the known token limits of models like GPT-4o and Sonnet 3.5. Future larger-context models or techniques to summarize long logs could allow more complex feedback without overload.

The head-to-head comparison of GPT-4o vs. Sonnet 3.5 hints at differences in AI reasoning styles. Sonnet performing approximately 23% better might be due to its training or possibly a larger context length (Sonnet is known for handling long documents well). It might have kept more of the log in mind when formulating advice. However, since both improved the driver significantly, the core mechanism is robust. This also underscores the point that as AI models improve, their ability to coach other AIs should improve too. We can expect that next-generation language models with better understanding of cause and effect (or even some built-in code analysis abilities) could provide even more effective feedback. The concept of *AI*

feedback agents may become a standard tool in software development and autonomous systems: an AI debug assistant working alongside human engineers.

The fact that the AI-trained driver generalized partly to a new track is encouraging. It means the AI wasn't just overfitting to one specific course's quirks; it learned some transferrable driving principles (e.g., how to adjust speed for turns in general, not just a particular turn). However, the incomplete transfer (only 28% of the new track) also tells us that the training was somewhat specialized. Likely the AI taught the car about scenarios it saw, and the new track introduced a scenario (perhaps a combination of obstacle and turn, or a different curve shape) that it hadn't encountered. To improve generalization, training could incorporate a variety of tracks or incorporate reinforcement learning so the AI can experience more diverse situations during the feedback process. In essence, the feedback loop could be expanded into a broader training regimen covering multiple environments to produce a more robust driving policy.

One notable consequence of our approach was the emergent behavior of prioritizing safety over speed. This wasn't explicitly coded but arose because the feedback AI's mandate was to "reduce crashes." In every suggestion, the AI naturally tended to recommend caution: slow down here, don't take that turn so sharply, etc. The resulting driver was extremely safe (zero crashes on the training course after enough iterations) but slower. This result is not a failure; rather, it highlights how the goals we set translate directly into AI behavior. If a different balance is desired, we would need to include that in the feedback criteria. It is representative of a larger AI ethics question: if we train AIs with a single objective, they might over-optimize for it at the expense of other considerations. In self-driving cars, a balance is needed between safety and practicality. A next step could be to introduce a secondary AI or rule that encourages speed once crashes are minimized.

Implications: This project's findings suggest that AI systems can be used to accelerate the learning and optimization of other AI or code-based systems. In practical terms, this could transform how we approach debugging and improving complex algorithms. Instead of waiting for human analysis of failures (which could take days or weeks), an AI pair could cycle through solutions in minutes. For instance, in robotics or software development, whenever an error occurs, an AI could immediately propose a fix – essentially an always-on *autonomous debugger*. Our results showed this working in a simulated car; one can imagine similar setups in other domains. The concept is especially relevant in fields where simulation is possible or failures are frequent: robotics, autonomous drones, even software compilation or data center optimization. By the time a human checks in, the AI might have already eliminated many trivial bugs and tuned the system's performance to a higher baseline.

From an educational perspective, this experiment also demonstrates the power of combining critical thinking with cutting-edge AI tools. The idea stemmed from recognizing a limitation (AIs need humans to fix them) and creatively applying a known concept (backpropagation) in a new way. It shows that students equipped with modern AI APIs and a solid conceptual understanding can contribute meaningfully to AI research.

Conclusion

In summary, the project successfully validated that an AI-driven backpropagation-style feedback loop can optimize a self-driving car algorithm beyond what was achievable with manual coding or a single-pass AI assist. The two-AI system (one driving, one coaching) was able to identify mistakes and iteratively correct them, resulting in the autonomous car completing courses that previously caused it to crash. The hypothesis was confirmed: AI can indeed be used to train AI, yielding improved performance in a complex task. This approach reduced the reliance on human intervention and achieved faster learning cycles – the car improved in a matter of a few simulated runs, a process that might have taken a human programmer much longer.

There are, of course, boundaries to this approach: it could not yet surpass the most advanced human-created solution in the hardest scenario, and its lessons didn't fully generalize to every new situation. However, these limitations point toward clear directions for future research. By enriching the feedback (perhaps involving additional AI perspectives or longer training across diverse scenarios) and by refining objectives (incorporating metrics like speed), there is potential to further enhance the effectiveness of AI-to-AI training.

Ultimately, *Optimizing AI Systems through Backpropagation* provides a promising glimpse into a future where AI systems autonomously improve each other, minimizing the need for continuous human oversight in iterative learning tasks. Such a future could accelerate progress in technology development, with AI quickly ironing out the kinks in everything from self-driving cars to software code, and humans moving into a higher-level supervisory and creative role. The project's findings contribute to this vision, demonstrating that even at the 8th-grade research, meaningful innovation in AI methodology is possible.

Acknowledgements

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A Review of Conventional & Alternative Treatments of Alzheimer's Disease & Proposed Combo Treatment By Owen Gavrila

Abstract

Alzheimer's Disease (AD) is a neurodegenerative disease that causes the loss of communication between neurons in the brain, eventually resulting in their death and a massive loss in cognitive function and ability. Scientists prioritize buildups of amyloid-beta protein (Aβ) plaques and tangles of hyperphosphorylated tau proteins as the leading causes of the loss of neural intercommunication and the hallmarks of AD. The purpose of this review paper is to explore a conventional preventative treatment for AD used in medicine today, as well as multiple alternative and rather untested treatment options. The primary treatment options for AD are drugs that work to clear Aβ plaques and tau tangles from the brain; however, they have varying side effects among patients, are not a cure for AD, and can be very expensive. Alternatively, treating AD through diet, the gut microbiome, electrical stimulation, and glymphatic stimulation has also been explored. Each area has shown very promising results after recent testing, as cognition and quality of life are frequently significantly improved. Using a combination of information acquired, this review also suggests a possibility for a new treatment option using probiotics to address deficiencies in the gut microbiome of patients with AD, potentially combating or halting the progression of the disease early on. The purpose of this review, outside of exploring treatment options, is to educate about the basics of AD and to introduce the idea that there are many different ways to treat AD.

Keywords: Alzheimer's Disease; Dementia; Neurodegenerative; Amyloid-Beta; Tau; Lecanemab; Diet; Ketogenic Diet; Gut Microbiome; Electrical Stimulation; Lymphatic System; Glymphatic System

Introduction

Dementia is an umbrella term that encompasses many different neurodegenerative diseases, the most common of which is Alzheimer's disease (AD). Dementia itself has been written about for thousands of years, with early descriptions first appearing around the Greco-Roman period. However, it wasn't until around 120 years ago that Alois Alzheimer discovered an "unusual disease of the cerebral cortex." His mentor, Emil Kraepelin, later named the condition Alzheimer's disease in his honor (1).

According to the Alzheimer's Association, there are currently nearly 7 million Americans living with AD, and this number is expected to rise to around 13 million by the year 2050 (2). AD is a neurodegenerative disease in which the loss of communication between neurons causes them to die, resulting in the shrinkage of the brain and loss of cognitive function. Common symptoms of AD include memory loss, frequent confusion, difficulty with problem-solving and decision-making, and mood swings (1). AD most commonly affects people aged 65 or older; however, in rare cases, early-onset AD can affect people as young as 40.

The current leading hypothesis for the causes of AD presents two factors as the main source of the disease: Aβ plaques and hyperphosphorylated tau protein tangles. Aβ proteins are used in the brain for a multitude of biological processes; however, the issues begin when these proteins begin to form large plaques that interrupt signaling between neurons in the brain. Tau proteins work to stabilize microtubules that exist within neurons; however, they can become hyperphosphorylated, causing them to be unable to bind with microtubules and instead bind with other tau proteins, causing tangles within neurons. The combined chaos of tangles on the inside of the neurons, as well as the plaques building up on the outside, prevents the cells from transporting materials needed to function, and results in eventual cell death. While there have been many drugs developed targeting these plaques and tangles, they have been mostly unsuccessful since results can vary greatly between patients. Because the causes of AD are still not fully known or understood, slowing the progression of AD in patients has been less successful than expected, and a cure has not been determined. Therefore, within the past 30 years, scientists have focused on other factors perpetuating AD, and thus, treatments have been devised to focus on those factors outside plaques and tangles. The purpose of this review paper is to explore alternative treatments to AD, such as the effects of one's diet, treatment via electrical stimulation, and the impact of the glymphatic system, as well as conventional, widely-used drug treatments.

Methods

The database PubMed was used to identify sources using keywords such as "Alzheimer's Disease" and "Lecanemab" (a medication commonly prescribed for early-stage dementia), "Diet", "Electrical Stimulation", "Gut Microbiome", or "Glymphatic System". The studies that were selected and used in this Review included recent (2021 - 2025) clinical trials available in English that tested subjects with different stages of AD from areas around the world. The studies included the effects of pharmaceutical medication, diet, electrical stimulation, and sleep on the cognitive decline caused by AD. Studies that were excluded from this review included summaries of clinical trials rather than trials with available data.

Results

Conventional Treatments

Medication: Lecanemab

The most common form of treatment for AD is pharmaceutical medications that aim to clear out Aβ protein plaques and tau protein tangles, which are the main hallmarks of AD. A relatively new treatment that was released in 2023 is the drug known as Lecanemab, which targets buildups of Aβ proteins and prevents future formation. The drug is an antibody that binds to soluble Aβ protofibrils – more toxic forms of Aβ plaques – and "marks" them to be broken down by the body's immune system (4). During the testing phase of the drug, a group in 2021 tested different concentrations of Lecanemab (2.5 mg/kg biweekly, 5 mg/kg monthly, 5 mg/kg

biweekly, 10 mg/kg monthly, and 10 mg/kg biweekly) on subjects with mild cognitive impairment caused by AD or mild AD dementia (5). The study aimed to reach a threshold of an 80% probability of a 25% or more decrease in ADCOMS (AD Composite Score) for any one dose level over the placebo scores. The study found that the subjects receiving the target ED90 dose of 10 mg/kg biweekly had a 76% probability of scoring lower than the placebo by 25% on ADCOMS. While this did not reach the desired 80% threshold, other analyses computed by the group found that there was an upwards of 97% chance of any level of decrease in ADCOMS score over the placebo for the group receiving 10 mg/kg biweekly of Lecanemab. Although this shows positive progress from Lecanemab, the results still are not groundbreaking (it does not cure the disease), and can vary greatly for different individuals. This is on top of the fact that the drug is not a cure or prevention for AD; rather, it just slows its progression. Furthermore, the cost of the Lecanemab drug alone is on average $26,500 per year in the US (7), making it likely unattainable for those without medical insurance or government aid. Moreover, the drug does not even work for everyone, and for some, it can even have serious, life-threatening side effects (i.e., swelling and/or bleeding in the brain, anaphylaxis, and infection). There are many other drugs similar to Lecanemab that target Aβ and other potential causes of AD, such as tau tangles; however, they all show similar results. With the minimal efficacy and underwhelming results of conventional drug treatments for AD, a change in focus to more accessible, safer, and less expensive alternatives is reasonable.

Alternative Treatments

Diet

An area that can be frequently overlooked when considering treatments for AD is a patient's diet. A study from 2024 found that patients from Sweden, Finland, Germany, and France with prodromal AD (mild cognitive impairment) benefited significantly from both lifestyle and dietary changes (10; Figure 1). In the study, patients in the control group were given standard advice about diet and mental and physical exercise. The first intervention group was given dietary and exercise requirements as well as increased social activity for mental stimulation. The dietary requirements followed the Nordic Nutrition Recommendations (NNR) or were adapted to the specific recommendations of the patient's home nation (France or Germany). The second intervention group received the same dietary requirements as the first, with additional cerebral food supplement (Fortasyn Connect). Both intervention groups saw decreased rates of cognitive decline caused by AD, but the lifestyle + medical food group showed particular progress, as well as decreased vascular risk factors.

Another study from 2021 determined the effects of a ketogenic diet on those diagnosed with AD in the Hamilton, New Zealand, area (12). In the study, a total of 26 participants were studied. The first group (13) started with a ketogenic diet for 12 weeks, then transitioned into a generally recommended diet plan for another 12 weeks. The other group completed the same protocol in reverse (general diet for 12 weeks followed by ketogenic diet for 12 weeks). Overall, patients complying with the modified ketogenic diet in this study saw increased quality of life

and daily function compared to those following the generally recommended diet, with statistically significant mean individual increases in ADCS-ADL (Alzheimer's Disease Cooperative Study - Activities of Daily Living Scale) and QOL-AD (Quality of Life - Alzheimer's Disease) scores (Philips et al. 2021).

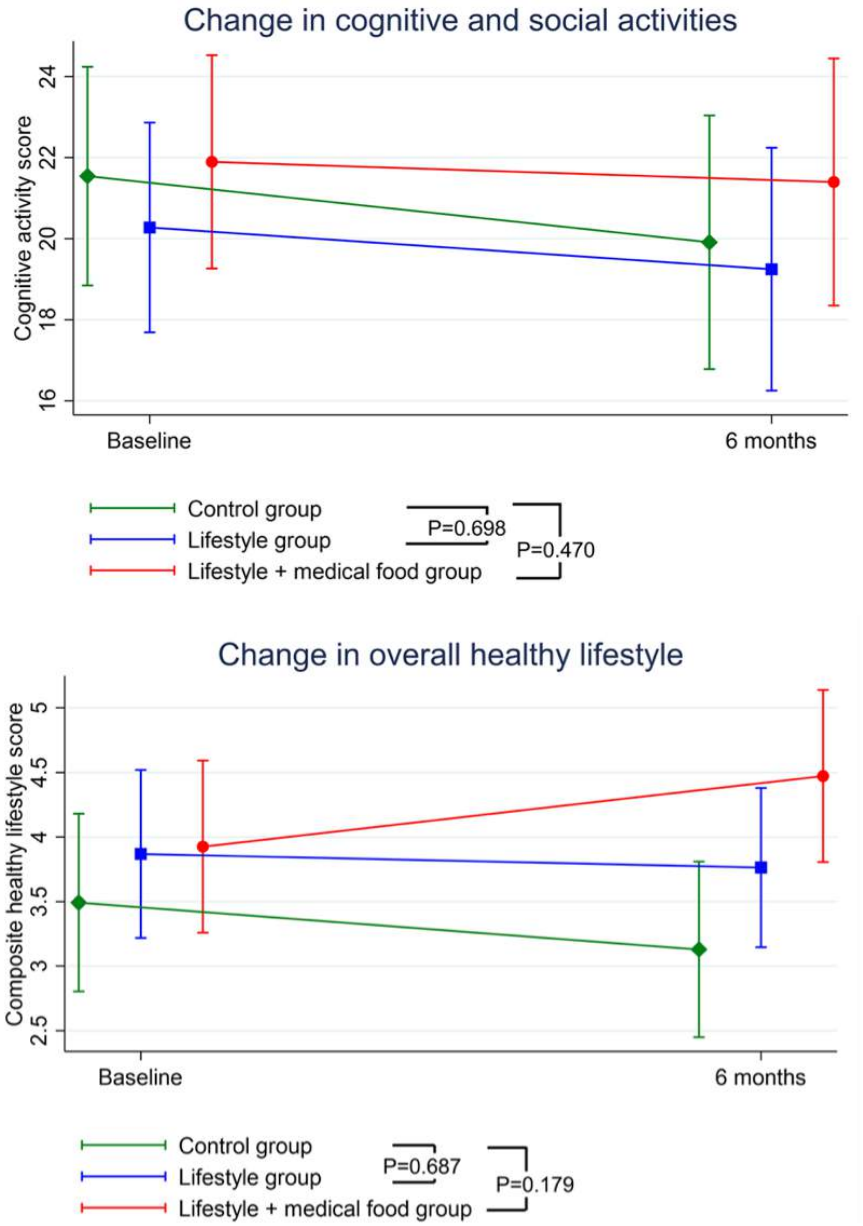


Figure 1: Change in cognitive and social activities as well as overall healthy lifestyle in patients with prodromal AD when following different diet and exercise plans, including a control group following general recommendations, a lifestyle group following specific exercise and social guidelines, and a lifestyle group also receiving brain health supplements (10).

Gut Microbiome

A novel approach to recognizing AD is through the microbiota in the gut. The human gut

contains over one trillion bacteria, of which there are numerous different species with varying purposes within the immune system. Many scientists believe that the communities of bacteria in a person developing AD differ substantially from a person without the disease (Figure 2), and perhaps the differences contribute to the onset of AD. According to a group from Washington, after performing fecal metagenomic sequencing (examining genetic sequence to determine microbiome composition through a fecal sample) on a group of cognitively normal individuals with and without preclinical AD, patients with confirmed preclinical AD had distinctly different gut microbial taxa than those without preclinical AD, specifically including *Dorea formicigenerans, Faecalibacterium prausnitzii, Coprococcus catus, Ruminococcus lactaris,* and *Anaerostipes hadrus*. Furthermore, it was found that the change in bacteria present correlated with Aβ and tau biomarkers for those with preclinical AD. However, there was no correlation with biomarkers of neurodegeneration (Figure 3), meaning changes in the gut occur very early on in AD development (13). Scientists further support that an imbalanced gut microbiome can lead to the overproduction of lipopolysaccharides, which can lead to brain inflammation and cause disruptions between neurons. They can also facilitate the formation of Aβ plaques.

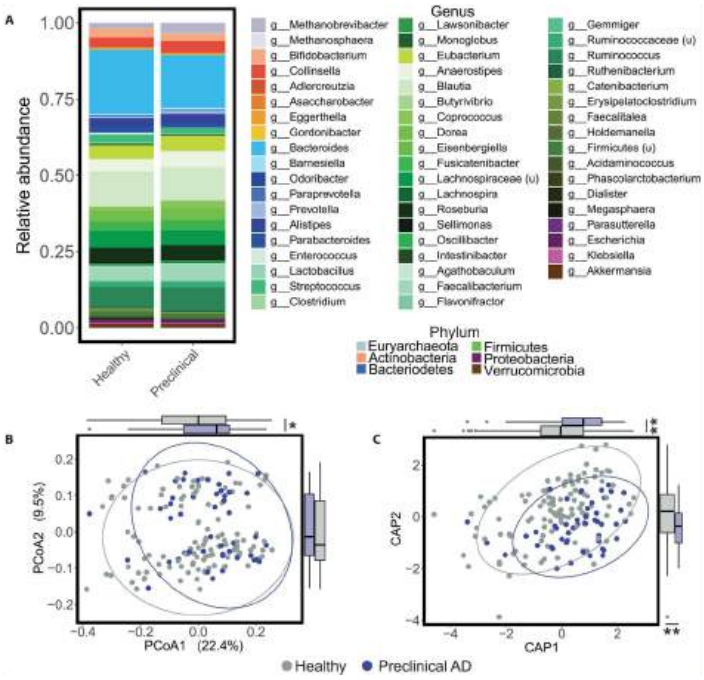


Figure 2: (A) Bar plots representing the relative abundance of specific genera of bacteria in the gut microbiomes of patients with and without preclinical AD. (B) Gut microbiome composition was different along the PCoA axis for healthy individuals and individuals with preclinical AD, after accounting for outside factors such as body mass index, diabetes, hypertension, etc. (C) Gut microbiome compositions were also different along the CAP axis (13).

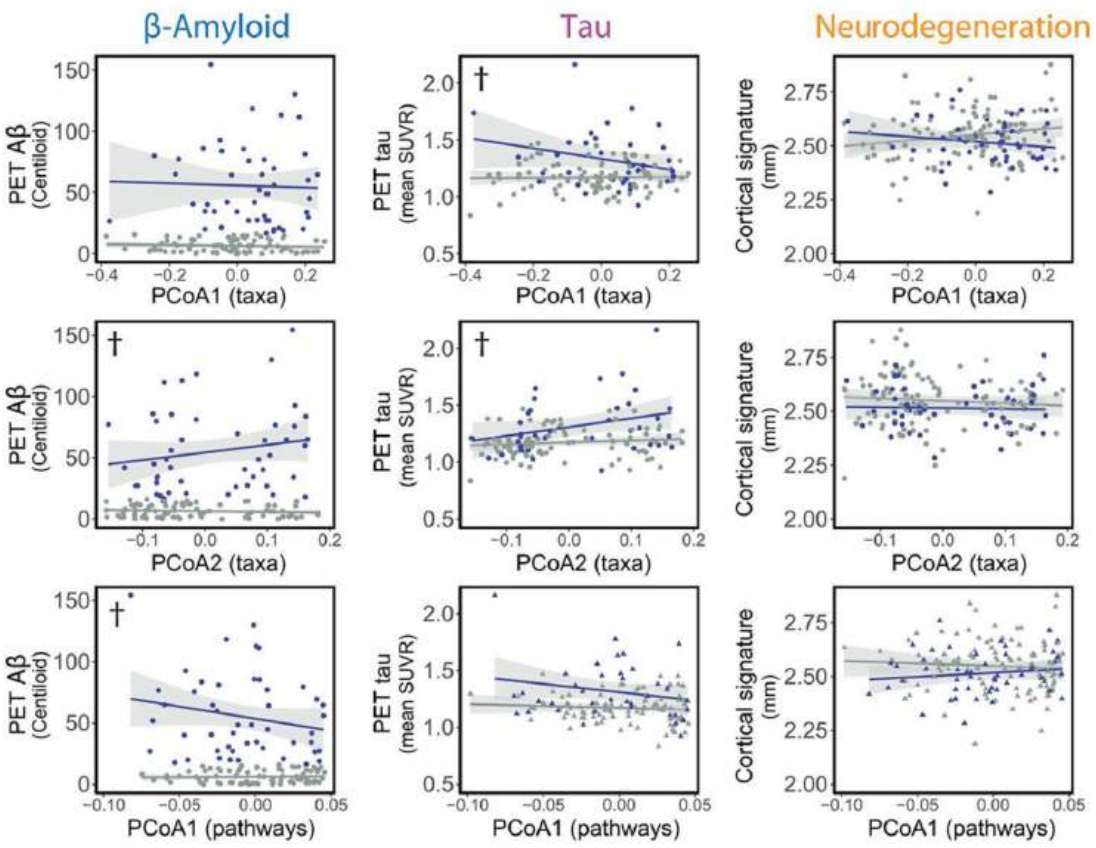


Figure 3: Linear regressions of PET Aβ, PET tau, and cortical thickness (a measurement of neurodegeneration for patients with AD), showing a significant difference in Aβ levels for patients with abnormal gut taxonomies represented in Figure 2B (13).

Electromagnetic Stimulation

A relatively new and rather untested form of treatment for AD is electrical stimulation of the brain. In the case of treating AD, the most common form of electromagnetic stimulation is repetitive transcranial magnetic stimulation (rTMS), a non-invasive process that delivers multiple small magnetic pulses that help stimulate brain tissue through the skull. A study in Korea in 2024 tested the effect of rTMS on patients with confirmed early-stage AD. The location of stimulation chosen was the parietal cortex (Figure 4), as early-stage AD frequently shows atrophy of that region of the brain (17). The study split eligible participants into two groups: one that would receive the rTMS treatment and one that would receive sham (control) treatment. The group receiving rTMS underwent 40 trains (sequences of magnetic pulses) per day, with each train consisting of 40 pulses at 20 Hz in the span of two seconds, resulting in a total of 1,600 pulses every day for five weeks. Using primarily the Alzheimer's Disease Assessment Scale–Cognitive Subscale-13 (ADAS-Cog-13), the study found a significant improvement in cognitive ability for the rTMS group over the sham group at both the fourth and eighth week intervals (Figure 5). It was also found that the rTMS increased functional connectivity between the hippocampus and precuneus (located in the parietal lobe, it is primarily responsible for processing and memory

retrieval), improving memory retrieval and overall cognitive function in participants over the sham treatment (17).

Another similar study, split between Canada and Australia, tested the effects of rTMS on patients with mild to moderate AD (18). The study also used a similar control method, with a sham (control) treatment that produced the same sounds and sensations as rTMS treatment. However, this study focused on the left and right dorsolateral prefrontal cortex areas, which are mainly involved in memory, attention, and decision-making. Patients in this study experienced a less intensive treatment program compared to the previous study described above, undergoing 25 trains of rTMS, with 30 pulses per train at 20 Hz over a 10-second interval. A total of 135 patients' results were analyzed, and minor adverse effects such as headaches and dizziness were noted by 82% of rTMS and 79% of sham group patients (18). The results of the study showed overall cognitive improvement following the trial for up to two months, and then a return to the baseline cognitive ability. Furthermore, these results indicated no significant difference in cognitive improvement between the ADAS-Cog scores of the rTMS and the sham groups, both immediately after intervention and six months post-trial. Therefore, it becomes increasingly clear that the location and extent of electromagnetic stimulation are extremely important and have a great impact on the outcomes of the treatment, and certain methods may become viable to treat AD in the future.

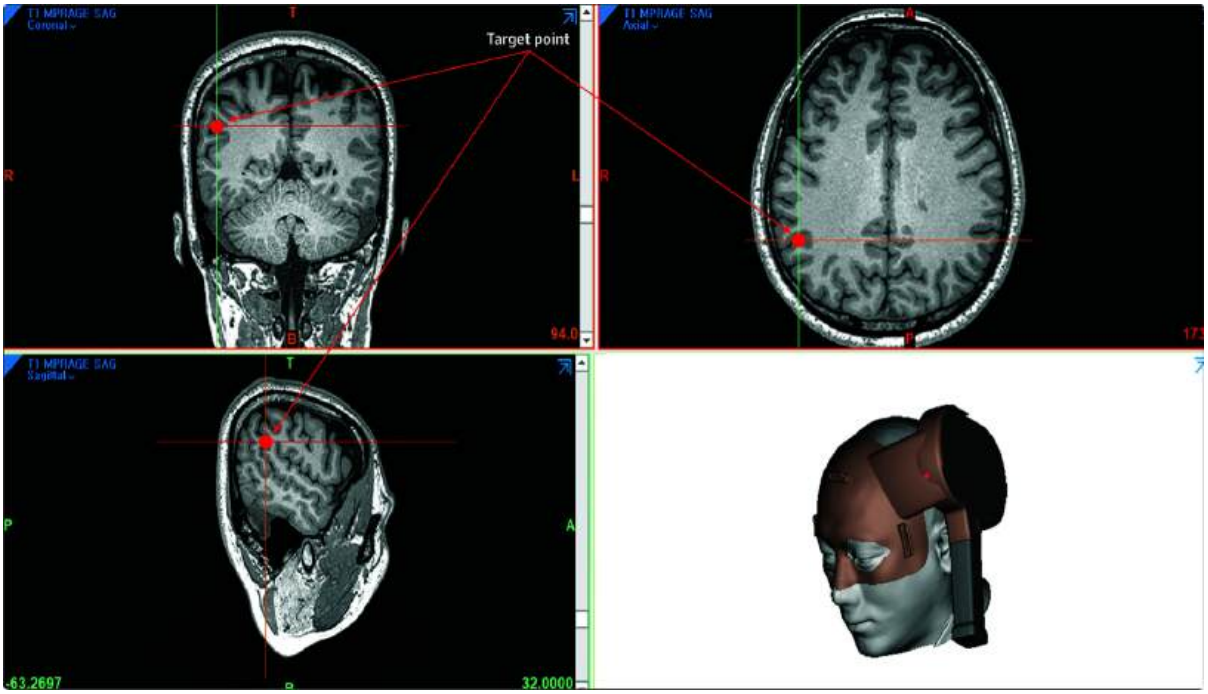


Figure 4: Location of rTMS treatment targeting the parietal cortex (17).

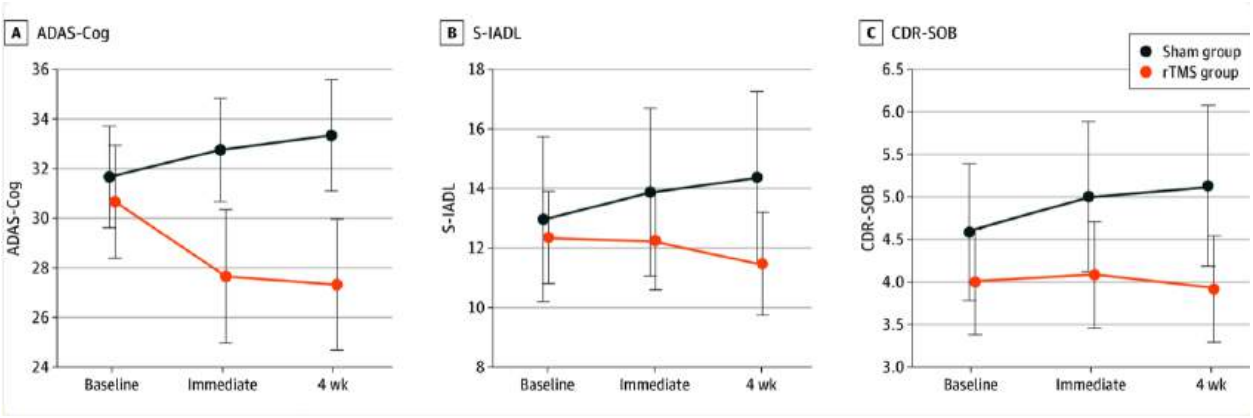


Figure 5: Resulting scores of different tests following electromagnetic stimulation of parietal cortex, showing improved scores by rTMS over the sham group (lower score indicates improved ability) (17).

Glymphatic System

Another bodily system that has an effect on AD development is the glymphatic system, which is the same as the lymphatic system except it only relates to the cleaning of the brain rather than the whole body. The glymphatic system is made up of three main parts: the periarterial space, the brain parenchyma, and the perivenous space (Figure 6). During deep sleep, particularly non-rapid eye movement sleep, cerebrospinal fluid (CSF) flows into the brain through the periarterial space and then enters the brain parenchyma. There, it mixes with interstitial fluid (ISF), and waste products such as Aβ and tau proteins are collected. The CSF then flows out of the brain through the perivenous space, carrying away buildups of Aβ and tau. As the body ages, the glymphatic system becomes less effective at clearing waste products (Figure 7), allowing for buildups of Aβ plaques and tau tangles, common indicators of AD (21). Furthermore, a consequence of AD is frequently interrupted sleep, especially during the slow-wave sleep (SWS) stage (the deepest phase of sleep, during which the body and brain enter a recovery and repair mode and when the glymphatic system is most active), which prevents the glymphatic system from working efficiently.

A research group from 2023 decided to test the effect of acoustic stimulation on SWS in subjects with mild to moderate AD (22). Participants were provided with the commercially available DREEM 2 headband device, and they were instructed to activate and wear it during their normal sleeping hours at home. The device delivered 2 rounds of 40-dB pink noise acoustic stimulation (STIM) or no stimulation if sufficient SWS was determined to have been achieved (SHAM). The results showed a significant increase in SWS in participants receiving acoustic stimulation through the DREEM 2 headband on night 16 of the study compared to night 2 (22). With increased SWS sleep, the glymphatic system in the brains of patients with AD should be more efficient at clearing out waste products, slowing the buildup of Aβ plaques and tau tangles. The advantage of this treatment is that it can take place at home and is very easy to implement, as it simply requires placing the headband on one's head before going to sleep. It is also very

inexpensive compared to conventional drug treatments, making it much more available to anyone with AD.

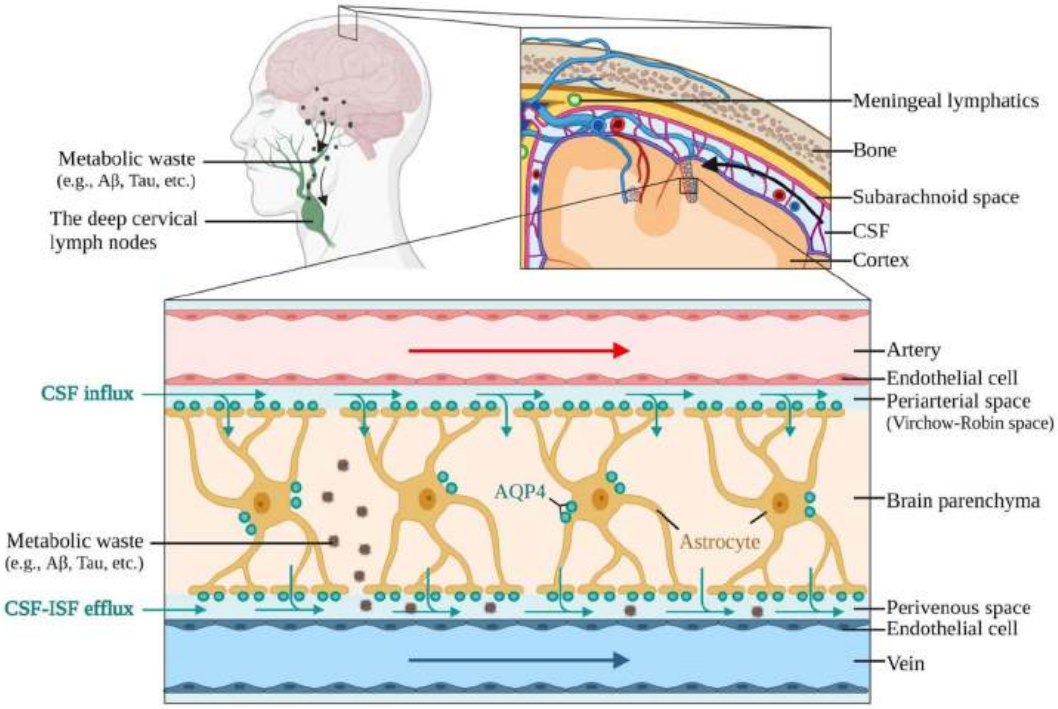


Figure 6: Diagram of the glymphatic system and the process it follows to clear waste from the brain (Formolo et al. 2023).

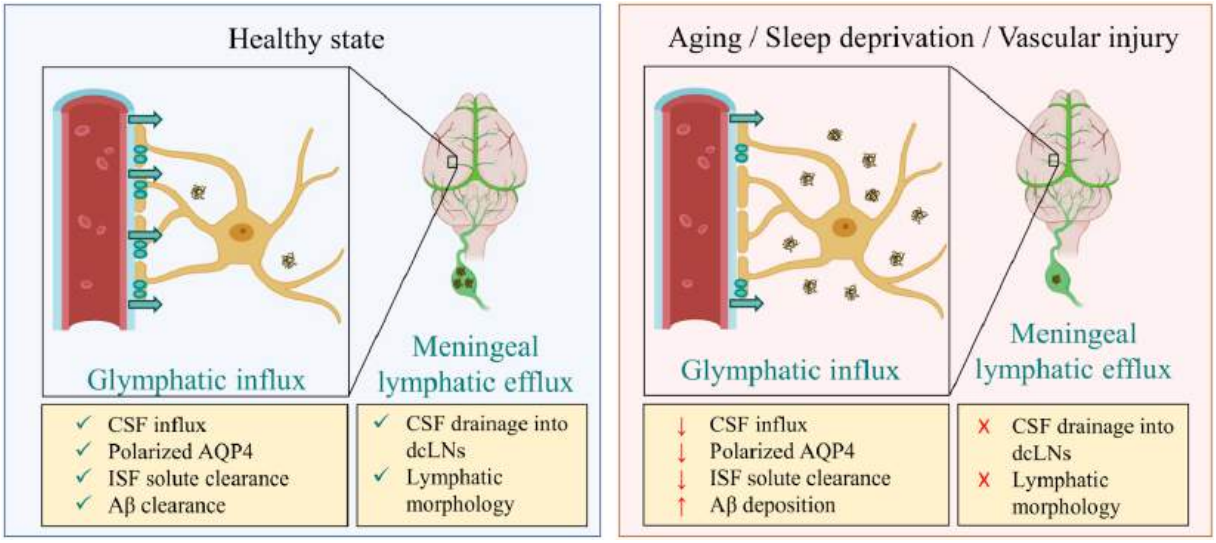


Figure 7: The glymphatic and meningeal lymphatic systems for mice in different states of health. Aging, sleep deprivation, and vascular injury are associated with impairments in the function of the glymphatic system, preventing effective and efficient clearing of waste products in the brain (21).

Discussion

Diet and Microbiome Treatments

It is well-known that a patient's diet can affect the progression of AD. When fed a healthy diet consisting of certain medical foods or a ketogenic diet, patients saw a significantly slower progression of symptoms compared to those consuming a normal, doctor-recommended diet (12, 10). This is because a strict diet that cuts out excess carbohydrates and sugars promotes healthy vascular function and helps maintain a balanced gut microbiome, both of which support a healthy brain. Furthermore, there have been studies showing significant differences between the bacterial taxa of the guts of healthy patients and patients with preclinical AD, and those with abnormal microbiomes also showed elevated Aβ levels (13). Knowing this, scientists may be able to examine the bacteria in a patient's gut to possibly diagnose early AD and begin to explore treatment possibilities. Diet could be one route for addressing the differences in bacterial taxa and counteracting the negative effects of an abnormal gut microbiome. For instance, specific probiotics that contain certain bacteria could be ingested by a patient to fill in deficiencies for patients with abnormal microbiomes. A healthy microbiome would promote the production of substances such as dopamine and serotonin, boosting memory and cognition (25). Balanced bacteria would also strengthen the intestinal lining of the gut, preventing harmful substances, such as undigested food and lipopolysaccharides, from leaking into the bloodstream and traveling to the brain (a theory commonly linking the gut to AD). It could be possible to take advantage of the gut microbiome as a preventative factor in treating AD.

Electromagnetic and Glymphatic Treatments

Electromagnetic treatment for AD most commonly consists of rapid transcranial magnetic stimulation (rTMS), which targets specific areas of the brain that are susceptible to factors that cause AD, such as Aβ plaques and tau tangles. The treatment delivers many short magnetic pulses to said specific area of the brain, and the pulses stimulate neural activity, helping the brain to combat the side effects of AD as the disease progresses. This idea is supported by multiple studies that have performed rTMS on patients with AD, showing increased scores in cognitive tests with only minor side effects noted (17, 18). A downside of this form of treatment is its cost, which can range from $6,000 to $12,000, depending on the number of sessions. While this is less expensive than pharmaceutical treatment, it is still very costly for most patients, even with insurance coverage. Another form of treatment to combat the effects of AD is sleep treatment that promotes the effectiveness of the glymphatic system — the system through which CSF flows, collecting waste products such as excess Aβ and tau and removing them from the brain. The treatment acoustically stimulates the brain using the DREEM 2 headband that individuals can wear while sleeping. A study shows improved slow-wave sleep (SWS), the stage during which the glymphatic system is most active, for participants using the headband (22). This improved sleep allows for the glymphatic system to have time to properly cycle CSF and work to clear the buildups of plaques and tangles that interrupt neural function. Sleep-targeted treatment is a very attractive solution due to its accessibility and ease of use. For example, the

DREEM 2 headband used in the study described above was previously available commercially for $499.99; however, it has since been removed from public access after the company was bought out (22). Fortunately, other companies are working to replace the DREEM 2. Due to its convenience, with further testing and support, acoustic sleep treatment could become one of the foundational at-home treatment options for AD.

Proposal for a New Treatment Option

To make a treatment for AD more widespread and available for more people, at-home options must be explored as alternatives to conventional pharmaceuticals. Given the connection between the gut microbiome and the onset of Alzheimer's disease, it may be beneficial to test whether correcting bacterial imbalances in the guts of individuals with preclinical or mild AD—such as through probiotic interventions—can slow or alter disease progression. Because this specific field of study is very new and minimally researched, the results may be very consequential and help push forward new research for AD. Support for this was demonstrated in a 2022 study in Iran, which found that while probiotic supplements containing only a single bacterial strain (either *Lactobacillus rhamnosus* or *Bifidobacterium longum*) did not lead to statistically significant improvements in cognition, there were minor overall gains observed (i.e., provide some examples), suggesting potential for further investigation (24). Therefore, the way to maximize the efficacy of a probiotic supplement like this would be to individually map the gut bacterial taxa of each patient with AD and compare that with what is naturally occurring in healthy patients. Then, the supplement would be manufactured to contain the specific bacteria missing from the patient's gut. Because this treatment is personalized, it would be quite expensive, so another option could be to begin testing probiotics that contain multiple different strains of commonly deficient bacteria in patients with AD, such as *Bifidobacterium longum*, *Faecalibacterium prausnitzii*, and *Ruminococcus lactaris*. A simple way to consume these probiotics could be through a yogurt supplement containing colonies of specific bacteria to match the needs of individuals with AD. A supplement like this would likely need to be consumed once every 5-7 days, as the lifespans of different probiotics within the gut can last between one and two weeks. Therefore, the gut would continue to contain the beneficial bacteria throughout the treatment period, which could possibly continue through a patient's life as long as they are experiencing symptoms of AD.

Combo Treatment & Conclusion:

Although they are the most common and well-known options for combating AD, drugs such as Lecanemab may not be the best and most efficient solutions. For instance, they can be extremely expensive, many have unpredictable outcomes that vary greatly between patients, and they do not cure the disease; instead just decrease the symptoms and progression of the disease. Exploring alternative treatment options could be the path to finding a cure for this disease. Every alternative treatment option explored in this review paper shows promising outcomes after preliminary research, and with more testing, they may prove to be useful in tackling AD.

Furthermore, many of these alternative treatments, such as acoustic stimulation and dietary changes, are very simple to implement and are much more cost-effective than pharmaceutical options, and they can also be used in combination with each other rather easily. An effective treatment plan that would be easy for patients to follow could include a probiotic supplement in yogurt that aims to enrich the gut microbiome, filling in any missing gaps that an individual may have, combined with the use of an acoustic stimulation sleep headband to stimulate the glymphatic system, ensuring the proper clearing of harmful substances in the brain and body. Both of these options are simple and achievable, with patients being able to complete them at home, and combining them would target multiple areas that may facilitate the development and progression of AD. Overall, this review paper teaches about AD and how it can be treated in many different ways. With more research into novel treatment approaches, scientists can get closer to finding a cure for this disease. Perhaps we may one day be able to cure AD simply by eating yogurt and sleeping with a headband.

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