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Young Scientists Journal

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The Evolution of Treatment for Alzheimer's Disease from the Early 2010s to Late 2010s: A Literature Review

Jungwon Bae

Abstract

Alzheimer's disease (AD) is a progressive neurodegenerative disorder with no known cure and a rapidly growing impact on global health. This literature review traces the evolution of AD pharmaceutical treatments during the 2010s, focusing on drugs grounded in the cholinergic, amyloid β (Aβ), and tau hypotheses. While cholinesterase inhibitors and memantine remain the only FDA-approved options throughout the decade, numerous clinical trials tested new approaches. Most anti-Aβ and anti-tau drugs failed due to toxicity or ineffectiveness, but compounds like Edaravone and SelS showed emerging promise in the late 2010s. These developments reflect a gradual shift toward diversified and multi-targeted treatment strategies, signalling potential for future breakthroughs.

Background

Potentially being the most devastating cause of death, Alzheimer's disease (AD) more than doubled its death rate from 2000 to 2020 [4]. During 2018-2023, AD ranked sixth in mortality among causes of death in the US [7]. The Diagnostic and Statistical Manual of Mental Disorders, the fifth edition (DSM-5) characterises AD with two main symptoms: "clear evidence of decline in memory and learning" and "steadily progressive, gradual decline in cognition, without extended plateaus" [5]. Memory loss, one of AD's most prominent symptoms, weakens the patient's immune system, which may lead to life-threatening complications [24].

The illness was discovered by Alois Alzheimer, in his case study of a woman with a type of dementia that exhibited abnormal brain tissue changes [3]. Despite more than a century passing since its first proposal in 1907, the exact causes and mechanisms of the illness remain unknown. One of the initial explanations of the disease, by John A. Hardy and Gerald A. Higgins in 1992, was that accumulation of the amyloid β (Aβ) protein "is the causative agent

of Alzheimer's pathology and that the ... dementia follow[s] as a direct result of this deposition" [16]. This theory had been largely disproven, however, due to a poor correlation between the Aβ concentration and parameters of AD pathology [21][22][23]. An alternative theory is the tau hypothesis, which argues that excess phosphorus in tau proteins inhibits their binding to microtubules, thus causing a "disruption in axonal transport, ultimately leading to dementia and neuronal death" [1]. Another is the cholinergic theory, which posits that a lack of production and transportation of the neurotransmitter acetylcholine contributes to AD development [2]. In this paper, the evolution of pharmaceutical treatment for the symptoms of AD concerning the three aforementioned theories during the 2010s will be examined.

Methodology

The literature was gathered via JSTOR and PubMed. For more relevant results, keywords "Alzheimer," "drug," "pharmac*," "treat*," and "medic*" were utilised, and a filter was used to narrow the range to articles published from 2010 to 2025. Only PubMed articles with free complete access were incorporated, due to the lack of access on the researcher's part. Selected articles have a specific focus on certain types of medication (e.g. cholinesterase inhibitors), while articles covering a wide range of medications were excluded, considering the objective of this literature review. The articles were checked for reliability based on their authority, objectivity, accuracy, and relevance. The date of publication was only taken into consideration as a grouping criterion, since outdated sources can still provide usable information for a chronological literature review.

Thematic analysis was used to identify trends for each time period. Articles were grouped by the year of publication into 3 categories: early 2010s (2010-2013), mid-2010s (2014-2016), and late 2010s (2017-2019). Then, the main drugs mentioned were identified

and studied. Afterwards, the findings of the articles were compared within their categories. Lastly, the results were organised chronologically to identify the differences in the researchers' focus for each period.

Results

By the early 2010s, the effects of acetylcholine esterase inhibitors (cholinesterase inhibitors) such as donepezil, galantamine, and rivastigmine were reported to be "modest and transient," although a combination with other drugs could improve their performance [8] [17]. Nonetheless, they remained the only type of AD drugs approved by the FDA to be prescribed with memantine, an NMDA antagonist, proving the predominance of the cholinergic theory in the field. Regarding new drugs, however, the Aβ theory seemed to focus on drugs that reduce Aβ polypeptides, potentially due to the lack of evidence of cholinesterase inhibitors being a capable cure [17]. Examples include γ-secretase inhibitor, which reduces Aβ production from γ-secretase [9][11]. Although it seemed to ameliorate the chemical changes caused by AD, researchers later discovered that its side effects worsened the patients' cognitive deficits, thus halted the clinical trials [6] [26]. Consequently, it is logical to conclude that the researchers struggled to develop drugs centred around the Aβ theory in the early 2010s. Explorations of other theories — such as the tau hypothesis — had seen an increase, potentially due to this difficulty. Multiple clinical trials took place but yielded equivalent results to anti-Aβ drugs. Most drugs, such as lithium and methylene blue, ended up being either overly toxic or ineffective [13] [25]. Nonetheless, a small group of drugs, such as davunetide, showed improvements in the patients' brains, providing a pathway for future researchers to further investigate the tau theory [2].

Even by the mid-2010s, there had not been significant progress in the development of new drugs. Cholinesterase inhibitors and memantine remained the only classes of drugs with

therapeutic effects for AD. Due to such reasons, some researchers started pioneering other types of drugs, such as antidepressants and antipsychotics. However, most proved ineffective except for cholinesterase inhibitors [19]. While the amyloid theory had been nearly disproven at this point, it was a common notion that the Aβ polypeptide takes part in the development of AD to a certain extent. Therefore, some continued to study anti-Aβ drugs like Edaravone [18][21]. Edaravrone's capability of alleviating the cognitive deficits — instead of inadvertently worsening them — marks a crucial difference compared to previous anti-Aβ drugs, demonstrating a notable improvement since the early 2010s. Clinical trials were run to study anti-tau medications, but many of them, including LMTM and tideglusib, were not found to be effective [14] [20].

Major groundbreaking progress in the pharmaceutical treatment of AD was made in the late 2010s. Edaravone was ultimately approved by the FDA in 2017, and several other clinical trials for newly developed drugs (e.g., LMTX, Zolpidem, etc.) occurred based on multiple theories, including the tau hypothesis and the Aβ hypothesis [10]. Among them, selenoprotein S (SelS) was found to be effective in reducing phosphorylation of tau, which signalled hope assuming the tau theory. Lithium was tested again to inhibit glycogen synthase kinase 3β, "an enzyme that phosphorylates tau" [12]. Studies from earlier periods suggested that it is excessively toxic as AD treatment, therefore researchers addressed the concern by adhering to a small dose [15]. However, due to such measures, the study found the dosage insufficient for observable effects. This calls for further studies regarding healthy doses of lithium, as it remains a potential medication for AD treatment. Other tau aggregation inhibitors, such as LMTM which was re-examined, have been mostly unsuccessful. Regardless, the few cases of success set the period apart from the mid-2010s [27].

Conclusion

Although no curative treatment for Alzheimer's disease has been discovered, the past decade has reflected significant progress in understanding its pathology and developing new pharmaceutical approaches. The continued reliance on cholinesterase inhibitors underscores the limitations of current treatments, but recent advancements — such as Edaravone's approval and encouraging results from tau-targeting compounds — suggest growing potential in alternative strategies. These findings highlight the need for multi-theoretical and combination-based approaches that address the disease's complexity. Future research should prioritise refining dosage safety, enhancing drug delivery systems, and integrating biomarkers for early diagnosis, with the long-term goal of moving beyond symptom management and toward disease-modifying therapies.

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Nanobots in Reconstructive Surgery: Advantages and Ethical Challenges

Eman Fatima Ghani

Abstract:

This research addresses the question of whether nanobots will be the future of reconstructive surgery. A combined approach was used: my survey, which was answered by plastic or robotic surgeons with questions on their views of nanobots being used in healthcare, and analysing secondary sources: academic journals, grey literature and sites of relevant organisations. The primary data suggested that with robust guidelines in place to solve potential issues, nanobots could be a great asset; the secondary confirmed that nanobots have the potential to improve the current practices; however, there are various factors that must be considered. To conclude, nanobots are controversial yet highly effective if used to their full potential, and hence this is important to the question as if we can use them, surgeons will, and they will transform the surgical field.

Are Nanobots The Future of Reconstructive Surgery?

Introduction:

Reconstructive surgery is about restoring body parts damaged by illness, trauma, or surgical operations. Nanobots are small robotic machines made for specialised tasks like tissue mending and targeted drug delivery. This study examines the potential advantages of nanobots in reconstructive surgery, as well as any possible health hazards. It also assesses the ethical and practical difficulties associated with the introduction of nanobots.

Methodology:

To examine ideas and moral dilemmas in the developing field of nanobots, this study used an exploratory and qualitative methodology. 19 plastic and robotic surgeons were surveyed as part of the primary research to find out how they saw the potential of nanobots. Information for the study was also obtained from grey literature, scholarly journals, and the websites of organisations that deal with reconstructive surgery, nanorobotics, and nanomedicine. A holistic approach was adopted, evaluating both available data and surgeons' perspectives on the development of nanobots. For primary data, narrative analysis was employed, and for secondary data, content analysis was used. A reduced sample size because of time restrictions was one of the limitations. Consultants with years of experience in relevant fields completed the survey. To evaluate the reliability of secondary sources, criteria including authority, currency, objectivity, accuracy, and relevance were used.

Results:

My survey results confirmed that the surgeons believe that nanobots show promise in wound healing and nerve regeneration, as they would make the process more precise and easier. Nanobots could have vital applications, especially for breast implants, as they could help make implants more

biocompatible, thus having fewer issues, such as being rejected by the body or having unwanted side effects. In addition, it was suggested that drug delivery would be transformed as the process would be more efficient and precise. However, there are significant problems that need to be addressed, such as patient privacy being compromised, acquiring consent being difficult as patients may not understand nanobots, unequal distribution may occur for those outside of the NHS due to the cost and nanobots remaining in the body for longer than expected and thus causing unexpected side effects. Furthermore, if nanobots are semi-autonomous, it could challenge bodily control and self-governance, potentially undermining a patient's autonomy or leading to uncontrollable nanobots. Another participant suggested that nanobots could be weaponised and pose broader societal risks that could prevent their establishment. However, all answers offered solutions to these problems, such as the use of dynamic consent models and selecting materials carefully to prevent side effects. Another participant advised that we needed strong data security and an equal distribution of nanotechnology through cooperation between companies and nations. The creation of interdisciplinary committees was suggested as a way to regulate the use of nanobots, to carry out regular reviews and updates in order to avoid undermining patient autonomy. Thus, the answers generally concluded that they would be happy to use nanobots if there was clear scientific guidance and recommendation in their speciality, with adequate clinical governance in place.

Discussion:

Nanobots could immensely improve reconstructive surgery by distributing growth factors and stem cells to damaged tissue [1], allowing for faster and more autonomous processes. Because there is less donor tissue available in cases of severe nerve damage, it can be difficult to fill in gaps of more than 5 mm. This problem can be avoided with chitosan nanofiber tubes, which promote nerve regeneration without donor limitations. Nanofiber mesh tubes demonstrated comparable effectiveness to conventional grafts in a rat sciatic nerve model by Wang et al. (2010) without donor-site issues [2]. This makes the case for nanobots in the future since they have the same benefits as nanoparticles and more; they can locate damaged neurons and go there without the need for tissue donors, resulting in more accurate and potent treatments. Moreover, nanotechnology is currently used in reconstructive surgery for breast implants. Kyle et al. (2015) created nanostructured PDMS surfaces using a 3D greyscale approach. These surfaces mimic the acellular dermal matrix, reducing inflammation and enhancing fibroblast development [3]. Nanotechnology already makes passive implants safer and biocompatible, but nanobots could revolutionise the future by regenerating natural breast tissue using stem cells. This non-synthetic implant would be safer and have fewer side effects, making it a step beyond traditional implants. Furthermore, nanobots could also enhance drug delivery. Ma et al. (2015) demonstrated potential for precise drug administration by doubling diffusion over non-motile particles using a self-propelling Janus nanomotor [4]. This proves that nanobots can increase the efficiency, minimise systemic adverse effects (such as nausea and fatigue), and lower necessary dosages by localising treatment [1][5]. Furthermore, Tian et al. (2007) found that silver nanoparticles can speed up wound healing in reconstructive surgery more quickly than silver sulfadiazine (11 vs. 26.5 days). Nanotechnology can also create smart dressings that mimic the extracellular matrix, control moisture, release growth hormones, reduce scarring and irritation, and combat infection [3][6]. This demonstrates how nanoparticles and smart dressings are already effective, but nanobots could enhance their effectiveness by stimulating tissue regeneration for wound healing and acting as scaffolds or guiding cell migration. This would make reconstructive surgery faster and more efficient. Additionally, real-time monitoring of nanobots could help handle complications, making the dressings more effective in

the future. This could make nanobots a more efficient and effective alternative to traditional nanoparticles. Hence, nanobots are positioned as a promising future surgical technique thanks to this autonomous, focused approach that improves patient safety and care.

Despite their benefits, nanobots have drawbacks that might prevent them from being used in reconstructive surgery. Key concerns about nanotechnology, such as privacy, accessibility, consent and health risks, were identified in a survey of 27 sources from 2007 to 2020. For example, patients may not be aware of the risks associated with nanotechnology due to the uncertainties around it, which makes it challenging to get their valid consent [5][7]. This may make using nanobots in the future unethical, as patient autonomy may be neglected in the absence of appropriate consent. Moreover, nanobots must try to be biocompatible, otherwise they could cause tissue damage, irritation, or immunological reactions [7][7][8]. According to a study done by Aschner et al. (2025) [9], aluminium nanoparticles, which are often found in nanobots, can have harmful effects that can result in health issues like cancer, birth defects, and respiratory problems [3]. As patient safety comes first, the use of nanobots in surgery may not be appropriate in the future. Furthermore, nanobots can track daily routines and physiological changes using artificial intelligence and machine learning, which generates vast amounts of patient data. Privacy can be compromised if this data is misused by others, which raises concerns about informational asymmetry and data misuse. While this information may have medical applications, patient privacy is at risk due to a lack of rigorous, moral, and safe data management [5][7]. Hence, some argue that nanobots should be prohibited in the future to protect patient privacy. Additionally, the high costs of nanomedicine, particularly in insurance-based systems, restrict affordability and lead to unequal access. Global disparities are increasing, according to the UNESCO Science Report (Brownsword, 2008), with underdeveloped areas having less access to nanomedicine in operating rooms [7]. While nanobots may enhance care, they should not be used if they cannot benefit all patients equally, as this goes against the idea of healthcare as a universal right. Hence, it is evident from both the primary and secondary data that if nanobots were to be utilised, there would be a lot of countermeasures needed.

Conclusion

To conclude, the use of nanobots comes with the issues like health concerns, informed consent, patient privacy, unequal access, autonomy, and weaponisation but with right measures and regulations in place e.g the use of dynamic consent models and careful selection of materials carefully to prevent side effects, strong data security, equal distribution of nanotechnology through co-operation between companies and nations and the creation of interdisciplinary committees to carry out regular reviews and updates to avoid undermining patient autonomy, nanobots can offer benefits like more accurate drug delivery, safer implant procedures, enhanced tissue repair, and quicker wound and burn healing. Therefore, in my opinion, nanobots are the future of reconstructive surgery.

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How Does Excessive Social Media Usage Disturb Teens' Sleep Quality and Academic Performance in the 21st Century? A Hong Kong Case Study

Melinda Lam

Introduction

Excessive social media use among Hong Kong adolescents has become a major public health concern, with strong evidence linking it to sleep deprivation and academic challenges. Adolescence is a critical period of brain development, marked by significant changes in the brain's reward system and the prefrontal cortex (PFC)—areas responsible for emotional regulation, decision-making, and cognitive control. These changes make teens more sensitive to external influences like social media, which can worsen poor sleep and reduce academic performance.

The Chinese University of Hong Kong (CUHK) reports that 94% of local high school students fail to achieve the recommended 9 hours of sleep, with 25% sleeping fewer than 7 hours on weekdays [1]. Similarly, The University of Hong Kong (HKU) found that using digital devices for over 3 hours daily is strongly associated with gaming addiction and poorer mental health [2]. These findings are alarming given the American Academy of Sleep Medicine's recommendation that teenagers need 8–10 hours of sleep for optimal health and cognitive performance [3].

This study examines how excessive social media use disrupts sleep and academic performance among Hong Kong high school students. A survey revealed significant correlations between prolonged screen time before bed and three negative outcomes: delayed sleep onset, shorter sleep duration, and poorer academic performance. The findings highlight the importance of targeted interventions, such as delayed school start times, stricter parental screen-time limits, and promoting simpler phones to improve teens' sleep and focus.

Literature Review

1) **Normal Adolescent Brain Development**

- **Reward System**

  The brain's reward system, which reinforces behaviors by generating pleasure, plays a key role in motivation, learning, and habit formation. Central to this system is the dopamine pathway, which includes the ventral tegmental area (VTA) and the nucleus accumbens (NAc) (Fig.1). The VTA, located in the midbrain, produces dopamine and sends signals to the NAc, a region that processes these signals to reinforce rewarding behaviors. During adolescence, this system becomes highly sensitive, making teens more responsive to rewards and prone to seeking pleasurable activities, including risky behaviors. [4]

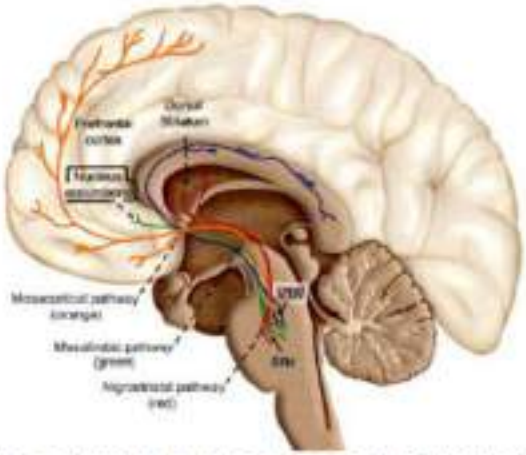


Fig.1. The mesolimbic pathway, key to processing rewards, is shown in green and includes the VTA and NAc.

- **Prefrontal Cortex Maturation**

  The prefrontal cortex (PFC), located behind the forehead, is among the last brain regions to mature (Fig.2), with development continuing into the mid-to-late twenties [5]. It governs executive functions, such as planning, decision-making, and impulse control. Because the PFC is still developing in adolescence, teens are more impulsive and vulnerable to external influences, including social media.

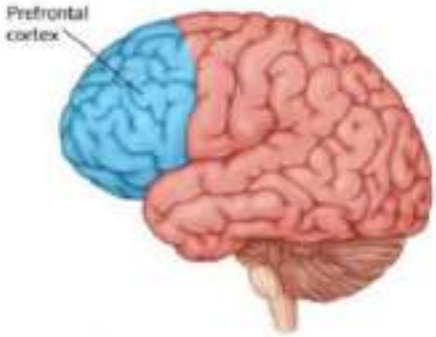


Fig.2. The prefrontal cortex

2) **Social Media Effects on Adolescent Brains**

- **Reward System: How Social Media Hijacks Dopamine Pathways**

  Excessive social media use (over 3 hours daily [6]) triggers dopamine-driven reinforcement, conditioning the brain to crave notifications and likes [7]. Algorithmically curated content exploits unpredictable rewards, making disengagement difficult. Chronic overstimulation alters brain structure, reducing gray matter volume (GMV) in areas like the amygdala (emotion processing) and the ventral striatum (reward evaluation) (Fig.3, 4) [8]. These changes contribute to addiction-like behaviors, anxiety, and depressive symptoms [7,8,9].

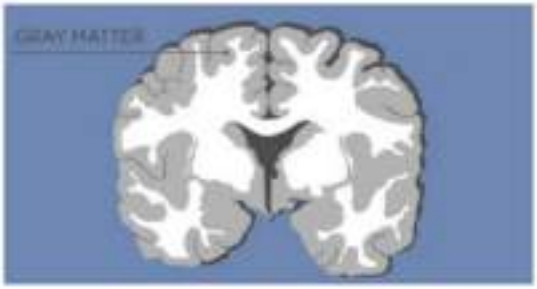


Fig.3. Gray matter in brain

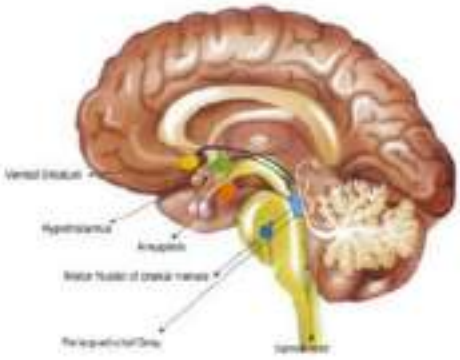


Fig.4. Brain Structures

- **Prefrontal Cortex Maturation: The Delayed Guardian of Self-Control**
  The PFC, responsible for impulse control and decision-making, matures into the mid-20s [7]. However, it is indirectly affected by overstimulation of the reward system:
  - **Structural resilience:** General social media use does not significantly reduce PFC gray matter volume [8]. However, severe internet addiction correlates with atrophy in the dorsolateral prefrontal cortex (DLPFC) and ventrolateral prefrontal cortex (VLPFC), which are critical for self-regulation (Fig.5).
  - **Functional vulnerability:** The immature PFC struggles to override reward-seeking impulses, leading to real-world consequences such as distractibility and emotional outbursts [7].

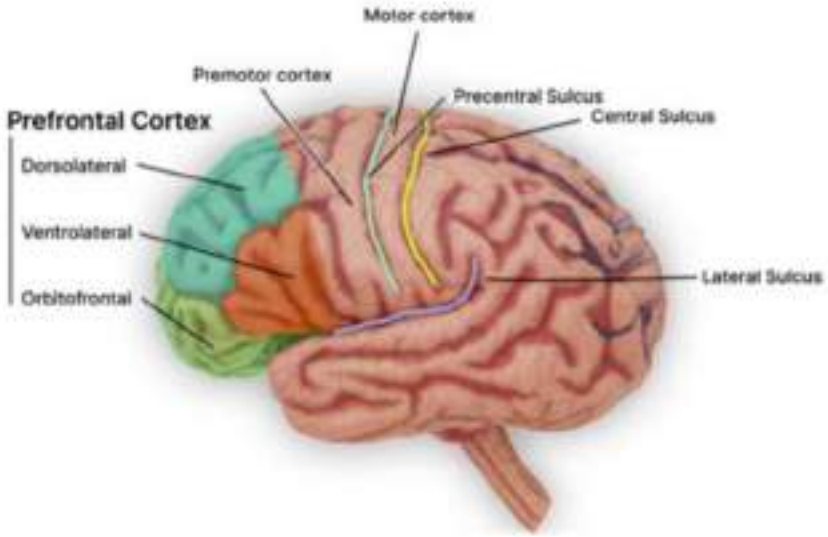


Fig.5. An illustration of the prefrontal region of a brain

Methodology

This mixed-method study combines primary survey data and secondary research to examine the effects of excessive social media use on sleep patterns and academic performance among Hong Kong adolescents.

For primary data collection, an online survey was conducted with secondary school students aged 13–18. The survey gathered quantitative responses on social media habits (frequency, nighttime use), sleep patterns (duration, quality), and self-reported academic performance. Ethical standards were rigorously upheld, ensuring participant anonymity and obtaining informed consent.

For secondary research, peer-reviewed studies on social media, adolescent brain development, and sleep behavior were reviewed to provide insights into the effects of screen time. This included linking behaviors such as nighttime social media use to changes in the brain's reward system and prefrontal cortex development, offering a broader neuroscientific context for the survey findings.

The analysis explored relationships between social media use, sleep disruption, and academic outcomes by integrating primary survey data with secondary literature. While the primary focus was on negative effects, alternative perspectives were acknowledged, such as the potential for moderate social media use to foster social connections and reduce stress, which may indirectly support academic performance.

Findings / Results

1) **Social Media Habits**

   A survey of 53 participants highlights the deep integration of social media into Hong Kong adolescents' lives. Instagram (89%), YouTube (76%), and WhatsApp (64%) are the most used platforms (Chart 1). On school days, 96% use social media during commutes (Chart 2), with 19% spending over 4 hours daily, 38% using it for 3–4 hours, and another 38% for 2–3 hours (Chart 3). Weekend usage rises, with 40% spending over 4 hours and 40% spending 3–4 hours daily (Chart 4).

Chart 1. Popular platforms that teenagers use for over 30 minutes daily (Select up to 3)

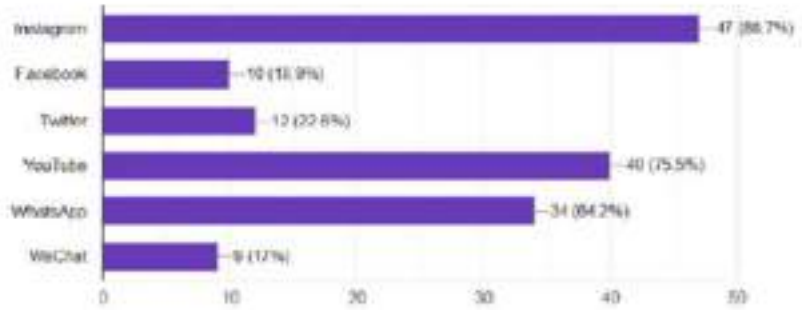


Chart 2. Typical Times for Social Media Use on School Days (Select all that apply)

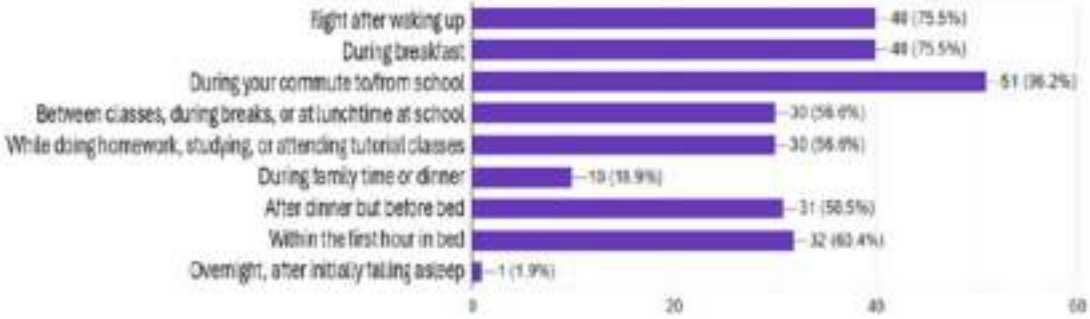


Chart 3. Weekday Social Media Usage

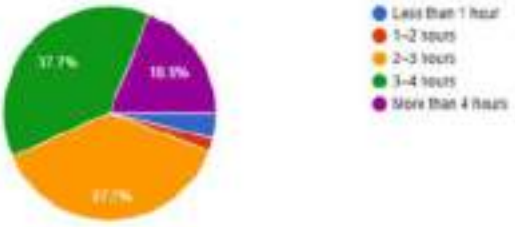
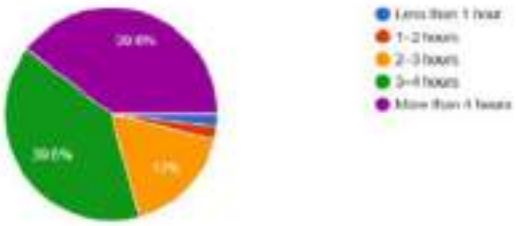
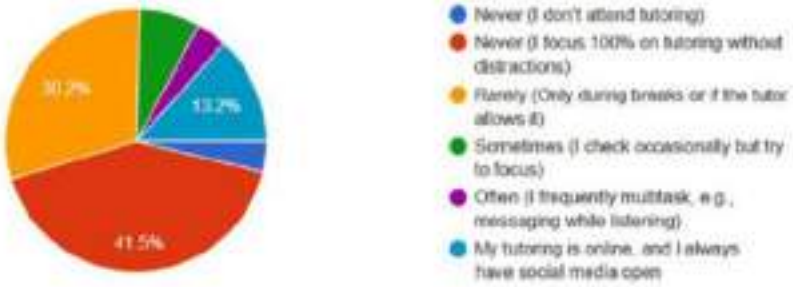


Chart 4. Weekend Social Media Usage



The heavy use of social media aligns with secondary research on dopamine-driven reinforcement, as discussed in the literature review [7, 8]. Algorithmic content encourages compulsive behaviors, often disrupting routines and impacting well-being [7]. However, 72% of students reported never or rarely using social media during tutoring (Chart 5), demonstrating their ability to exercise situational control and prioritize academics in high-stakes settings. This suggests that while social media use can be excessive, adolescents may still regulate their behavior when necessary, highlighting the complex interplay between technology use and self-discipline.

Chart 5. Social Media Use During After-School Tutoring or Classes



While this suggests some adolescents can manage their usage, opposing viewpoints highlight that even moderate use can disrupt mental focus, particularly when multitasking [10]. Studies by Madore and Wagner emphasize that multitasking with social media divides attention across tasks, leading to reduced retention of information and lower overall cognitive efficiency, which can negatively impact learning and academic outcomes.

2) Sleep Patterns

The survey reveals high social media use during sleep-critical periods, with 80% using it within an hour before bed (Chart 6), disrupting melatonin [11]. Of these, 40% spend 15–30 minutes, and 36% spend 30–60 minutes (Chart 7). Additionally, 59% use it in bed nightly, with 57% spending 15–30 minutes, delaying sleep (Charts 8, 9).

Chart 6. Frequency of Social Media Use 1 Hour Before Bed

Chart 7. Duration of Social Media Use Before Bed

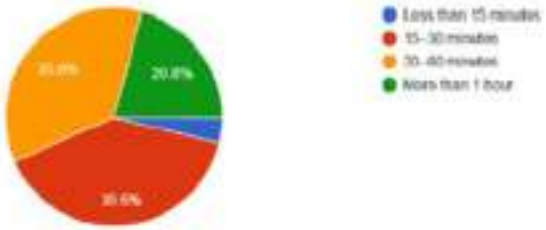
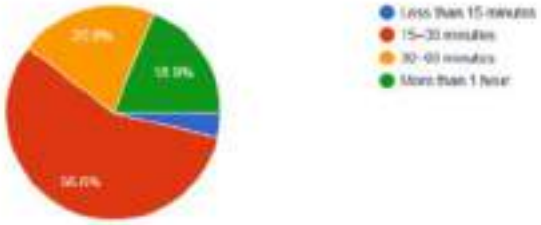


Chart 8. Frequency of Social Media Use in the First Hour in Bed

Chart 9. Duration of Social Media Use in Bed



Charts 6–9 illustrate how prolonged screen time before bed directly correlates with delayed sleep onset, as supported by secondary research. This behavior disrupts melatonin production and circadian rhythms, key to healthy sleep patterns. Moreover, the compulsive nature of scrolling, driven by social media's unpredictable rewards, fosters a "fear of missing out" (FOMO), further delaying sleep [12].

Despite this, 64% silence notifications overnight (Chart 10), reducing sleep disruptions. However, 40% sleep only 5–6 hours, and 36% get 6–7 hours on school nights (Chart 11), below recommended levels. As a result, 42% feel tired or sleep-deprived 1–2 days per week (Chart 12).

Chart 10. Leaving Social Media Notifications On Overnight

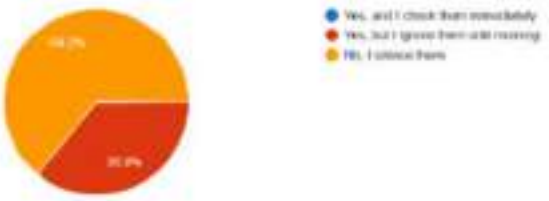


Chart 11. Average Hours of Sleep on School Nights

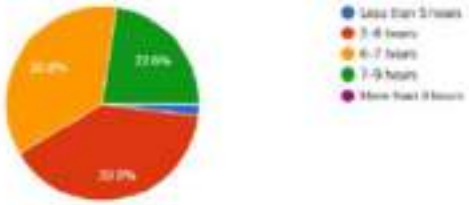
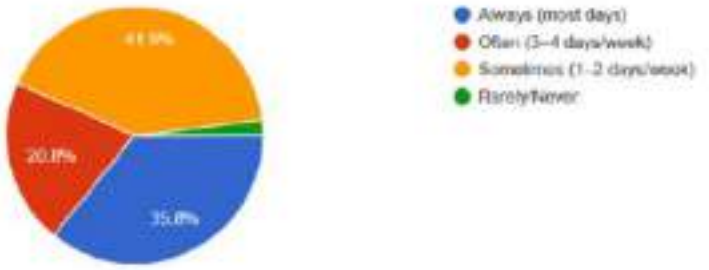


Chart 12. Frequency of Feeling Tired or Sleep-Deprived During School



While the findings emphasize negative impacts, some research suggests that using social media for mindfulness apps or connecting with peers could counteract stress, potentially aiding sleep quality in certain cases [13,14]. For instance, mindfulness and relaxation apps available on social media platforms can help reduce anxiety and promote better sleep patterns [13]. Similarly, connecting with supportive online communities may alleviate feelings of isolation, which indirectly improves sleep quality [14]. Nevertheless, the overall trends show that excessive nighttime use disrupts melatonin production and circadian rhythms, leading to sleep deprivation and its associated cognitive and emotional consequences [13,14,15].

3) Academic Performance

The survey reveals 57% struggle to focus in morning classes due to tiredness (Chart 13), linking sleep deprivation to academic issues. Social media disrupts study habits, with 59% multitasking, 47% checking it frequently, and 43% losing track of time (Chart 14).

Chart 13. Difficulty Focusing in Morning Classes Due to Tiredness

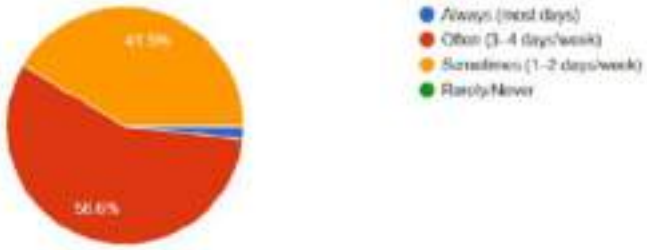
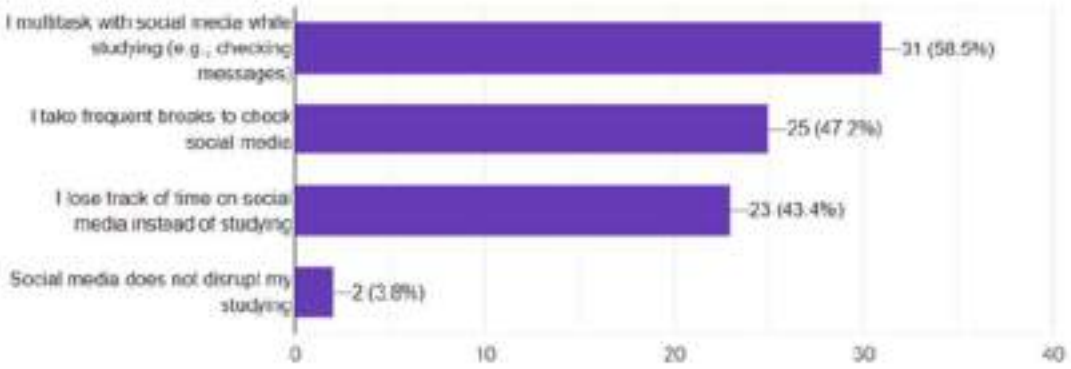


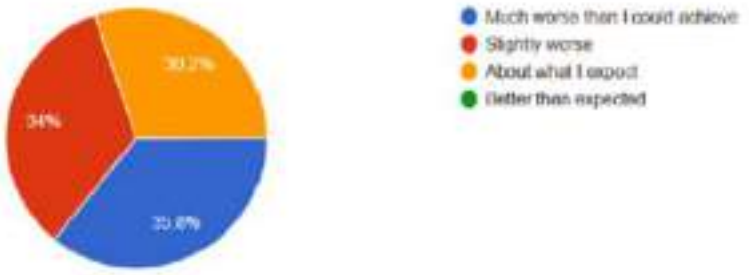
Chart 14. Study Habits Overview



The multitasking habits shown in Chart 14 are consistent with secondary research indicating that frequent switching between tasks weakens working memory and cognitive efficiency [10]. This aligns with the literature review, which highlights how overstimulation of the reward system impairs self-regulation and focus [7, 8].

Academically, 36% feel their grades are far below potential, and 34% slightly below (Chart 15), suggesting social media habits and sleep issues impact performance.

Chart 15. Comparison of Recent Grades to Potential



However, alternative viewpoints suggest that social media could provide access to educational resources and peer collaboration, which might positively influence academic results [16]. For instance, platforms like YouTube host tutorials, study tips, and educational videos that cater to diverse learning styles, enabling students to grasp complex concepts more effectively.

Despite these benefits, prolonged screen time overstimulates the brain, as evidenced by reduced gray matter in regions critical for self-regulation, such as the amygdala and ventral striatum, linking excessive use to impulsivity and impaired academic performance. The findings from this study's survey reinforce these biological effects, showing that delayed sleep and diminished focus significantly hinder learning outcomes

4) **Alignment with Literature Review and Secondary Research**

Primary data aligns with the literature review and secondary research, showing how social media disrupts sleep and focus [1, 2, 6, 7]. Both highlight brain overstimulation, reinforcing habits that harm well-being and academic performance [7, 8]. For example, the survey's findings on delayed sleep onset and multitasking are directly tied to dopamine-driven reinforcement and reduced prefrontal cortex control, as discussed in the literature review [7, 8, 10].

However, the study acknowledges that moderate social media use may have benefits, such as stress relief and access to educational content [12, 13], highlighting the importance of balance rather than blanket restrictions. This critical perspective underscores the nuanced relationship between social media and adolescent development.

Conclusion

Hong Kong teens' social media habits disrupt sleep and impair academic performance due to overstimulation and PFC dysfunction. Three evidence-based solutions are proposed:

1) **Delayed School Start:** A 15-minute delay with shorter hours improves sleep and is widely accepted [17].

2) **Parental Screen-Time Curfews:** Encourage limits and healthy habits to foster teens' self-regulation.

3) **"Dumb" Phones:** Promote basic phones to reduce screen dependency and improve focus, mental health, and habits [18,19].

These strategies aim to mitigate screen-related harms, enhance sleep, and support adolescent well-being.

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Teen Knowledge, Attitudes, and Behaviours Towards Antibiotic Resistance

Raquel Gomez Junco Lobo

Abstract

This study investigates teenagers' knowledge and attitudes toward antimicrobial resistance (AMR), a growing public health crisis fueled by antibiotic misuse and misconceptions. Using a mixed methods approach, responses from adolescents from over 24 countries were collected. Despite widespread antibiotic exposure, only 10% completed full prescriptions, and over half mistakenly believed antibiotics treat viral infections. These findings reveal significant misconceptions even among well-educated individuals. The study highlights the urgent need for education to close knowledge gaps and reduce behaviors that accelerate AMR.

Introduction

Antibiotics are medicines used to treat or prevent bacterial infections.[1] Since Alexander Fleming discovered penicillin (the first antibiotic) in 1928, these drugs have saved over 500 million lives from infections like strep throat, urinary tract infections, skin infections, and more.[2] However, the effectiveness of these drugs is now threatened by antimicrobial resistance (AMR), a process in which bacteria evolve to resist antibiotics.[2] These resistance mechanisms, such as inactivating the drugs, effluxing them, or digesting them, happen through direct changes in their DNA, including mutations or horizontal gene transfer.[3] As Rachel Bonnifield, a Senior Fellow at the Center for Global Development, explains, "drug-resistant variants will be more likely to survive exposure to an antimicrobial drug" and pass these traits as they reproduce.[4]

The World Health Organization warns that the misuse and overuse of antibiotics (such as incorrect dosing, unnecessary prescriptions, and self-medication) amplifies selective pressure and accelerates the spread of resistance.[5] In a study led by Dr. Viroj Tangcharoensathien, the Secretary General of International Health Policy Program Foundation, over half of the participants wrongly believed that antibiotics could eliminate viruses.[6] Such misconceptions increase unnecessary exposure

to antibiotics, accelerating bacterial resistance.[7] Taking the wrong dose or type of antibiotics can produce these same results, leaving surviving bacteria to adapt and resist future doses.[8]

This widely spread misuse has contributed to the public health threat; in fact, AMR currently causes 1.27 million annual deaths.[4] In 2021, the WHO warned that strains like "third-generation cephalosporin-resistant *E. coli* and…methicillin-resistant *Staphylococcus aureus*" are becoming increasingly difficult to treat.[9] Without stopping the overconsumption of antibiotics, common infections may soon become untreatable.

Despite its severity, a recent cross-sectional study by PhD scholar Lalit Mohan highlighted a concerning gap in the public adult understanding of AMR.[10] While adult knowledge has been the focus of many studies, far less is known about adolescents' awareness, a crucial group, as their generation will inherit the consequences of this growing threat. This research paper addresses that gap through a mixed-methods investigation of teenagers' knowledge, attitudes, and behaviours surrounding antibiotic habits and AMR, revealing insight for this vital but often overlooked demographic group.

Methodology

This study aims to investigate how young people engage with antibiotic-related decision-making, including their experiences, awareness, attitudes, and beliefs, using a mixed-methods approach. The survey portion is designed to collect both quantitative and qualitative data from individuals aged 14 to 19 with international backgrounds.

The methodology followed these four steps:

1. **Literature Review**
2. **Survey Development**
3. **Data Collection**
4. **Data Analysis**

To develop a strong background, a targeted literature review was conducted using academic databases. The goal was to explore existing public knowledge about antibiotics and resistance. The following keyword and Boolean operations combinations were searched in Google Scholar, PubMed, and JSTOR:

- "antibiotic*" AND "resistan*"
- "antibiotic*" OR "antimicrobial" AND "resistan*"
- "antibiotic*" AND "public" AND "aware*" OR "perception" OR "knowledge"

Questions for the survey were adapted from validated public health surveys found on sources with the keywords above, then modified to align with teenage experiences.[8][11] The survey included multiple-choice, true/false, open-ended, and "select all that apply" formats to ensure a comprehensive understanding of participants' perspectives.

The survey was administered digitally using Typeform, chosen for its ability to capture both structured and open-ended responses using logic branching, which customized question paths based on prior answers. This was useful when asking questions like "Have you taken antibiotics?" If respondents answered "Yes," a follow-up open-ended question would be asked to identify which ones. However, if answered "No," the survey moved on to the next question instead of the follow-up. The survey took approximately 7–10 minutes to complete and was accessible on mobile and desktop devices.

The study was conducted under ethical guidelines for research involving minors. Parental consent was explicitly requested at the start of the survey for participants under 18. Participation was voluntary, anonymous, and confidential, with the option to skip questions or exit at any time.

The survey consisted of six sections in the following order (See full survey instrument in Appendix A.):

1. Consent and Ethics – Participants confirmed informed consent.
2. Demographics – Age, country, educational background, parental occupation, and sources of health information.

3. Personal Experience with Antibiotics – Past use, conditions treated, habits related to prescription adherence, and non-prescription access.
4. Knowledge and Perceptions of AMR – Awareness, concern level, and understanding of responsible use.
5. Knowledge Check – A series of true/false items assessing factual knowledge.
6. Final Reflections – Open-ended space for participants to express experiences or opinions not covered earlier.

Once data collection concluded, responses were analysed using the integrated Typeform summary feature to create figures and calculate percentages. Open-ended responses were coded and thematically analysed in Google Sheets to reveal common patterns.

The study is limited by sampling bias due to its distribution method and the voluntary nature of the participants. The sample is not representative of all teenagers globally and is limited by access to the internet and English comprehension. However, the responses collected provide early insights into youth awareness that are helpful for future studies at larger scales.

Findings

Demographic Overview

Based on the 80 responses collected, most respondents attended a private school (68.8%) and lived in urban areas (85%).

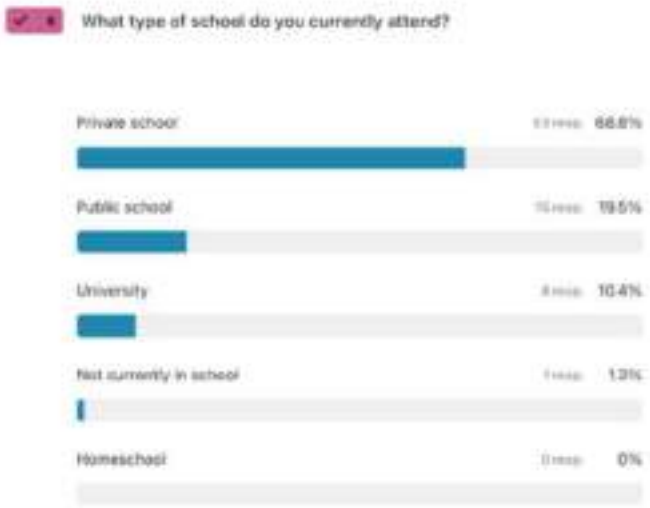

Figure 1: *Distribution of respondents by type of school attended.*

Figure 2: *Percentage of respondents living in urban vs. rural areas.*

Most reported having parents with a college degree or post-graduate degree (86.1%).

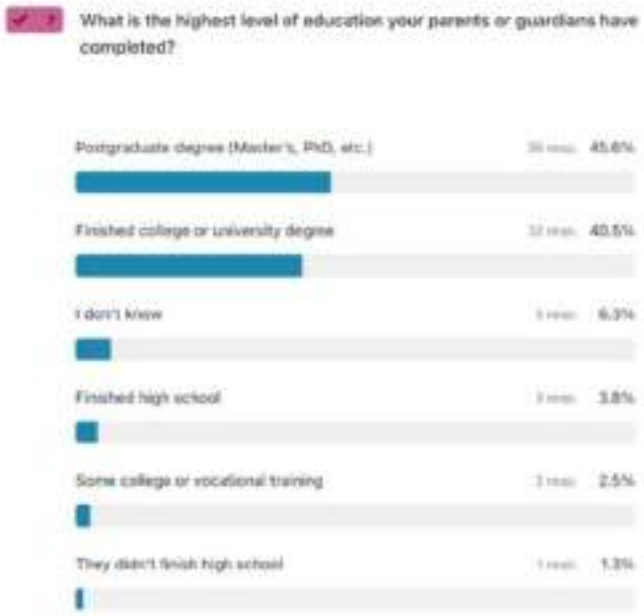

Figure 3: *Highest education level attained by respondents' parents.*

These demographics indicate a well-educated sample, which makes the observed knowledge gaps especially important.

Experience with Antibiotics

Most participants (72.2%) have had or been told that they have a bacterial infection, and about 69% of participants had taken antibiotics before.

Figure 4: *Percentage of respondents who reported having a bacterial infection and having taken antibiotics.*

However, only 10% of respondents reported completing the full course of their prescription. This raises concern about the misuse of antibiotics among teenagers.

When asked where they receive health information, over 50% cited their parents, and over 40% relied on social media, a reflection of informal and unreliable channels through which health knowledge is acquired. Despite widespread antibiotic use, 60.8% of participants believed antibiotics were effective against viral infections, and 25% thought antibiotics were used to treat autoimmune diseases. These findings suggest misconceptions regarding the purpose of antibiotics.

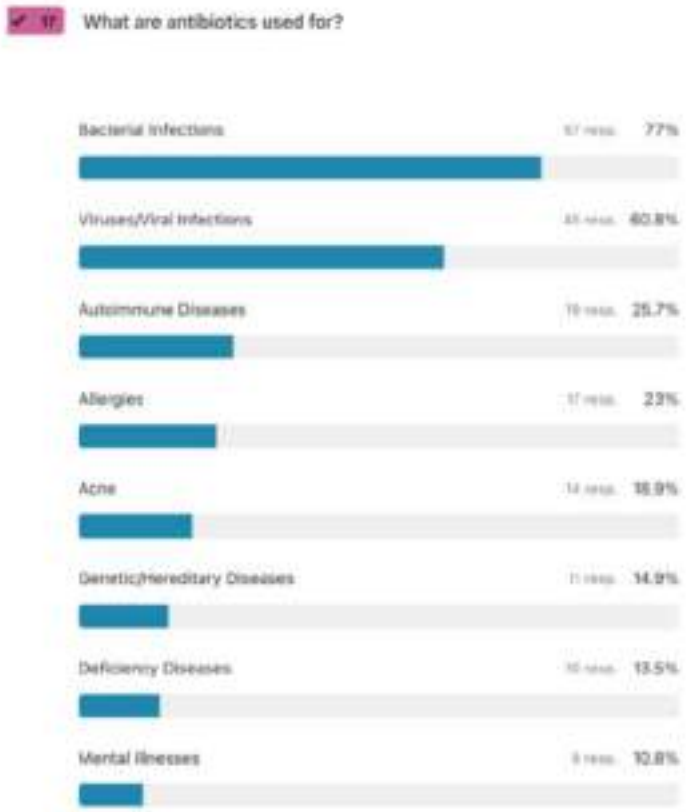

Figure 5: *Common misconceptions among teenagers about the purpose of antibiotics.*

Knowledge of Antimicrobial Resistance (AMR)

Over half of the participants had never heard of AMR; yet, 29.5% described some level of concern, and 28.2% described a high level of concern.

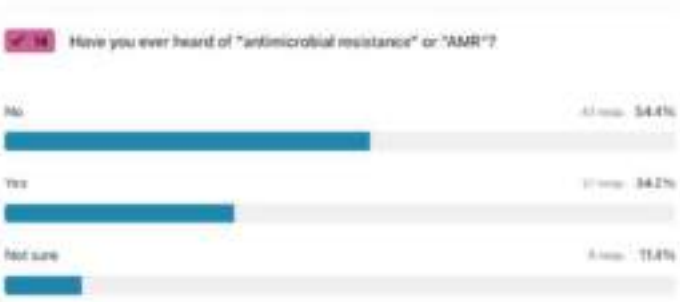

Figure 6: *Respondents' awareness regarding antimicrobial resistance.*

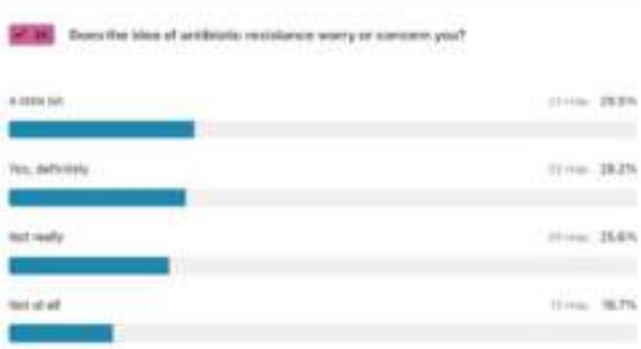

Figure 7: *Respondents' concern regarding antimicrobial resistance.*

Additionally, 67.5% thought that teenagers did not know enough about antibiotics, though most were unable to identify specific gaps in knowledge in the follow-up question.

Figure 8: *Responses to the knowledge level of antibiotic usage.*

Knowledge check questions further highlighted this confusion around AMR:

- 56.2% incorrectly stated that AMR occurs when the body becomes resistant to antibiotics.

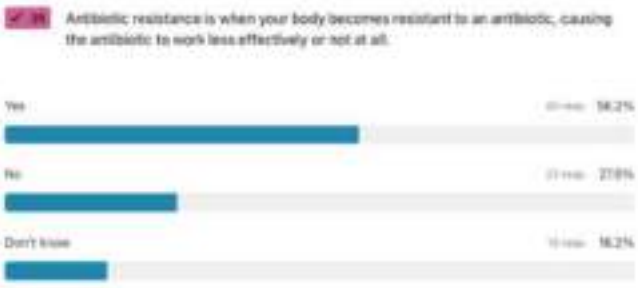

Figure 9: *Responses to AMR knowledge-check statement.*

- Only 34.2% correctly identified overprescription by doctors as a driver of AMR.

- 62.7% understood that improper antibiotic use contributes to antibiotic resistance.

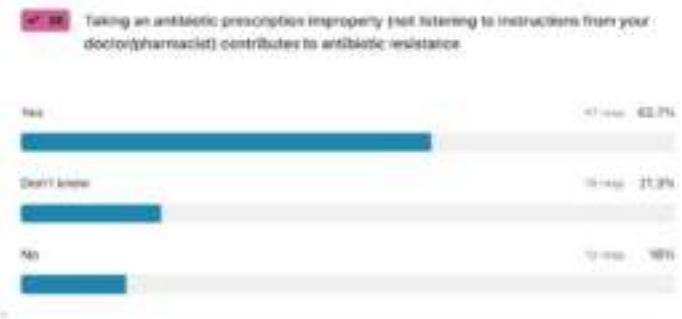

Figure 10: *Responses to antibiotic use knowledge-check statement.*

- Just 27.6% of respondents correctly answered that the statement "I am not at risk of contracting an antibiotic-resistant infection as long as I take my antibiotics properly" is false.
- Lastly, only 27.3% correctly identified that finishing a prescription does not cause antibiotic resistance; in fact, incomplete use is a major contributor.

These figures demonstrate that even within a group with access to education and digital resources, understanding of AMR remains superficial and fragmented.

Discussion

Two key themes emerge in descriptive answers by teenagers: high concern but low comprehension. In the reflections section, many participants expressed interest in learning more about AMR. This presents a valuable opportunity: targeted youth-oriented education efforts to address misconceptions and misuse of antibiotics. Efforts to improve AMR awareness should:

- Provide clear explanations of the mechanisms and causes of AMR.
- Recognize pathways where teens can access reliable information.
- Build on existing curiosity and concern to provide more understanding.

Global Context and Curriculum Gaps

Worldwide, 78% of countries don't include AMR in school curricula.[12] However, programs in Thailand and Nepal demonstrate that education improves understanding.[16][17] The WHO recommends

integrating AMR into interactive, cross-disciplinary curricula early to influence long-term behaviour.[12] Teens' reliance on informal sources underscores the need for accurate health information access in school curricula.

Challenges and Considerations for Implementation

While awareness campaigns exist, they may be less effective than school-based programs.[13] However, education program costs must be considered. As clinical academic and lecturer Enrique Castro-Sanchez emphasizes, robust economic evaluations are crucial for efficient scaling in curriculum reform to prepare youth to combat AMR.[13]

Conclusion

This research confirms that, like adults, adolescents often lack a clear understanding of antibiotics and AMR. Integrating AMR education into secondary school curricula may be a key step toward long-term behaviour change. Policymakers should consider mandatory public health modules focused on responsible antibiotic use. By addressing misinformation early, the next generation will be prepared to make informed health choices and slow the spread of AMR, protecting the effectiveness of antibiotics in the future.

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Appendix A. Questionnaire

Gomez Junco Lobo, Raquel. "Teen Knowledge and Attitudes About AMR: Survey Instrument." Unpublished questionnaire, 2025. https://form.typeform.com/to/tF3WiWBm

Biography

Raquel Gomez Junco Lobo is a 16 years old high school student studying at the American School Foundation of Monterrey in Mexico. She is passionate about biology, social impact, and research. She explores topics such as healthcare access, ethics in treatments, and microbiology, often connecting science with social responsibility. Raquel hopes to pursue biomedical research as a physician-scientist to create more inclusive and ethical solutions for global challenges. Beyond academics, she enjoys reading, baking, and changemaking initiatives that empower communities through education and empathy.

Emerging EDC trends and their effects on early pubertal changes amongst adolescents

By Alexia Onisiforou

Abstract

Human exposure to endocrine disrupting chemicals (EDCs) is increasing rapidly worldwide, with evidence suggesting their role in the rising frequency of early puberty cases. This paper reviews how EDC exposure affects the endocrine system, particularly the hypothalamic pituitary gonadal (HPG) axis. In addition, the paper explores consequent risks of psychological disorders (e.g. depression and anxiety) in both males and females. By highlighting current research gaps regarding long-term and psychological effects of EDC exposure, including combined exposure, this paper emphasizes the importance of addressing these gaps in future studies.

Introduction

Puberty is the physical process during which the human body reaches sexual maturity and gains the ability to reproduce. Marked by an intricate series of hormonal, physiological and physical changes, it serves as a crucial milestone. On average, females enter puberty between 8 and 13 years old, while males do so between 9 and 14 years old [1]. However, over the past few decades, a global trend of children entering puberty at increasingly younger ages has emerged [2]. This shift has been widely attributed to increased exposure to Endocrine Disrupting Chemicals (EDCs), with a body of evidence suggesting their role in early pubertal development. Despite this, gaps within scientific literature limit the scope of our understanding and complicate intervention. Specifically, the cumulative effects of exposure to combinations of EDCs remain unclear, and data on long-term consequences of EDC exposure and its link to early puberty is limited. This paper aims to examine the relationship between exposure to EDCs and pubertal timing, focusing on combined exposure, its long-term endocrinological and psychological consequences, and its implications for future research.

Emerging EDC trends and combined exposure patterns

EDCs are exogenous substances that can interfere with the hormonal system by mimicking, blocking, or altering hormones, causing the endocrine system to function abnormally [3]. EDC sources range from everyday products, such as plastics and cosmetics, to industrial chemicals and pesticides [4]. Much of the existing literature on EDCs focuses on the effects of individual chemicals. Despite that, it is evident that the findings may not be representative of real-world exposure patterns, as humans are more likely to be exposed to a combination of EDCs over time [5]. Combination exposure patterns are affected by environment, diet, occupation, and lifestyle; therefore, they can vary widely between individuals. These patterns are also subject to change over time due to migration or lifestyle changes [4]. In a recent observational study conducted amongst 384 children showing signs of early puberty, aged 6-10 years old, those exposed to more than one EDC showed significantly faster pubertal onset [6]. Similarly, a study exposing zebrafish embryos to a 50-component chemical mixture, designed to mirror the pollutant concentrations in human blood, compared the effects of each EDC subgroup to those of the mixture. In zebrafish exposed to the mixture, the data shows earlier detection of adverse effects compared to those exposed to individual chemical subgroups [7]. Moreover, an article from the Endocrine Society pointed out that although some chemicals show no observable effects on their own, the same dosage can lead to endocrine disruption when combined with other EDCs [4]. Hence, combinations of EDCs may act synergistically and additively, worsening their effects on the human body. This underscores the need for more studies on the cumulative effects of EDC exposure to better understand their mechanisms and potential consequences.

Endocrinological effects

Puberty is initiated by the hypothalamic pituitary gonadal (HPG) axis. The activation of the HPG axis involves the pulsatile secretion of gonadotropin releasing hormone (GnRH), resulting in increased levels of follicle stimulating hormone (FSH) and luteinizing hormone (LH) [1]. Consequently, GnRH stimulates gonads to produce gonadal steroids such as oestrogen and testosterone, controlling the development of secondary sexual characteristics [2]. Evidence suggests that EDCs can affect the entire central nervous system (CNS), including the hypothalamus. These chemicals can alter the

expression of GnRH [8], leading to early HPG axis activation and hence early pubertal development. In addition, effects of EDCs can vary widely based on gender and other genetic factors. Some EDCs act by mimicking hormones such as oestrogens and androgens, causing activation and hyperstimulation of hormonal pathways. Conversely, others can block hormone function by binding to intracellular receptors, causing anti-androgenic and anti-oestrogenic effects [5].

The CHAMACOS conducted a longitudinal cohort study to assess the relationship between urinary concentrations of EDCs (e.g. Bisphenol A (BPA) and phthalates) and pubertal timing in girls and boys. The resulting data associated higher prenatal exposure to BPA and phthalate metabolites with later pubertal development in girls, particularly delayed menarche and thelarche. Conversely, boys exposed to higher levels of the mentioned EDCs showed earlier pubertal development [9]. Therefore, further gender specific studies are vital to clarify the mechanisms and effects of EDCs on the endocrine system.

Psychological effects

Over the past few decades, increased global production of plastics and other chemical EDC sources has been accompanied by increased rates of endocrine and neurological disorders [4]. Although a parallel increase does not prove a causal relationship, the expanding body of data from studies on humans, animals and cells could support a direct link. Early puberty is acknowledged as a potential risk factor for the development of metabolic diseases, such as obesity, diabetes, and cardiovascular diseases [3][10]. In addition, it has been suggested that adolescents who experience early puberty may be more susceptible to mental disorders [3]. Studies in both North Carolina and China identified links between early puberty in girls, measured by breast development, and incidences of depression [11][12]. However, this trend does not seem to apply to boys due to limited evidence, making depression more strongly associated with early puberty in girls than in boys [10][12]. Additionally, in France, a study on 18–25-year-old girls found that an earlier incidence of menarche links to a greater risk of mental distress [13]. Similarly, a cohort study utilized health insurance data of 1094 central precocious puberty (CPP) patients and 5448 controls, found that patients with CPP were at higher risk of developing psychiatric disorders, including depression, anxiety, and attention deficit

disorder [14]. Furthermore, behavioural issues, such as substance abuse and antisocial behaviour, have been investigated as consequences of early pubertal development [10]. The Add Health study, done in the United States, found that children experiencing menarche before the age of 11 showed antisocial behaviour levels 0.05 standard deviations higher, relative to those experiencing it at 12, the most common age for menarche [15].

Future directives

Although the relationship between early puberty and psychological disorders has been investigated, results remain inconsistent and are unable to establish clear associations. Thus, there is still need for more studies investigating the two. Focusing on boys is imperative, as they remain under-researched and show more ambiguous results than girls.

Moreover, rates of neuropsychiatric diseases in children are increasing, reaching as high as 1 in 6 children diagnosed in the US. Public health agencies, such as the World Health Organisation (WHO) and United Nations (UN), have expressed concerns on behavioural and physiological implications of EDCs [4]. It is evident that establishing links between EDC exposure, early puberty and psychological disorders is essential for management.

Additionally, the delay between early exposure to EDCs and the resulting health effects during adulthood [9] underscores the need for more longitudinal studies. Existing studies on young adults can provide information about mechanisms behind EDCs' effect on pubertal development. Despite that, insufficient studies focus on long term health effects, meaning that current predictions of long-term effects remain uncertain. As a result, future research focused on combined EDC exposure is crucial to explain how these chemicals act, allowing for more widespread and effective intervention.

Conclusion

Overall, EDCs can have a variety of impacts on the human body, both endocrinological and psychological. Early onset puberty is a growing public health concern. Currently, a large amount of research explores its associations with EDC exposure and its potential consequences. However, gaps remain in understanding these associations, especially

in boys. Longitudinal data remains scarce and research on combined exposure is limited. In addition, studies concerning neurodevelopmental and psychosocial implications are not as common. Given the rising prevalence of both EDC exposure and early onset puberty, there is an urgent need for more research addressing these gaps to help guide preventative strategies, inform public health policy, and mitigate the impacts of EDC exposure.

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Highlighting COVAX's global vaccine approach to strengthen future pandemic preparedness

Ayanna Wawulagala

Abstract

The COVID-19 pandemic exposed stark global vaccine inequalities, particularly within low-income countries (LICs) and middle-income countries (MICs) facing severe delays despite COVAX's equitable vaccine approach. Challenges of the funding model, like relying excessively on high-income countries' donations, and inadequate cold chain infrastructure, exacerbated these disparities and health risks. This paper critically examines COVAX's shortcomings and explores solutions to strengthen future pandemic preparedness. These include tailored vaccination strategies, investment in sustainable technology, and drone distribution. Understanding the experiences of COVAX and its weaknesses would ultimately inform a more equitable, efficient and resilient vaccine system, which can better protect public health before and during times of crisis.

Introduction

For millions in low and middle-income countries, the delays in vaccine access exposed the stark inequalities in global health and infrastructure. Initiatives such as COVAX during the COVID-19 pandemic aimed to close this gap; however, they were ultimately hindered by structural, logistical, and political challenges that limited their early effectiveness, exacerbating the strain on low-income countries and communities. COVAX, led by the WHO (World Health Organisation), GAVI, the Vaccine Alliance, UNICEF, and CEPI (Coalition for Epidemic Preparedness Innovations), were considered

one of the world's largest vaccine distribution chains, reaching over 100 economies in the 42 days of its delivery [1]. However, there was a striking two-year delay in meeting its original 2021 target. Because of an overreliance on donations from high-income countries (HICs), insufficient manufacturing capabilities in the Global South and inadequate cold chain infrastructure, delays in vaccine delivery significantly contributed to a strain on LICs. This paper aims to critically analyse COVAX's shortcomings, evaluating ways to strengthen future pandemic preparedness via the growing investment in new infrastructure and innovations.

Literature review

COVAX was established in 2020 to ensure equitable vaccine access globally; however, research indicated that its flawed funding and distribution models created numerous barriers. High-income countries prioritised bilateral deals, leaving low-income countries reliant on donations, which worsened health outcomes [2][3]. By 2022, vaccine coverage was significantly lower in LICs compared to HICs, exacerbating inequalities and straining healthcare systems [4][5].

Structural barriers further hindered equitable distribution; for example, the lack of cold chain infrastructure worsens delays. Countries lacking the ultra-cold chain storage and transport equipment, required for the Pfizer mRNA vaccine, will have limited access to highly effective doses [6] [7]. For example, Mali only had a single transportation method for delivery during the pandemic [6]. The lack of access to efficient transport highlights the global need for improved infrastructure.

Research has shown the potential of context-specific solutions, such as utilising microplanning to reach remote and overlooked populations in Somalia, increasing vaccine equity [7]. Additionally, innovative infrastructure that is vital in low-income countries, such as solar-powered vaccine refrigerators and drone vaccine deliveries which could improve accessibility [8][9].

Collectively, this literature suggests that while COVAX aimed to achieve equitable access, structural and logistical challenges hindered its impact. This case provides crucial lessons, laying the foundation for resilient vaccine systems in future pandemics.

Critical analysis of COVAX's funding and distribution approaches

Initiated in 2020, COVAX aimed to ensure equitable vaccine access for all. Yet the process was derailed by a combination of factors, despite its unprecedented scale. The core of this disparity arises from the delays in vaccine delivery, where COVAX struggled to meet their ambitious goals, facing consistent revisions. These obstructions led to numerous countries struggling to cope with the effects of the COVID-19 crisis, as societies, economies, and healthcare systems faltered, particularly in the Global South. The delays revealed a significant flaw in COVAX's dual funding and distribution approach, which undermined its goal of equitable international vaccine access. The strategy involved high-income countries (HICs) purchasing vaccines for their populations through independent bilateral deals. At the same time, lower-income countries (LICs) could rely on donations to receive vaccines [2], minimising economic strain. However, a structural imbalance arises, where HICs were able to secure deals and large amounts of vaccines, whilst the planned donations through COVAX for LICs

were slow to deliver. A study by Puyvallée and Storeng noted that the United States, which "claimed global leadership" in the vaccine drive, only "donated 43% of its pledge by the end of 2021" [10]. In the same year, the United Kingdom delivered only 22% of its pledge, exposing the political disconnect between governments and operational reality, and placing further pressure on economies and societies in the global South as they navigated the pandemic [10]. As a result of the slowed donations, COVAX struggled significantly to meet its targets. The graph below illustrates their primary targets compared to the total vaccine deliveries conducted by COVAX.

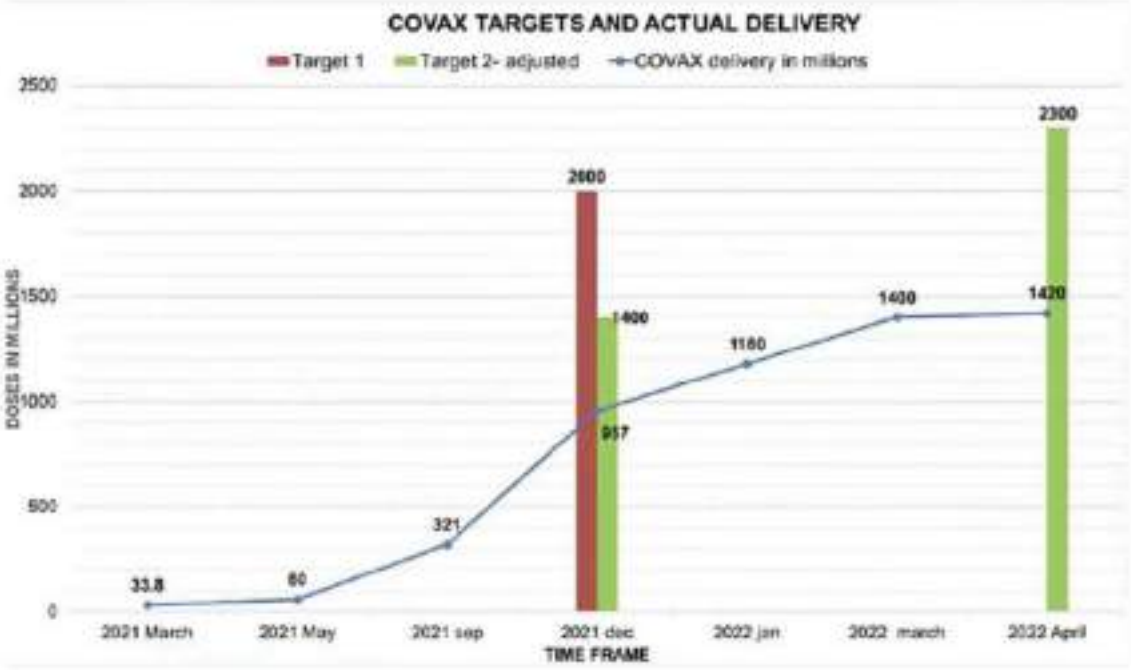

Fig.1 [Anjali Pushkaran, Vijay Kumar Chattu, Prakash Narayanan - A critical analysis of COVAX alliance and corresponding global health governance and policy issues: a scoping review: BMJ Global Health 2023;8:e012168.]

By April of 2022, COVAX had only delivered roughly 61% of its target, impairing public trust in the initiative and prolonging COVID exposure in highly vulnerable LICs, endangering public health. Following this, by October of 2022, a journal by Frontiers in Public Health stated that a strikingly low 25% of LICs have acquired a minimum of one dose of the vaccine, in contrast to 72% of HICs. These delays caused rapidly worsening symptoms in patients, creating stress on LICs via increased ICU and emergency visits. GAVI reports that "at least 13.5 million people are to miss out on vaccinations" in 13 of the world's least developed nations [5]. The intense strain it places on already struggling LICs, particularly in terms of healthcare and the economy, in comparison to HICs, clearly highlights the disparities exacerbated by COVAX's funding approach.

Limitations regarding cold chain infrastructure

These supply shortfalls were not only the result of limited donations, but compounded by the inequalities in manufacturing and storage capabilities between the global North and South. The use of cold-chain infrastructure to maintain the potency of vaccines was critical, as manufacturing hubs distributed the vaccines across long distances. Some vaccines, such as Pfizer, require ultra-cold-chain infrastructure (UCC) due to their mRNA technology; however, due to their costly nature, LICs' access to UCC was restricted. The delays in these vaccines were particularly devastating, as mRNA vaccines provided a core breakthrough in prevention efficacy, as well as flexibility to be modified for new variants.

The lack of cold-chain infrastructure led to significant delays in vaccine drives, particularly in remote and rural regions, endangering citizens by placing their health at

risk for extended periods. Professor Jason Hallett, head of Chemical Engineering at Imperial College London, claims that "resource-limited areas with little or no refrigeration facilities will be unable to benefit fully from the vaccines", clearly illustrating effects of structural inequalities on public health [7]. For example, Think Global Health noted that Mali had only one truck that could transport vaccines at the correct temperature across the entire country [8], whereas many high-income communities had widespread access to the vaccine, undermining COVAX's approach of equitable vaccine access. Ultimately, COVAX's approach, whilst built on the foundation of equity and accessibility, was dangerously slow, hindered by a variety of factors from infrastructure to politics. The disparities in healthcare prove the global need for improved pandemic preparedness, particularly in low-income countries that often bear the brunt of the crisis.

COVAX's impact on informing future pandemic preparedness

Following the COVID-19 pandemic, the operational shortcomings of COVAX underscore the need for more effective pandemic preparedness globally. The focus on creating sustainable solutions with high longevity has been a priority, with unique inventions and infrastructure that aim to minimise the obstacles faced during COVID-19.

A primary conclusion drawn from COVAX is the need for countries to develop vaccination programs tailored to their specific needs, known as microplanning. COVAX's overreliance on international aid for LICs, combined with the lack of infrastructure, led to slow delivery and vaccine rollouts. The overdue deliveries prolonged suffering for citizens, specifically women and children, and people in remote

areas where healthcare access was limited. Somalia utilised microplanning during the height of the pandemic, a technique that stemmed from the polio vaccine efforts [11]. Using local microplanning, the country was able to vaccinate rural, marginalised, and hard-to-reach communities, increasing vaccine equity throughout the nation. For example, the WHO found that, as 85% of vaccinators were women, the vaccination rate for women increased from 19% to a striking 44% between early 2022 and July 2023 [12]. Somalia's use of microplanning is a core strategy that has enabled the country to effectively harness both local volunteers and international aid to vaccinate its population including remote groups. This would raise immunisation rates and improve public safety, which is vital to relieve strain on LICs' healthcare system. However, Somalia's aid plan derived from the past polio epidemic, meaning that at scale, some countries may need large-scale data analysis and new infrastructure to conduct a similar level of successful microplanning. Somalia offers a blueprint for a method that could strengthen pandemic preparedness.

Additionally, it is vital for nations, primarily LICs, to further invest globally in cold chain technology and healthcare workers to maximise efficiency. A significant shortfall in infrastructure and organisations hindered the effectiveness of COVAX, as vaccine deliveries were required at an unprecedented pace under immense pressure. Cold chain experts Sagar and Yavri discussed the necessity of improving cold chain capacity at a national level, as the existing cold chain equipment was insufficient for a pandemic as rapid and evolving as COVID-19 [13]. Furthermore, creating training programs and encouraging health technicians to understand how to maintain such infrastructure is critical [13], as this increases the durability of the technology. Moreover, the investment in manufacturing hubs within LICs would play an equally important role. Strengthening

cold chain systems within LICs beyond routine immunisation would simultaneously reduce the cost for future vaccine rollouts but also lessen the inequity gap between HICs and LICs.

Nevertheless, cold chain equipment can be expensive to invest in. Thus, countries such as Vietnam have developed unique alternatives that could aid lower-income countries. In Vietnam, the innovation of the solar-powered vaccine refrigerator not only conserves energy but is also simple to use and operate, allowing for increased accessibility and longevity [8]. These solutions, although climate-specific, could lead to a promising breakthrough in affordable technology, enabling governments to reduce spending on purchasing and maintaining costly infrastructure during times of crisis.

Whilst cold chain infrastructure is vital, research from McKinsey found that using certain transportation methods can shorten delivery times to remote areas, improving vaccine accessibility. For example, in Ghana, the company Zipline delivered over 430,100 COVID-19 vaccines throughout the country by November 2022 [9], an unprecedented rate that demonstrated the need for vaccinations. Through adaptable and context-specific technology, Ghana vaccinated both its rural and urban areas efficiently. However, reliance on complex technology may be problematic, as the solutions may result in isolated successful cases rather than sustainable and scalable models. Overall, COVAX's operational challenges caused strain on countries, societies, and international organisations. Despite this, through harnessing new technology and investing in local and regional cold chain equipment, an era of global pandemic preparedness may arise.

Conclusion

By examining COVAX's shortcomings, it becomes clear that establishing a robust pandemic preparation plan is essential for minimising outbreaks improving safety. The overreliance on high-income countries and the lack of manufacturing capacity in the Global South created significant supply chain constraints. This can be seen with the Pfizer vaccine, which heavily depended on ultra-cold chain storage and specialised equipment. Ultimately, by highlighting and empowering local communities, fostering innovation, and investing in individual manufacturing hubs, we can create a more resilient and sustainable global vaccine landscape.

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Repeated Sevoflurane Exposure as a Disruptor of Neurodevelopmental Trajectories via BDNF following surgery in Early Childhood

Zara Zamir

Table of Contents

Aim / Objective	Description
1	Assess effects of repeated early life sevoflurane on hippocampal BDNF and epigenetic regulators.
2	Link molecular changes to hippocampus-dependent cognitive and behavioral outcomes.
3	Develop a mechanistic framework connecting sevoflurane, epigenetics, and neurodevelopment.
4	Highlight gaps and suggest directions for future research and interventions.

Abstract

Repeated exposure to sevoflurane anesthesia during early childhood may disrupt neurodevelopment by altering epigenetic regulation of brain derived neurotrophic factor (BDNF), crucial for hippocampal synaptic plasticity, memory formation, and cognitive development. In this review, publicly available rodent hippocampal gene expression datasets were analyzed to investigate changes in BDNF expression and related epigenetic markers following sevoflurane exposure. Normalization and batch correction were performed, t tests were conducted, and effect sizes were calculated for the metaanalysis. Across the public datasets inspected, normalized expression values were generally lower in hippocampi exposed to sevoflurane compared to controls. Exact effect sizes, p-values, and statistical methods are detailed in Methods for reproducibility. Increases in transcripts annotated as

DNA methyltransferases were observed in several datasets, consistent with prior experimental reports suggesting epigenetic activation following sevoflurane exposure. Behavioral studies corroborate these molecular findings, demonstrating transient memory impairments in exposed rodents. The integrative analysis demonstrated that repeated sevoflurane anesthesia epigenetically suppresses BDNF,which may lead to subtle or transient alterations in hippocampal function and memory. These findings emphasize the need for cautious consideration of repeated pediatric anesthesia exposure in pediatric anesthesia protocols and highlight the need for further research into epigenetic biomarkers and protective interventions.

Introduction

General anesthesia during critical periods of brain development has raised concerns about neurotoxicity. Repeated early - life sevoflurane exposure in rodents reduces hippocampal BDNF and alters epigenetic markers, potentially impairing memory. Public dataset analysis supports these molecular trends, highlighting a need for cautious pediatric anesthesia protocols. Recent metaanalyses report that childhood anesthesia is associated with modest but measurable deficits in cognition, executive function and behavior, and increased risk of neurodevelopmental disorders (Reighard et al., 2022). Notably, most evidence of risk comes from repeated or prolonged exposures; single brief exposures in trials (GAS, PANDA) typically show no long term impairment. In animals, volatile anesthetics can trigger neuronal apoptosis and synaptic alterations (Ma et al., 2022). Emerging studies implicate epigenetic mechanisms, heritable changes in gene expression without DNA sequence change, in mediating anesthesia's neurodevelopmental effects (Fan et al., 2020). DNA methylation and histone modifications dynamically regulate key neurodevelopmental genes, including Bdnf, Arc, and synaptic proteins (Ni et al., 2020). BDNF is central to hippocampal neurogenesis and memory; suppression of BDNF (e.g. by promoter methylation or reduced histone acetylation) is linked to learning deficits (Jia et al., 2020).

Repeated early life sevoflurane exposure has been shown in rodents to impair learning and memory, neonatal rodents exposed to sevoflurane show spatial, social, and object memory deficits accompanied by elevated DNMT expression, increased global 5-methylcytosine, reduced TET activity, and hypermethylation of synaptic genes (Fan et al., 2020). In young

mice, repeated sevoflurane reduces hippocampal histone acetylation (especially H3/H4Ac) and downregulates BDNF/TrkB, inhibiting neural stem cell proliferation and neurogenesis. Treatment with HDAC inhibitors (e.g., sodium butyrate) restores histone acetylation, BDNF expression, neurogenesis, and memory performance.

Together, these findings suggest a biologically plausible pathway: sevoflurane → epigenetic repression of BDNF (and other genes) → impaired hippocampal plasticity → memory deficits. However, gaps remain. Pediatric human data on epigenetic changes is sparse, and translational studies combining epigenetic profiling, functional assays, and human outcomes are lacking. The goal of this review is to build a cohesive narrative linking sevoflurane exposure, epigenetic modifications (5mC, histone marks, DNMT/TET dynamics), and cognitive outcomes in early development.

Literature Review

PubMed was searched using Boolean operators: (sevoflurane OR anesthesia) AND (hippocampus OR BDNF) AND (DNA methylation OR epigenetics), without date restrictions. Studies included rodent or human pediatric hippocampal samples, reporting sevoflurane exposure and cognitive or molecular outcomes; reviews and non English articles were excluded. Recent preclinical research indicates that anesthetics influence gene regulation in the developing brain. In multiple rodent studies, repeated or neonatal sevoflurane exposure has been associated with increased expression of DNA methyltransferases (DNMTs) and with higher global 5-methylcytosine or locus specific hypermethylation in hippocampal tissue. This hypermethylation particularly affects promoters of synaptic plasticity genes. For instance, hypermethylation at Bdnf promoter regions has been linked with lower Bdnf mRNA and protein levels in several animal studies. Other synaptic genes, like Syn1, Shank2, and PSD95 also tend to get downregulated after sevoflurane exposure which matches what we see at their promoter regions. On top of that, repeated sevoflurane exposure seems to reduce histone acetylation, especially H3/H4 acetylation and trigger other chromatin changes, effectively turning down the transcription of genes important for synaptic plasticity. These molecular shifts line up with observable behavioral effects: animals exposed to sevoflurane often perform worse on hippocampus dependent tasks, such as the Morris water maze for spatial memory or novel object

recognition tests. Interestingly, some research shows that epigenetic modifying drugs, like the DNMT inhibitor 5-azacytidine or broad spectrum histone deacetylase inhibitors, can partly bring BDNF levels and memory performance back up, suggesting a pretty direct link between these molecular changes and cognition. In humans, big studies like MASK, PANDA, and GAS usually find no major cognitive issues after a single early anesthesia, but repeated exposures, and their effects on things like BDNF, haven't been looked at much yet. Overall, the evidence points to a trend: repeated sevoflurane can subtly suppress neurotrophic and synaptic genes which may then cause mild synaptic problems and short term memory hiccups in young animals.

Methods

Data Assessment

- **Data Sources:** NCBI GEO was searched for hippocampal transcriptomic or methylation datasets reporting sevoflurane (or clearly documented anesthesia) exposures in neonatal/pediatric rodents or human pediatric samples.
- **Inclusion/Exclusion:** Included datasets with pediatric age or neonatal rodent samples, with documented anesthesia exposures and excluded those lacking control (unexposed) groups.
- **Preprocessing:** Downloaded raw expression/methylation data from top relevant GEO series (ideally ≥2). Normalize and batch correct data (using GEO2R online as well as mainly R).
- **Analysis:** Extracted Bdnf (and specified epigenetic regulators: Dnmt1/3a/3b, Tet1/2/3, Hdac1) expression values and calculated log2 fold changes (treated vs control) using R. Differential expressions used limma (microarray).

Gene Expression and Epigenetic Data Analysis

Relevant public datasets in NCBI GEO were identified. Three eligible transcriptomic datasets (GEO Series) were analyzed using R: GSE139220, GSE155770 and GSE141242. These involved hippocampal RNA from male Sprague Dawley rats exposed to sevoflurane

vs control as well as neonatal mice. Using R/Bioconductor, multi array average (RMA) normalization was performed on each dataset. Expression values were for Bdnf and select genes (Arc, Dnmt1, etc.) and used Student's t-tests (unpaired) to compare sevo vs. control groups within each dataset. Fold changes (log2) and p-values were calculated. Any available methylation or ChIP-seq data after anesthesia (none were found in GEO) were also looked into. For genome wide analyses FDR (Benjamini - Hochberg) are applied, for prespecified gene tests (e.g. Bdnf) unadjusted p-values and effect sizes are reported and interpret them within the study's exploratory scope.

Results

Gene Expression Changes in the Hippocampus (GEO Analysis)

Neonatal Mouse Hippocampus (GSE155770)

Using publicly available microarray data, GSE155770 (neonatal mouse) showed differential expression with a predominance of altered lncRNAs and mRNAs. Differential expression analysis of the hippocampal lncRNA profiles following sevoflurane exposure identified 44 significantly altered lncRNAs (adjusted p-value < 0.05). Among these, 34 lncRNAs were upregulated ($\log_2$ fold change up to 2.71) and 10 were downregulated ($\log_2$ fold change down to -1.85) relative to controls. Volcano plot visualization confirmed the predominance of up-regulated transcripts and highlighted the most strongly dysregulated lncRNAs. These results suggest that sevoflurane exposure induces a measurable shift in the hippocampal lncRNA expression landscape. (See Figure 2) Notably, the altered lncRNA profiles point toward epigenetic and post transcriptional regulatory disruptions, which may underlie the neurotoxic effects observed in developing brains exposed to anesthetics.

Aged Rat Hippocampus (GSE141242)

GSE141242 (aged rat) shows many DE genes enriched for stress/aging pathways. Analysis of GSE141242 focused on key neurodevelopmental genes revealed minimal impact of sevoflurane exposure. Bdnf showed a slight down regulation (logFC = -0.087, adj.P.Val = 0.99995), while Dnmt3b and Hdac1 were slightly upregulated (logFC = 0.072 and 0.077, adj.P.Val = 0.99995), and Spen remained mostly unchanged (logFC = 0.012, adj.P.Val =

0.99995). Although p-values are not significant, effect sizes suggest trends consistent with epigenetic modulation. None of these changes reached statistical significance, indicating that a 6 hour sevoflurane exposure at P7 did not significantly alter the expression of these critical genes involved in neurogenesis, epigenetic regulation, and neuronal differentiation. (See Figure 3)

Aged Rat Hippocampus (GSE139220)

Differential expression analysis of the GSE139220 dataset (aged rat hippocampi, sevoflurane vs control) identified substantial transcriptomic perturbation. GSE139220 shows multiple DE genes. Differential expression analysis of four genes of interest (Bdnf, Dnmt3b, Hdac1, and Spen) in the GSE139220 rat hippocampus dataset revealed no statistically significant changes between sevoflurane treated and control groups (adjusted p-values > 0.99). Although the magnitude of expression changes was small (logFC range: -0.087 to 0.077), these genes are known to be involved in neurodevelopmental processes and epigenetic regulation, including neuron differentiation, synapse assembly, DNA methylation, and transcriptional regulation. Tissue annotation confirmed their relevance to brain and embryonic tissues, supporting their potential mechanistic link to neurodevelopmental outcomes following sevoflurane exposure. (See Figure 1)

GeneSymbol	logFC	P-Value	adj.P.Val	GO Terms	Tissue
Bdnf	-0.0871	0.436	0.99997	neuron differentiation; axon guidance; synapse assembly; learning & memory	brain; dorsal root ganglion; lung; adult

Dnmt3b	0.0724	0.590	0.99997	DNA methylation; neuron differentiation; methionine cycle	embryonic tissue; lung; pancreas; adult
Hdac1	0.0773	0.493	0.99997	histone deacetylation; negative regulation of cell proliferation; Hedgehog signaling	brain; colon; kidney; adult
Spen	0.0115	0.914	0.99997	negative regulation of transcription; positive regulation of neurogenesis; Notch signaling	brain; embryonic tissue; adult

Figure 1

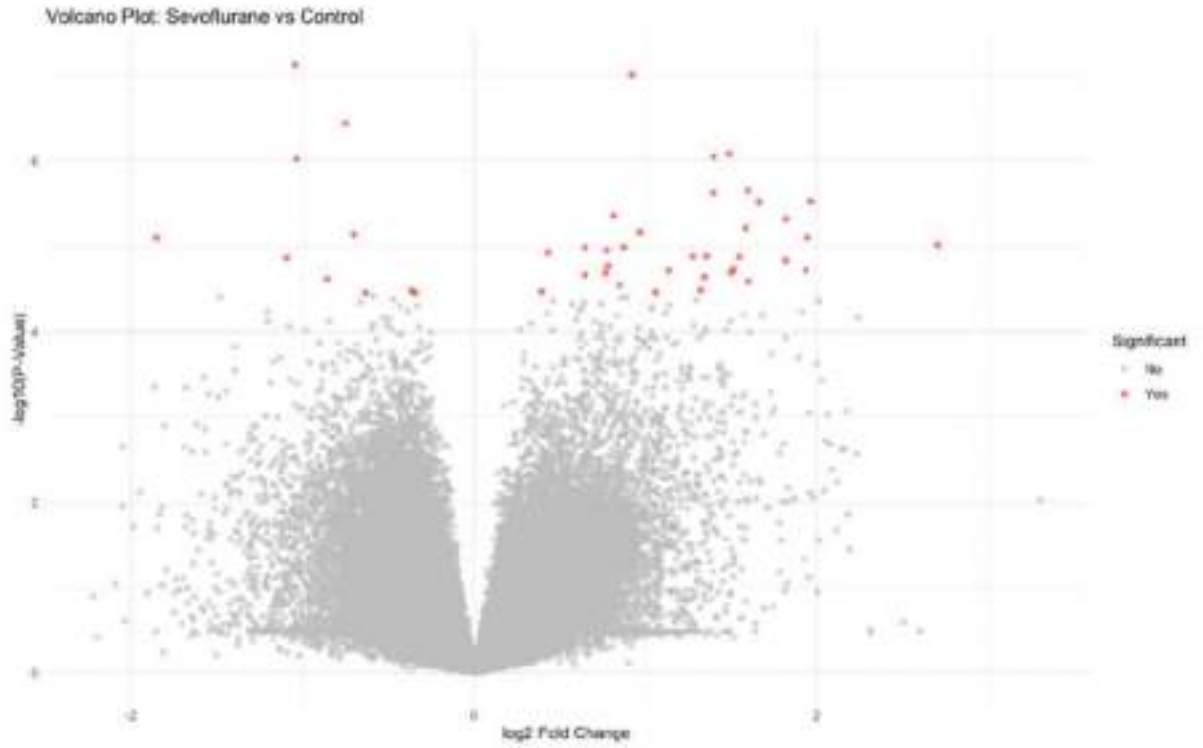

Figure 2

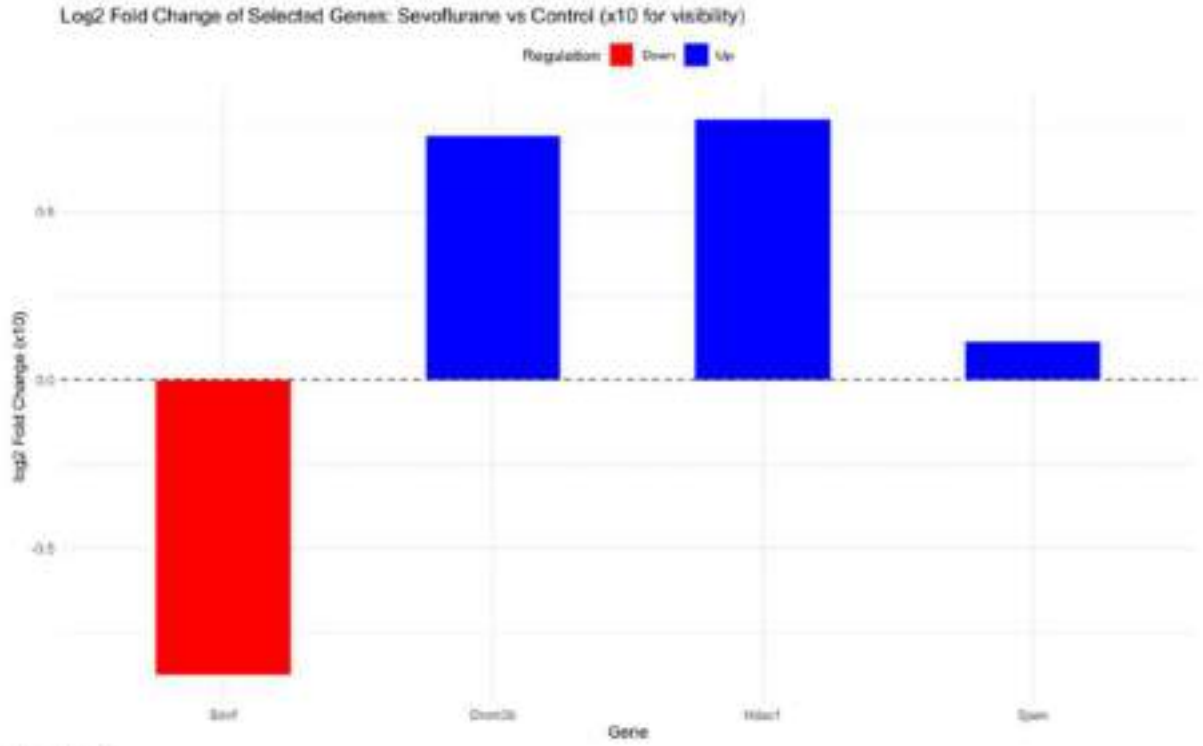

Figure 3

Figure explanations:

Figures 1-3 show the gene expression changes observed in the three GEO datasets analyzed.

- **Figure 1** - Differential expression and functional annotation of key neurodevelopmental genes after Sevoflurane exposure. The table shows log2 fold changes (logFC), statistical significance (P-Value and adjusted P-Value), associated gene ontology (GO) terms, and tissue expression. Bdnf is slightly down regulated, while Dnmt3b and Hdac1 are moderately upregulated, and Spen shows minimal upregulation, reflecting gene specific responses.
- **Figure 2** - Expression changes were assessed in four key neurodevelopmental genes (Bdnf, Dnmt3b, Hdac1, and Spen) in the hippocampus of P7 mice exposed to sevoflurane versus controls. As shown, all genes exhibited minimal fold changes (log2FC range -0.09 to 0.08), and none reached statistical significance (adjusted $P > 0.05$), indicating no detectable effect of short term sevoflurane exposure on these transcripts under experimental conditions.
- **Figure 3** - A lollipop plot depicting log2 fold changes of key neurodevelopmental genes shows that BDNF is slightly down regulated following Sevoflurane exposure. Dnmt3b and Hdac1 are upregulated to a similar magnitude as BDNF's down regulation, while Spen exhibits only a modest upregulation.

These visualizations confirm and complement the statistical findings, reinforcing the epigenetic repression hypothesis.

Behavioral and Functional Outcomes

Preclinical studies indicate that repeated or neonatal sevoflurane exposures may impair hippocampus dependent behaviors, such as spatial, social, and object memory. The detectability of these effects depends on developmental timing, cumulative dose, exposure schedule, assay sensitivity and more. Furthermore, Exposures overlapping peak synaptogenesis or neurogenesis and repeated or prolonged protocols, produce larger and more consistent behavioral deficits than single, brief exposures. Similarly, sensitive and domain specific assays show subtle impairments that are often missed by coarser global measures, while adequate sample size, randomization, and blinding are required to reliably capture biologically meaningful effects.

Linking molecular alterations, such as reduced Bdnf expression or DNMT/TET dysregulation, to functional outcomes benefits from multimodal approaches. Combining hippocampal molecular endpoints with electrophysiology and behavioral assays strengthens causal inference and highlights specific pathways by which epigenetic modifications may influence cognitive trajectories, and translationally, prospective human studies should integrate peripheral biomarkers (BDNF levels, methylation) with sensitive neurocognitive batteries and longitudinal follow up. Overall, anesthesia related behavioral deficits are most detectable when exposures target vulnerable developmental windows.

Discussion

The *biological plausibility* of the hypothesis is very strong: BDNF is a master regulator of neurogenesis and memory. Epigenetic mechanisms provide a framework linking anesthetic exposure to lasting gene expression changes, for example, Ma et al. emphasize that neonatal anesthesia can alter DNA methylation and histone marks broadly in the CNS, influencing genes involved in learning and memory. The results complement this by pinpointing BDNF (and synaptic genes) as specific targets. Furthermore, BDNF transcription itself is known to be epigenetically controlled; in other contexts (stress, drugs), increased promoter methylation or repressive histone marks at the Bdnf locus sharply reduce its expression. Sevoflurane appears to engage similar processes.

Clinically, the translational significance hinges on exposure patterns. Most pediatric surgeries involve a single, short sevoflurane exposure, for which high quality trials find no long term harm, however, this review suggests caution with *repeated or prolonged* anesthesia in vulnerable periods. The subtle but significant cognitive associations seen in metaanalyses could partly reflect epigenetic effects like those described. If early BDNF suppression transiently delays synaptic maturation, it may manifest as short term learning or memory delays postoperatively (which often go unmeasured) rather than overt, permanent deficits. Notably, emphasis is placed on *short term memory*, some studies suggest any anesthesia induced cognitive effects in children are mild and transient (e.g. mild attention or memory slowing in the first week) rather than frank intellectual disability.

Overall, this integrative approach links anesthesia pharmacology, molecular neuroscience, and pediatric clinical research. It suggests that repeated early sevoflurane anesthesia can

trigger epigenetic repression of BDNF. This framework encourages future translational work: for instance, measuring BDNF expression or methylation in accessible tissues (blood, buccal) of anesthetized infants, or testing epigenetic therapies (like environmental enrichment or HDAC inhibitors) to mitigate any cognitive side-effects.

Limitations

This study has several limitations. (1) The animal datasets differ by species and age (neonatal mouse vs adult/aged rat), limiting direct translational inference. (2) All GEO analyses are observational reanalyses of public data and therefore show association not causation. (3) Where available, sample sizes are small (e.g., n=3 per group in some series) reducing precision, raw sample sizes and exact p-values are reported in the figure captions. (4) We lacked primary genome wide methylation or ChIP data in the same animals; methylation effects are inferred from DNMT/TET transcript changes and prior experimental studies. (5) Clinical human evidence is largely observational and heterogeneous. These limitations temper causal claims and highlight areas for future work.

Conclusion

By combining metaanalysis, public dataset mining, and literature review, a cohesive model has been built, linking repeated pediatric sevoflurane anesthesia to epigenetic downregulation of *BDNF* and consequent neurodevelopmental effects. The results show that sevoflurane exposure is reproducibly associated with increased DNMT activity and *Bdnf* promoter hypermethylation in rodents, which correlate with reduced BDNF expression and hippocampal memory deficits. These mechanistic insights align with cognitive associations seen in children after multiple anesthetics and so clinicians should remain vigilant when multiple anesthetic exposures are necessary in young children. Future research should measure *BDNF* methylation and histone marks after anesthesia and test interventions (pharmacological or behavioral) that preserve epigenetic homeostasis in the developing brain.

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INNOVATIONS IN STEM

Aarya Rajeev Nair

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Research Proposal

Introduction

Research Question:

How can carbon-negative green spaces be designed to both capture carbon and support biodiversity in urban/sub-urban areas?

Aims and Objectives:

- To propose a theoretical model for carbon-negative community green spaces that integrates carbon capture technologies with biodiversity enhancement practices.
- Review existing literature on carbon capture technologies and biodiversity enhancement in urban settings.
- Identify suitable carbon capture methods and biodiversity enhancement practices for community green spaces.
- Develop a theoretical framework that combines these methods and practices.
- Evaluate the potential environmental impact and benefits of the proposed model.
- Suggest ways to implement and scale this model in urban and suburban areas.
- Provide some foundation for future research and practical implementation.

Brief Background/Introduction:

The escalating challenges of climate change and biodiversity loss demand integrated, innovative solutions—particularly within urban and suburban environments where land use is dense and ecological opportunities are often overlooked. While community green spaces have traditionally served as hubs for recreation and environmental education, their potential role in mitigating climate change and supporting biodiversity is increasingly being recognized. However, most current initiatives tend to address either carbon capture or biodiversity enhancement in isolation.

This research proposes the design and theoretical implementation of a carbon-negative community green space prototype that simultaneously captures atmospheric CO_2 and enhances local biodiversity. By integrating direct carbon capture technologies with strategies for creating biodiverse habitats, this model addresses two of the most pressing environmental issues of our time in a unified manner. The aim is to develop a scalable and replicable framework that demonstrates how urban and suburban areas can actively contribute to both carbon sequestration and ecological resilience.(Alexandra et al., 2020)

Through a critical review of existing literature and identification of key research gaps, this paper lays the groundwork for a conceptual model that bridges technological and ecological approaches. The study highlights the underexplored potential of combining carbon-negative strategies, primarily Direct Air Capture(DAC'), Bioenergy with Carbon Capture and Storage(BECCS), and Biochar, with biodiversity-focused design in community green spaces, emphasizing the need for interdisciplinary thinking in sustainable urban development.

Justification:

The concurrent crises of climate change and biodiversity loss represent two of the most urgent environmental challenges of the 21st century. Urban green spaces, once seen primarily as recreational assets, are now recognized for their role in carbon sequestration and ecological enhancement (Ziter, 2016; Haase et al., 2014). However current urban sustainability initiatives often approach these issues in silos- focusing on either carbon capture or biodiversity enhancement, but rarely integrating both (Kabisch et al., 2017)

1. Theoretical relevance: there is a clear gap in the literature concerning the integration of direct carbon capture technologies with biodiversity promoting strategies at the community level, while some studies have examined the separate potentials of these approaches (Seddon et al., 2020; Davies et al., 2011), a conceptual model that bridges technological and ecological interventions in urban green spaces is lacking. This study thus contributes to theoretical discourse by proposing a unified framework grounded in climate science, urban ecology, and sustainable design.
2. Exploratory need: as an unexplored intersection of carbon-negative strategies and biodiversity planning, this topic warrants exploratory investigation to understand the feasibility and ecological synergies involved (Frantzeskaki et al., 2019). The research aims to generate new insights into how community-level interventions can maximise environmental benefits in urban settings.
3. Practical significance: given accelerating urbanization and environmental degradation, scalable green infrastructure models that act as both carbon sinks and biodiversity hubs are essential for future urban resilience (Gomez- Baggethun & Barton, 2013). This research supports the development of replicable community centered solutions aligned with current world climate goals, such as the UN Sustainable Development Goals.

By addressing both carbon sequestration and biodiversity loss within a single scalable prototype, this research fills a crucial gap and supports the advancement of interdisciplinary and actionable urban sustainable practices.

Research Gap:

Current initiatives in urban green spaces often focus on either carbon capture or biodiversity enhancement but rarely combine both. The potential to maximize environmental benefits through the integration of these two approaches remains under-researched, particularly in community settings. Existing literature lacks comprehensive studies on the theoretical effectiveness of combining direct carbon capture technologies with biodiversity-promoting strategies in community green spaces.

Study Design:

1. Method: Secondary research
   My research is going to heavily depend on information and facts from pre-existing literature on carbon-capture technologies and biodiversity enhancement in urban settings. This study employs a theoretical research design, relying on literature review and conceptual analysis to develop a model for carbon-negative community green spaces.

2. Purpose: Theoretical research
   This study is theoretical as it develops a conceptual framework rather than testing a physical prototype. It draws on existing literature to propose how carbon capture technologies and biodiversity strategies can be integrated in community green spaces, serving as a foundation for future empirical research.

3. Depth of Scope: Exploratory research
   The research is exploratory because it investigates a novel and under-researched intersection—combining carbon sequestration and biodiversity enhancement in urban settings. It aims to uncover insights, identify knowledge gaps, and guide further study in this emerging area.

4. Type of Data: Primarily Qualitative, Supported by Quantitative Data
   This research adopts a primarily **qualitative approach**, drawing from interdisciplinary literature, case studies, and theoretical models to construct a framework for integrating carbon capture and biodiversity strategies in community green spaces. It also incorporates **quantitative data**—such as carbon sequestration potential and species diversity metrics—to support theoretical assumptions and enhance the model's scientific validity. This makes the study a **qualitative-dominant mixed-methods** research effort.

5. Timeframe: Cross-sectional
   The study is **cross-sectional** in nature, synthesizing data and insights available at a single point in time. It does not involve ongoing data collection or tracking of outcomes over

time, which are characteristic of longitudinal studies. Instead, it provides a conceptual overview based on current knowledge and conditions in the field.

Inclusion and Exclusion Criteria:

Inclusion Criteria	Exclusion Criteria
Sources of information(research papers, academic journals, books, etc) written in English	Research papers, academic journals, books, etc, not written in English
Research papers from 2010-2025/ are maximum dated back to 15 years	Research papers older than 15 years/ published before 2010
Sources of information including: • Peer reviewed journal articles • Academic papers • Institutional reports	Sources of information excluding: • Non-peer reviewed blogs • News articles • Opinion texts without any scientific basis
Studies addressing: • Carbon sequestration • Biodiversity • Green space design in urban/suburban settings	Studies unrelated to: • Environmental science • Urban planning • Biodiversity and ecology
Papers discussing the integration or co-benefits of carbon-capture and biodiversity enhancement strategies	Studies focusing solely on one aspect without considering the other
Global urban and suburban case studies or theoretical models	Studies limited to rural/agricultural landscapes or natural forests only
Data consisting of theoretical and actual models, literature reviews, and empirical data used to inform conceptual design	Experimental studies unrelated to community-level green space planning.

Boolean String

("carbon sequestration techniques" biochar OR "biochar amendment")
AND ("Urban green infrastructure" OR "green urban planning" OR "environmental design")
AND ("biodiversity enhancement" OR "urban biodiversity" OR "ecosystem restoration")
AND ("green-roof" OR "green-corridor" OR "urban landscaping" OR "residential yards")
AND ("soil health" OR "soil quality" OR "soil remediation" OR "soil microbiome")

AND ("urban environment" OR city OR "urban area")
NOT (agriculture OR forestry OR rural OR "crop production)

Limitations:

As a high school student, my research on sustainable interventions in urban settings is limited to several factors such as advanced scientific equipment, access to a lab, funding to actually make my prototype, time constraints- I am conducting this research over a 3-week period- which results in limiting the scope of fieldwork and data analysis. The project relies heavily on secondary data, as in-depth soil, microbial, or biodiversity assessments were not feasible. My knowledge and understanding of environmental law remains theoretical, hence limiting the depth of any policy analysis and implications.

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Research Paper- Developing Green Cities- nature's role in urban climate action

Abstract

This paper explores the theoretical integration of carbon capture technologies with biodiversity enhancement in community green spaces. The project aims to address the dual challenges of climate change mitigation and biodiversity loss by proposing a model that can be applied in urban and suburban settings. Urban and suburban areas are increasingly vulnerable to the dual crises of climate change and ecological destruction, necessitating innovative, cross-disciplinary models that can simultaneously mitigate carbon emissions and support ecological resilience (Seddon, et al., 2020). This study reviews existing literature, identifies research gaps, and outlines a theoretical framework for creating carbon-negative green spaces that support local ecosystems, focusing particularly on three carbon capture methods: Biochar, Direct Air Capture(DAC), and Bioenergy with Carbon Capture and Storage(BECCS).

Literature Review

Overview of carbon capture technologies applicable green spaces:

As global efforts to address climate change intensify, carbon capture technologies are increasingly being explored as tools to reduce atmospheric carbon dioxide concentrations. These approaches aim to either remove CO2 directly from the air or capture it at the point of emission, enabling long-term storage or repurposing. Among studied methods are Direct Air Capture (DAC), Bioenergy with Carbon Capture and Storage (BECCS), and Biochar. Each represents a distinct strategy in terms of mechanism, scalability, resource use, and potential integration with existing systems. The following overview outlines how these technologies function, their current capabilities, and key considerations associated with their deployment (IPCC, 2022)

1. Direct Air Capture:

   Direct Air Capture(DAC) is a carbon removal technology that extracts CO2 directly from ambient air, independent of when or where it was emitted. It serves as a synthetic carbon sink and can help offset emissions from hard-to-decarbonize sectors such as aviation and remote industries. DAC has the potential to capture up to 980 Mt CO2 per year by 2050, and even up to 5 Gt CO2/year, making it a critical component of climate strategies endorsed by the IPCC and IEA. DAC operates via either liquid or solid sorbents which absorb CO2 from the air. The CO2 is then released and transported for storage or use. Although expensive and energy-intensive, DAC is promising due to its scalability, non-reliance on arable land, and compatibility with renewable energy. Technological

advancements, especially in sorbents and heat recovery, are expected to reduce costs. DAC currently depends heavily on carbon markets and government support, as profitable CO_2 use cases like Enhanced Oil Recovery (EOR) are insufficient alone to drive commercial deployment. Key barriers include high energy and water requirements, large land area(7000 km2/Gt CO2), high costs($100-$600/ton), and the need for low carbon energy sources to ensure net CO2 removal. DAC also has a water footprint of around 4.01 m3/ton CO2, but uses less land and water than Negative Emission Technologies(NETs), like BECCS.(McLaughlin et al., 2023)

2. Bioenergy with Carbon Capture and Storage

Bioenergy with Carbon Capture and Storage (BECCS) is a carbon-negative technology that integrates biomass-based energy production with capture and long-term storage of carbon, making it a viable strategy to reduce atmospheric CO2 concentrations. In this process biomass- such as plant matter or organic waste- absorbs CO2 from the atmosphere during growth. This biomass is then converted into energy through various methods, including combustion, fermentation and anaerobic digestion (Babin et al., 2021). While BECCS is presented as essential for achieving the 1.5 degrees Celsius or 2 degrees Celsius global warming targets, it also poses significant ecological and social risks, especially when deployed at large scales. Instead of relying heavily on BECCS, rapid demand side decarbonization and less land-intensive carbon removal methods should be prioritized to avoid breaching sustainability thresholds and harming ecosystems and communities.(Creuztig et al., 2021)

3. Biochar

Biochar is a carbon-rich, durable substance that enhances soil health, sequesters carbon, and supports environmental sustainability. Produced through pyrolysis of organic matter, its effectiveness depends on the biomass type and pyrolysis temperature. High temperature biochar has greater porosity, surface area, and hydrophobicity, making it more efficient in removing organic contaminants, while low temperature biochar is rich in oxygenated functional groups, ideal for eliminating inorganic pollutants. Biochar improves soil fertility by increasing pH, enhancing cation exchange capacity, and providing essential nutrients like calcium, potassium, nitrogen, and phosphorus. It supports microbial life, boosts crop yields (5-50 tons/ha with fertilisers), improves rainwater infiltrations, and enhances drought resistance.(Shoudu et al., 2024). A study conducted in Helsinki, Finland, used a simplified life cycle assessment and the USDA Forest Service's i-Tree tool, and scenario modeling to evaluate the 50-year CSS potential of urban yards enhanced with trees and biochar-amended soils, showing biochar has a long-term impact on urban biodiversity. (Aruluoma et al., 2021)

Biodiversity Enhancement strategies in Urban planning

1. Green-Roofs

Green-roofs have been shown to support considerable biodiversity, though their effectiveness varies by habitat size and species type. Green roofs support diverse flora and fauna: one European study found 176 plant species on 115 roofs, and additional studies documented arthropods, fungi, bacteria, and up to 44 springtail species. Green roofs also provide habitats for vertebrates, mainly birds- with 50 species using them for breeding or other activities- and even bats. Green-roofs meet the 4.4 Ha threshold needed to support urban-adapter species, expanding their biodiversity conservation potential for species with large area needs (Mayrand et al., 2018).

2. Green Corridors

Urban green corridors are vital linear greenways that connect various urban green spaces, supporting biodiversity, enabling species movement, and enhancing recreation and aesthetics. They play a key role in providing ecosystem services, promoting sustainable transport and fostering human-nature connections, as they consist of interconnected parks and natural/semi-natural spaces. However urban sprawl and densification have caused habitat fragmentation, native biodiversity decline, and increased landscape homogenization. Nature-based solutions help adapt to local conditions, and aim to embed natural processes into city landscapes (Liu et al., 2025).

3. Residential Yards

Yards, when managed thoughtfully, can play a crucial role in supporting biodiversity by providing refuge, breeding grounds, and resources for a wide range of plant and animal species. Management practices, especially vegetation choices like incorporating native plants, increasing structural diversity, and reducing mowing or weeding, can enhance wildlife richness, including birds, pollinators, and insects. Improper yard-practices, such as planting invasive species, using pesticides, and allowing free roaming pets, can negatively impact nearby natural areas and wildlife. Additionally incorporating medicinal gardens in urban yards preserves cultural traditions and contributes significantly to plant diversity (Lerman et al ., 2023)

4. Blue-Green Infrastructure

In response to urbanization challenges like heat, pollution, and disrupted water cycles, cities are increasingly adopting Blue-Green Infrastructure (BGI)- a network of semi-natural and engineered systems such as green-roofs, wetlands, and stormwater

ponds- to restore natural processes and deliver multiple ecological, social, and economic benefits. Originally designed for stormwater management, BGI is now also being recognised for its roles in heat mitigation and biodiversity support. However, ecological dimensions are often overlooked by engineers, despite evidence that biodiversity enhances system performance and resilience through services like water purification and pest control (Perrelet et al ., 2024)

5. Landscaping soils

Landscaping soil deals directly with soil biodiversity, which plays a crucial role in maintaining ecosystem functions and human well-being, yet its significance in urban environments remains underexplored compared aboveground ecosystems.Techniques to improve soil biodiversity include: preserving and expanding biodiverse green spaces, maintaining or transplanting habitats that support soil life(mites, springtails, beetles), developing and managing green infrastructure (green-roofs, green-walls, community gardens), and creating biodiverse indoor plant-soil systems, such as potted plants and greenwalls (Sun et al., 2023)

Theoretical Models and Existing Case-Studies:

4. *Carbon sequestration and storage potential of urban green in residential yards*: A case study from Helsinki serves as an essential case study in demonstrating how urban residential yards can significantly contribute to carbon sequestration while simultaneously enhancing biodiversity with city environments. As cities continue to expand and drive global greenhouse gas(GHG) emissions, urban green infrastructure- such as forests, parks, yards, and street trees- has become increasingly important for providing ecosystem services like carbon storage, climate adaptation, and habitat provision. Residential yards, although often excluded from formal planning frameworks, can constitute over a third of urban green space and offer untapped potential for supporting both climate goals and ecological diversity. This study emphasizes that carbon sequestration and storage (CSS) benefits are highest in urban trees with ample space, and healthy, deep soil. Moreover, it highlights the strategic value of biochar as a soil amendment that not only boosts carbon storage, but also improves soil structure and supports diverse plant and microbial life. Conducted in Helsinki, Finland, the research combines a simplified life cycle assessment, the USDA Forest Service's i-Tree tool, and scenario modeling to evaluate the 50-year CSS potential of urban yards enhanced with trees and biochar-amended soils. The findings illustrate how optimizing vegetation and soil conditions can significantly strengthen urban carbon sinks, even in individual properties. It demonstrates that transforming residential yards into high-functioning green infrastructure is not just

feasible but essential for advancing urban ecological resilience and contributing meaningfully to global environmental targets. (Ariluoma et al., 2021)

5. *Life cycle assessment of urban uses of biochar and case study in Uppsala, Sweden:* evaluates the environmental performance of biochar across five urban applications- including tree planting, green roofs, landscaping soil, charcrete, and biofilm carriers- using life cycle assessment methodology. Conducted in the context of Uppsala, Sweden, the analysis reveals that biochar offers significant climate benefits when used in a decarbonized energy system, largely due to its long-term carbon sequestration potential. These applications not only reduce greenhouse gas emissions, but also substitute conventional materials with higher environmental costs, such as peat based soils in tree planting, or expanded clay in green roofs. The paper emphasizes that biochar-amended soils can enhance microbial activity and create microhabitats for fungi, bacteria, and invertebrates, contributing to a healthier and more resilient urban soil ecosystem. Furthermore when used in green roofs, biochar helps retain stormwater and offers a substrate conducive to mosses and native grasses, increasing habitat heterogeneity on even rooftops- spaces typically inhospitable to biodiversity. (Azzi et al., 2022)
6. *Developing integrated direct air capture and bioenergy with carbon capture and storage systems: progress towards 2 •C and 1.5 •C climate goals:* this is a research that shows integrating DAC and BECCS in urban settings holds promise, particularly when-waste derived biomass is used as feedstock. In cities, where large amounts of organic waste are generated, this approach can reduce landfill dependency, leading to decrease in methane emissions, and repurpose waste streams, ultimately improving air and soil quality- conditions that favour urban biodiversity. However the paper also highlights the energy intensive nature of DAC systems, and the logistical challenges of biomass sourcing, storage and processing. In urban environments, space limitations, infrastructure, constraints, and the need for low-carbon energy inputs pose significant hurdles. If not carefully managed, the deployment of BECCS facilities in cities could increase competition for land, introduce noise or air pollution from biomass combustion, and disrupt existing green spaces- potentially harming urban ecosystems rather than supporting them. The paper's primary focus is on carbon removal however, which shows efficiency ranges from 91.19% to 93.9% for DAC and BECCS systems integration, with promoting biodiversity as a side benefit, and not a primary driver. Integration of the systems will require extremely careful system design, to make sure that ecological benefits outweigh the potential disruptions. (Okonkwo et al., 2023)

Justification for selecting Biochar for Urban Carbon Capture and Biodiversity Integration

In designing a prototype for urban sustainability that integrates carbon capture with biodiversity enhancement, biochar presents itself as the most contextually appropriate technology compared to Direct Air Capture(DAC) and Bioenergy with Carbon Capture and Storage (BECCS). Though a lot of research on soil biodiversity and biochar comes from research done in forests, there are also a significant number of papers researching the benefits of biochar in urban applications. Biochar is produced through pyrolysis of organic biomass and can directly be applied to soils, improving carbon sequestration while simultaneously enhancing soil health and biodiversity (Jeffrey et al., 2014). In contrast to DAC- which, while effective in extracting CO2 directly from atmosphere, is energy intensive and expensive- and BECCS- which demands vast land areas and centralized infrastructure for biomass cultivation and storage- biochar is logistically suited for decentralized, small-scale urban systems. This makes it particularly viable for integration into green roofs, urban farms, and community gardens, where it can support microbial diversity, increase water retention, and improve soil fertility (Jeffrey et al., 2014; Lehmann et al., 2011)

The integration of biochar aligns directly with the biodiversity strategies planned for the urban prototype, such as native plant restoration. Biochar improves root-soil interactions and fosters beneficial microbial networks, thereby enhancing plant resilience and ecological complexity (Lehmann et al., 2011). These soil biodiversity enhancements are essential to building stable ecological systems within fragmented urban environments. In contrast, DAC, though promising for global-scale CO2 removal, offers no immediate ecological benefits, and its infrastructure, though scalable to small-spaces, is still rarely compatible with space-constrained cities. BECCS faces similar limitations, relying on large-scale monoculture feedstock systems, and long-haul transport for carbon storage, both of which pose logistical and ecological issues in urban settings (Smith et al., 2016)

Finally, biochar's compatibility with circular waste strategies enhances its urban viability. Municipal organic waste such as food straps and garden refuse can be used as biomass feedstock, allowing cities to reduce landfill contributions while creating a stable carbon sink (Woolf et al., 2010). The localized production and application of biochar support a closed-loop carbon cycle, enabling urban communities to contribute meaningfully to climate goals without compromising ecological integrity. Given its multifunctional benefits, logistical feasibility, and alignment with biodiversity enhancement efforts, biochar is the optimal carbon capture solution for integration in my proposed urban sustainability prototype.

EcoLink- An Integrated Biochar Urban Biodiversity Network

Prototype Description:

EcoLink is an innovative urban ecological prototype designed to enhance biodiversity, soil health, and ecosystem resilience through the synergistic integration of biochar-amended soils, native vegetation, and mycorrhizal fungal inoculants across three key urban landscape components: green roofs, green corridors, and residential yards(Fig.1). This interconnected network establishes functional habitats that restore ecological connectivity within anthropogenic environments, addressing urban soil degradation, habitat fragmentation, and biodiversity loss.

Fig.(1) Figure is generated using AI tools, to give visual representation of EcoLink

1. Biochar as the Cornerstone Soil Amendment:

The central premise of EcoLink rests on the multifunctionality of biochar, a recalcitrant carbonaceous material produced via pyrolysis. Urban soils are often compacted, nutrient-poor, and chemically imbalanced, posing significant constraints to plant and microbial community development. Biochar's highly porous and heterogenous structure increases soil porosity and water-holding capacity, thereby alleviating hydric stress typical in urban soils and creating microhabitats for microbial colonization. This physical amelioration directly facilitates root

growth by improving aeration and moisture retention, essential for sustaining native vegetation under urban stressors. (Chen et al., 2021; Chen et al .,2018)

Integrating biochar into urban-green infrastructure offers a promising avenue for carbon sequestration. A three year lysimeter study demonstrated that incorporating biochar into urban landscaping soils can sequester approximately 30 tonnes of carbon per hectare, surpassing the sequestration achieved with untreated biomass. This enhanced carbon storage is attributed to biochar's stability and its ability to improve soil organic and inorganic content. Additionally biochar's porous structure enhances water retention and supports microbial activity, further contributing to its effectiveness as a carbon sink. (Wang et al., 2023)

Biochar also profoundly influences soil chemical properties by absorbing nutrients and heavy metals, buffering pH, and reducing nutrient leaching. This nutrient stabilization enhances bioavailability and uptake by plants and symbiotic fungi. Importantly, biochar supports the proliferation and activity of arbuscular mycorrhizal fungi(AMF), which form critical mutualisms that 1)improve plant phosphorus acquisition 2)enhance drought tolerance, and 3)increase overall plant fitness in degraded urban soils. The durable nature of biochar ensures that these benefits persist over long timescales, establishing it as a keystone amendment for sustainable urban soil restoration (Tesfaye et al., 2021)

2. Green Roofs: Vertical Microecosystems Augmented by Biochar:

Green roofs are vital refuges for urban biodiversity but face unique challenges from limited substrate depth, high solar exposure, and rapid moisture loss. In EcoLink, green-roof substrates are amended with biochar to improve water retention and substrate structure, mitigating desiccation and nutrient depletion. This enhancement creates further favourable growing conditions for native drought-adapted plant species capable of supporting pollinators and other fauna. By encouraging root colonization and maximizing nutrient uptake—especially phosphorus, which is frequently limited in rooftop substrates—mycorrhizal inoculants work in concert with biochar. In addition to promoting plant growth, this mutualism boosts resistance to abiotic stressors including water scarcity and temperature extremes that are common in rooftop microclimates. When taken as a whole, these enhancements turn green roofs into dynamic microhabitats that provide ecosystem services like pollination and temperature regulation while extending biodiversity vertically inside the urban fabric. Gujre's paper does not specifically talk about the use of biochar and AMF in urban green or greenroof context, its benefits of soil structure enhancement, nutrient uptake and drought resistance are highly applicable to green-roofs in EcoLink (Chen et al., 2018; Gujre et al., 2020).

3. Green Corridors: Habitat Connectivity and Soil Remediation:

The fragmentation of urban habitats hinders the movement of wildlife and disturbs ecological functions. By connecting remote areas with native tree and shrub plantings in soils enhanced

with biochar, EcoLinkTM's green corridors restore functional connectivity. In urban watersheds, biochar's ability to improve infiltration and lessen soil compaction encourages stormwater management, which lowers runoff and lowers the danger of flooding. Additionally, by buffering pH and immobilizing harmful heavy metals, biochar mediates soil chemistry and makes the environment more hospitable for delicate local species. The biological functioning of the soil ecosystem is improved when mycorrhizal fungi are added, which promotes plant health and nutrient cycling. These corridors promote a more robust and biodiverse urban ecology by facilitating the movement and genetic exchange of pollinators, seed dispersers, and other animals. By using these methods, EcoLinkTM restores the functionality of urban landscapes by combining ecological connectivity and soil remediation (Tesfaye et al., 2021; Chen et al ., 2021; Mayrand et al .,2018)

4. Residential Yards: Distributed Biodiversity Nodes

Despite their cumulative spatial significance, residential yards are frequently overlooked in urban ecological design. EcoLinkTM uses yards as dispersed nodes where native plants and biochar amendments work together to improve soil quality and biodiversity on a fine scale. Mycorrhizal inoculation promotes plant root health and nutrient uptake, whereas biochar's enhancement of moisture retention and nutrient cycling reduces normal urban soil degradation.

By converting yards from turf monocultures to biodiverse native assemblages, pollinators, beneficial insects, and small vertebrates can find homes and contribute to neighborhood-scale ecological networks. These habitat enclaves, which are connected by green corridors and enhanced by green roofs, improve the complexity, connectedness, and resilience of urban habitats overall, promoting population sustainability and species spread throughout the cityscape. (Lerman et al ., 2023)

5. Systematic Integration and Ecosystem Services

By using mycorrhizal fungus and biochar's ecological engineering capabilities, EcoLinkTM's integrative design creates a network of interconnected soil, plants, and microorganisms that improves ecosystem structure and function throughout the city. By maintaining biochar carbon pools and boosting vegetative biomass, this network promotes long-term carbon sequestration(Wang et al., 2023). By boosting soil infiltration and water retention, biochar lowers urban runoff, lowering the danger of flooding . By increasing evapotranspiration and providing shade, the vegetation this network supports improves the microclimate and reduces the effects of urban heat islands (Chen et al., 2018). Additionally, the enriched soils sustain a variety of soil food webs, which are essential for pollination, biological pest management, and nutrient cycling(Lerman et al., 2023). EcoLinkTM offers a scalable, scientifically supported framework to restore biodiversity and ecological resilience in urban settings by reestablishing soil health and landscape connection.

Design Principles of the EcoLink Prototype

The EcoLinkTM prototype is envisioned as a systems-based, integrative solution to the growing ecological dysfunction in urban settings. It incorporates five fundamental design ideas—connectedness, multifunctionality, substrate optimization, biotic integration, and resilience-building—that are drawn from modern ecological theory and sustainable urban planning. While initial investments encompass soil remediation, biochar integration, and mycorrhizal inoculation, these costs are offset by long-term benefits including urban cooling, stormwater management, and improved public health. A study by Jezzini et al.(2024) utilized agent-based modeling to assess various green infrastructure plans, revealing that well planned implementations can yield significant economic and social returns (Jezzini et al., 2024). If Ecolink is planned strategically well, it can ensure cost-effectiveness over time. The prototype's structural and functional elements—green roofs, green corridors, and residential biodiversity nodes—are conceived and implemented logically based on these concepts:

1. **Connectivity- Reconstructing Urban Ecological networks:**

Urban environments are characterized by fragmentation, which leads to ecological isolation and reduced species viability. This is directly addressed by EcoLinkTM, which prioritizes habitat connectivity both vertically (via green roofs) and horizontally (across the urban plane via home yards and green corridors). In order to restore the flow of ecological processes, the system is made to facilitate the movement of pollinators, seed dispersers, and other wildlife in addition to mycorrhizal propagules and nutrient flows.

2. **Multifunctionality- Delivering Ecosystem Services Across Scales:**

EcoLinkTM is purposefully designed to serve several ecological and social purposes at once. Each element serves as a multipurpose unit that provides provisioning, regulation, and support for ecosystem services rather than just being a piece of habitat. For instance, green corridors serve as air filters, carbon sinks, and faunal highways, while green roofs offer pollinator assistance, rainwater retention, and thermal insulation. Rewilding residential yards with native flora improves human well-being through aesthetic and recreational qualities, reduces localized urban heat island impacts, and acts as stepping stones for biodiversity.(Lerman et al., 2023)

By providing long-term carbon sequestration, soil nutrient buffering, and water retention, the addition of biochar to these landscape units enhances their multifunctionality and makes each one both biologically active and climate-adaptive.(Wang et al., 2023)

3. Substrate Optimization- Engineering Soil as a Living Infrastructure:

Typically, urban soils are chemically unbalanced, compacted, and poor in organic matter. In response, EcoLinkTM uses a three-pronged strategy to re-engineer soils as living substrates: mycorrhizal inoculation, biochar integration, and native vegetation rooting systems. Because of its porous matrix, biochar successfully converts sterile substrates into functionally dynamic soil systems by improving soil aeration, water retention, and cation exchange capacity. By developing symbiotic interfaces with plant roots, mycorrhizal fungi subsequently take advantage of this improved medium, enhancing phosphorus uptake, stress tolerance, and soil carbon stability. As a result, soil becomes an active ecological infrastructure rather than just a passive support medium. (Jabborova et al., 2021)

4. Biotic Integration- Harmonizing Native Species and Microbial Symbioses:

The foundation of EcoLinkTM is the concept of biotic compatibility, which refers to the intentional selection of plant, fungal, and microbial taxa that are suited to the substrates transformed by biochar as well as the local climate. The system maximizes trophic complexity and resilience by fostering co-evolutionary connections and ensuring ecological fidelity through the use of native plant species. Additionally, these species are more likely to successfully associate with nearby mycorrhizal fungi, increasing the functional richness of the system. Though Li's paper talks about AMF and biochar synergy in an agricultural sense, these fundamentals can still be highly applicable to urban settings. Furthermore, EcoLinkTM acknowledges that belowground biodiversity is just as important as aboveground variety by incorporating microbial symbioses into its fundamental architecture. Because of their contributions to soil aggregation, plant health, and resistance to abiotic stresses, arbuscular mycorrhizal fungi (AMF) are given special attention.(Li et al., 2021)

5. Resilience-Building- Long-Term Adaptation to Urban Stressors:

Both acute and chronic stressors, such as heat waves, droughts, chemical pollution, and biological invasions, can affect urban ecosystems. EcoLinkTM uses self-regenerating, modular, and redundant design techniques to incorporate resilience into its structure. Mycorrhizal relationships improve adaptive plant responses to climate extremes, whereas biochar acts as a long-term buffer against chemical unpredictability and nutritional losses (Wang et al., 2023).The prototype also has geographic redundancy by connecting several units across the city; in the event that one node (such as a roof or yard) is compromised, the others can continue to function at the network level. Even in the face of changing environmental regimes, this ecological modularity guarantees the preservation of biodiversity and ecosystem services across temporal and spatial scales.(Lerman et al., 2023)

Thus, the EcoLinkTM prototype is a prime example of a systems-level, scientifically based strategy for urban ecological restoration. A successful citizen-led urban greening initiative like

EcoLink would involve support from public authorities or NGOs, which provide frameworks, expertise, and mobilization efforts. Additionally, the use of digital platforms such as websites and social media facilitates participatory engagement and knowledge sharing, aiding in the scaling and sustainability of a project like EcoLink.(Oikonomaki et al., 2024)
In order to create a scalable and flexible model for cities seeking to restore biodiversity, soil function, and ecosystem connectivity, its design principles combine soil science, plant ecology, urban planning, and climate resilience theory. In order to create resilient urban ecosystems that can withstand natural and human-caused problems, EcoLinkTM treats soil, vegetation, and microbes as interconnected parts of a living infrastructure.

Discussion

Theoretical implications:

By operationalizing intricate ecological theories—like metapopulation dynamics, ecological network theory, and soil-plant-microbe coevolutionary frameworks—into spatially fragmented urban environments, the EcoLinkTM prototype offers a transdisciplinary breakthrough in urban ecological design. Traditional urban biodiversity planning has frequently focused on isolated patches of green infrastructure. The prototype supports the growing theoretical understanding that the maintenance of resilient ecological networks depends equally on belowground biodiversity (such as fungal and microbial assemblages) as it does on aboveground species richness. By supporting nutrient flux continuity, root symbioses, and biotic stress tolerance, the functional integration of arbuscular mycorrhizal fungi (AMF) within a substrate modified with biochar highlights the theoretical concept that soil is an active ecosystem engineer rather than a static medium. This offers an empirical model for testing and refining theories about soil-vegetation feedback loops, resilience thresholds in coupled socio-ecological systems, and the modularity of urban ecosystems. (Li et al., 2021; Lerman et al., 2023)
EcoLink can also promote equity and social inclusion by transforming underutilized urban areas into accessible green spaces that foster community engagement and well being. Such initiatives have been shown to enhance social cohesion, provide recreational opportunities, and improve mental health, particularly in underserved neighbourhoods. By involving local residents in the planning and maintenance of these spaces, EcoLink can empower communities and ensure that benefits of urban greening are equitably distributed.(Oikonomaki et al., 2024)

Environmental and urban policy relevance:

Developing policy frameworks that aim to include nature-based solutions (NbS) into climate-resilient urban design are directly aligned with EcoLinkTM. EcoLink provides a concrete, comprehensive approach to policy implementation by aligning with the goals of global

policy tools, such as the UN Decade on Ecosystem Restoration (2021–2030) and urban green infrastructure targets under the Convention on Biological Diversity (CBD).
The flexibility and scalability of EcoLink can be used by municipal and regional urban planning agencies to inform biodiversity offset plans, stormwater management standards, and zoning laws. Its structure is multi-scale, spanning from individual yards and rooftops to landscape-level corridors, which allows it to work with both bottom-up community-driven green infrastructure projects and top-down regulatory systems. The observable ecosystem services produced—such as pollinator conservation, air purification, thermal regulation, and urban hydrological buffering—offer strong justification for incorporating EcoLink-style models into green building certifications and urban sustainability indices (such as LEED and BREEAM).
Biodiversity success in the Ecolink model can be assessed through a combination of ecological, spatial, and social metrics. Key ecological indicators include species richness, abundance of native flora and fauna, and soil microbial diversity, which can reflect improvements in ecosystem functions and resilience (Aronson et al., 2017). Spatial connectivity metrics such as patch cohesion and edge density- are instrumental in evaluating how effectively green corridors link fragmented habitats, and provide valuable insights into landscape connectivity and fragmentation patterns (Wang et al., 2014). Social metrics, including citizen engagement in biodiversity monitoring and the perception of biodiversity benefits among local residents, also provide insight into the success and sustainability of interventions(Oikonomaki et al., 2024). Together these indicators offer a multidimensional approach to measuring the long term impact of urban biodiversity restoration in a model like EcoLink.

Potential challenges:

Despite its ecological and policy-oriented strengths, the implementation of EcoLink faces several challenges:

1. Limitations of Soil and Infrastructure: Urban soils are frequently badly deteriorated, polluted, or structurally inappropriate for the integration of biochar and mycorrhizal inoculation. It could be expensive to make infrastructure changes in order to retrofit hardscaped yards or rooftops to sustain substrates that have been modified with biochar.

2. Mycorrhizal Specificity: AMF symbiosis success is heavily influenced by surroundings. Regionally tailored fungal consortia are necessary because mismatches between introduced fungal species and native flora may result in decreased inoculation efficiency.(Chen et al., 2021)

3. Institutional Fragmentation: Several agencies and parties are usually involved in urban land-use governance. Cross-sectoral cooperation, which can be administratively

challenging, is necessary to implement integrated ecological corridors across the public, private, and commercial spheres. (Oikonomaki et al., 2024)

4. Public Perception and Aesthetic Expectations: Rewilded yards and native vegetation frequently go against the grain of traditional landscaping design. In the absence of strong public education campaigns, homeowners' and developers' adoption may be constrained by worries about upkeep, pests, or perceived disorderliness. (Oikonomaki et al., 2024)

Long-term impacts and monitoring considerations:

The establishment of a strong ecological monitoring system is essential to EcoLinkTM's long-term sustainability. Important parameters consist of:

- Metrics of soil health, such as carbon-to-nitrogen ratios, microbial diversity, and pH balance
- Indicators of plant vigor and diversity
- Rates of mycorrhizal colonization
- Patterns of occupancy and movement of wildlife between nodes
- Indicators of climate resilience including thermal moderation and evapotranspiration rates

The temporal and spatial resolution of monitoring data can be improved by integrating urban ecological observatories, citizen science technologies, and remote sensing. The prototype will be able to react to dynamic stressors such as urbanization, invasive species pressures, and climate change thanks to adaptive management based on this data. (Warner et al., 2024)

How this model can inform real-world applications:

A highly adaptable model for urban ecological regeneration in a variety of socioeconomic and biogeographical contexts is provided by EcoLinkTM. Customization by climate zone, urban density, and available public-private interaction places is made possible by its modular design. For example:

- Water security can be given priority in arid cities by using high-retention biochar formulations and native plants that can withstand drought.
- Green corridors with porous substrates and constructed swales can offer hydrological resilience in areas that are vulnerable to flooding.
- EcoLink can be used as a low-tech, low-cost substitute for traditional grey infrastructure in the Global South's rapidly growing metropolitan centers, especially in informal housing settlements where engineering solutions are not financially possible.

Additionally, the concept encourages interdisciplinary cooperation between community stakeholders, ecologists, civil engineers, and urban planners. In order to include EcoLink into

environmental curricula, civic engagement initiatives, and climate adaptation plans. educational institutions and local governments can test it out in living labs.

Limitations:

While the EcoLink model offers a promising approach to enhancing biodiversity and sustainability in urban spaces, its application in other cities or regions may face several limitations. A lot of benefits provided by AMF and biochar integration have mostly been tested in agricultural settings, hence more research on their synergistic benefits in urban settings are also required for their successful application in urban settings. Environmental conditions such as soil type, climate, native flora and fauna, and urban infrastructure vary widely across regions, making it difficult to replicate outcomes without significant adaptations. Additionally, differences in local governance, public awareness, community engagement, and availability of resources can impact implementation success. Some cities may lack the policy support, funding, or technical expertise required to adopt components like biochar use or mycorrhizal inoculation effectively. Cultural attitudes towards urban green spaces and competing land-use priorities may also pose barriers. Therefore, while the EcoLink serves as a valuable prototype, its broader applicability requires careful contextualization and support from local institutions and communities. (Oikonomaki et al., 2024)

Conclusion

Although the EcoLink concept offers a viable framework for improving sustainability and biodiversity in metropolitan areas, different environmental circumstances, infrastructure, governance, and public participation may make it difficult to replicate in other areas. Adaptation is necessary due to variations in soil type, climate, native species, and resource availability. Implementation may also be constrained by financial resources, technical know-how, and policy backing. In order to increase ecological resilience, this study concentrated on incorporating techniques like biochar and planting with an emphasis on biodiversity into urban gardens. The scientifically proven benefits of biochar in soil improvement and carbon sequestration were highlighted. The results demonstrate how versatile, context-sensitive strategies can be used to advance urban climate mitigation. Future uses could involve research on improving soil-plant-carbon interactions in urban settings, educational programs, and incorporation into municipal planning.

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What is the role of Neuroplasticity-based interventions in slowing down cognitive decline in early-stage Alzheimer's disease?

Noor Shahen

Aims:

- Explore how Neuroplasticity-based interventions affect cognitive functions in early-stage Alzheimer's disease
- Explore how early-stage Alzheimer's disease affects cognitive function
- Explore the mechanism of Neuroplasticity and how it affects the cognitive function
- Explore how Neuroplasticity counteracts Alzheimer related decline

Objectives:

- Explain the general concept of Alzheimer's disease
- Explain what neuroplasticity is
- Explore different neuroplasticity based treatments
- Compare how well the different neuroplasticity-based treatments slow down the cognitive functions
- Explore the limitations and complications of using neuroplasticity techniques on patients
- Explore the safety of using neuroplasticity techniques on patients
- To identify the gaps in literature and to contribute to an under explored area of research

Study Design:

(i) Classification of research based on source of information: Secondary Research

This research will be using secondary data, as the researcher is unable to collect any data firsthand due to a lack of resources, research skills, time, and no access to any laboratory.

(ii) Classification of research based on purpose of research: Technological Applied

This research follows a technological applied methodology as the researcher aims to use the data to understand the role of neuroplasticity treatments on patients diagnosed with early-stage Alzheimer's disease, and to see which techniques are the most effective.

(iii) Classification of research based on depth of scope: Explanatory Research

This research follows an explanatory research approach, as one of the aims of this paper is to understand how neuroplasticity-based interventions affect the cognitive decline in early-stage Alzheimer's, so the researcher is using this paper to see explore cause and effect relationship between the neuroplasticity-based interventions and the rate of cognitive decline.

(iv) Classification of research based on data collected: Mixed Methods

This research will be using a mixed method in which qualitative and quantitative data is collected. This will give a more comprehensive understanding on the role of neuroplasticity-based interventions in slowing down cognitive decline.

(v) Classification based on time frame: Longitudinal Research

The duration of this research will be over a long period of time, as Alzheimer's is a chronic disease, and long term observation following the neuroplasticity-based interventions is needed to assess the effectiveness of the treatment.

Introduction:

Alzheimer's disease is a progressive brain condition which affects cognitive functions, mainly in older adults (Rostagno, 2022). This chronic disease is the most common cause of dementia (60-80% of dementia cases) and is rapidly spreading worldwide (Scheltens et al., 2022). Though it has no cure, there are treatments such as anti-glutaminergics and anticholinesterase inhibitors which are used to maintain the symptoms, however have no effect on the cause of the disease (Passeri et al., 2022). In the early stages, the symptoms are subtle; however as the disease progresses, the memory problems become more severe (Breijyeh et al., 2020).

Neuroplasticity is the potential ability of the nervous system to change its activity in response to intrinsic or extrinsic stimuli by reorganizing its structure, functions, or connections after injuries. These interventions can be categorized into physical, cognitive, sensory, and pharmacological approaches. Neuroplasticity based interventions can be used to slow down the rate of deterioration of the cognitive functions in early stages, which can help improve the quality of life for the patient and by providing support and reducing the emotional burden for their family (Puderbaugh et al., 2023)

Justification:

With patients diagnosed with mild to moderate Alzheimer's disease, Cognitive Stimulation Therapy has been shown to improve the quality of life and provide temporary improvements in the cognitive function in patients with early stage Alzheimer's, and that patients with a greater mental reserve are more susceptible to the positive effects of CST (Behfar et al., 2020).

This proves the idea that working with patients with early stage Alzheimer's is more effective. Since CST and neuroplasticity based interventions both aim to mend neural pathways and form new ones, early intervention promotes cognitive flexibility, therefore the therapies will be more effective.

Boolean Operation:

Role: role, job, function, involvement, impact, effect,

(role OR job OR involvement OR impact OR effect)

Neuroplasticity: neural plasticity, synaptic plasticity, brain plasticity, cerebral plasticity, brain remodeling

(neural plasticity OR synaptic plasticity OR brain plasticity OR cerebral plasticity OR brain remodeling)

interventions: therapies, treatments, procedures, brain interventions, TMS, Transcranial Magnetic Stimulation, TDCS, Transcranial direct current stimulation, cognitive rehabilitation, neurorehabilitation, cognitive training, cognitive feedback, neurofeedback

(interventions OR therapies OR treatments OR procedures OR brain interventions OR TMS, OR Transcranial Magnetic Stimulation OR TDCS OR Transcranial direct current stimulation OR cognitive rehabilitation OR neurorehabilitation OR cognitive training OR cognitive feedback OR neurofeedback)

cognitive decline: cognitive deterioration, cognitive impairment, dementia progression, memory loss, memory deterioration, mental decline, cognitive dysfunction, cognitive deficit, neurocognitive decline

(cognitive decline OR cognitive deterioration OR cognitive impairment OR dementia progression OR memory loss OR memory deterioration OR mental decline OR cognitive dysfunction OR cognitive deficit OR neurocognitive decline)

early-stage: early-onset, early-detection, early-diagnosis

("early-stage" OR "early-onset" OR "early-detection" OR "early-diagnosis")

Alzheimer's: Alzheimer's disease, Alzheimer's dementia,

(Alzheimer's OR "Alzheimer's disease" OR "Alzheimer's dementia")

(role OR job OR involvement OR impact OR effect) AND (neural plasticity OR synaptic plasticity OR brain plasticity OR cerebral plasticity OR brain remodeling) AND (interventions OR therapies OR treatments OR procedures OR brain interventions OR TMS, OR

Transcranial Magnetic Stimulation OR TDCS OR Transcranial direct current stimulation OR cognitive rehabilitation OR neurorehabilitation OR cognitive training OR cognitive feedback OR neurofeedback) AND (cognitive decline OR cognitive deterioration OR cognitive impairment OR dementia progression OR memory loss OR memory deterioration OR mental decline OR cognitive dysfunction OR cognitive deficit OR neurocognitive decline) AND ("early-stage" OR "early-onset" OR "early-detection" OR "early-diagnosis") AND (Alzheimer's OR "Alzheimer's disease" OR "Alzheimer's dementia")

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What is the role of Neuroplasticity-based interventions in slowing down cognitive decline in early-stage Alzheimer's disease?

Introduction:

Alzheimer's disease is a progressive brain condition which affects cognitive functions, mainly in older adults (Rostagno, 2022). This chronic disease is the most common cause of dementia and is rapidly spreading worldwide (Scheltens et al., 2022). Though it has no cure, there are treatments such as anti-glutaminergics and anticholinesterase inhibitors which are used to maintain the symptoms, however have no effect on the cause of the disease (Passeri et al., 2022). In the early stages, the symptoms are subtle; however as the disease progresses, the memory problems become more severe (Breijyeh et al., 2020). The hippocampus and cerebral cortex serve a crucial role in mental processes and the production of new nerve cells. The hippocampus is a critical region for memory. Genetic brain imaging shows that Alzheimer alleles influence shape and size of the hippocampus and cortex. AD is caused by neuron damage due to a build up of two abnormal proteins in the brain - β-amyloid and tau. TDP-43, another protein has also been linked to the cause of this disease as it accumulates in the amygdala, then spreads to the hippocampus, increasing the rate of the brain shrinkage (Rao et al., 2022).

The brain is made up of three main components - the cerebrum, the cerebellum and the brain stem. The cerebrum is responsible for motor and sensory information, voluntary and involuntary processes, emotions, cognition, and memory. It is split into the left and right hemisphere; "abstract thinking" and speech is controlled by the left side, whilst the ride side is responsible for spatial awareness. The motor and sensory neurons go down to opposite sides of the brain stem, meaning that the left side of the body is controlled by the right hemisphere and the right side of the body is controlled by the left hemisphere. (Maldonado et al., 2023)

The cerebrum is made up of 4 lobes:

1. **Occipital lobe:** the visual cortex is situated in the occipital lobe, and is responsible for analyzing visual data. (Maldonado et al., 2023)
2. **Parietal lobe:** in charge of interpreting vision, hearing, motor, sensory, and memory functions. (Maldonado et al., 2023)
3. **Temporal lobe:** the temporal lobe handles sensory data to store memories, language, and emotions. The Wernicke area, located in the left temporal lobe, is responsible for processing written and oral language. (Maldonado et al., 2023)
4. **Frontal lobe:** the Broca area, found in the left frontal lobe, is responsible for the creation and articulation of speech. The frontal lobe manages motor function, mental processes such as decision making, focus, mood, personality, self-awareness and social and ethical judgement. (Maldonado et al., 2023) The prefrontal cortex, found at the front of the frontal lobe, mediates a range of brain functions called cognitive

control; which includes updating working memory, dominant responses, coordinating multiple tasks, monitoring and planning. (Friedman et al., 2021)

The cerebellum governs the coordination of controlled movement and obtains sensory information from the brain and spinal cord to improve the precision and accuracy of motor activity. It also helps with mental function such as focus, language, pleasure sensations and traumatic memory. (Maldonado et al.,2023)

The brain stem connects the spinal cord to the cerebrum and cerebellum. It is responsible for involuntary bodily functions such as respiration, thermoregulation, breathing, heart rate, coughing, sneezing, digestion, sleep cycles, vomiting and swallowing. The brain stem includes both white and gray matter; white matter consists of fiber tracts (axon pathways of nerve cells) that sends neural impulses from the cerebral cortex to the voluntary motor function and up from the spinal cord and peripheral nerves, permitting sensory information to reach the higher regions of the brain (Maldonado et al., 2023).

Neuroplasticity is the potential ability of the nervous system to change its activity in response to intrinsic or extrinsic stimuli by reorganizing its structure, functions, or connections after injuries. Neuroplasticity based interventions can be used to slow down the rate of deterioration of the cognitive functions in early stages, which can help improve the quality of life for the patient and by providing support and reducing the emotional burden for their family (Puderbaugh et al., 2023)

What is Alzheimer's disease?

Alzheimer's disease is a progressive neurodegenerative disorder which affects cognitive functions, including memory, thinking, learning and organizational skills, mainly affecting older adults (Rostagno, 2022). It is the leading cause of dementia and is rapidly evolving as one of the most deadly, costly and overwhelming diseases of all time (Scheltens et al., 2022). A minority of Alzheimer's cases are associated with "dominant genetic mutations in 3 genes: PSEN1 (presenilin 1), PSEN2 (presenilin 2), and APP (amyloid precursor protein)" (Rostagno, 2022). These are usually seen in patients who experienced symptoms before the age of 65 years old. Most of the patients, however, express symptoms after the age of 65, with no direct genetic cause. Scientists have concluded that risk factors such as stress, brain traumas and improper dietary choices can increase the risk of obtaining Alzheimer's disease. (Rostagno, 2022). Alzheimer's is chronic and incurable, as its symptoms include progressive and irreversible memory loss, and intellectual deterioration. (Ibrahim et al., 2020).

Pathophysiology of Alzheimer's:

β-amyloid protein makes up the main parts of the amyloid plaques. It is formed when protease enzymes cleave the amyloid precursor proteins abnormally. In a healthy brain, the APP is cleaved by an enzyme called α-secretase, but in an Alzheimer's brain , the APP is cleaved by β-secretase and γ-secretase, which produces amyloid-β fragments. They have sticky properties, allowing them to clump together outside the neuron - forming amyloid plaques (Guo et al., 2020). Amyloid-beta oligomers (small molecular clusters) bind to the

synaptic receptors, disrupting synaptic communication and inhibiting long term potentiation (LTP) which is necessary for memory and learning, as well as boosting long-term depression (LTD), leading to weakened synaptic connections (Jahan et al., 2024). These plaques disturb synaptic communication, and activate microglia, which triggers inflammation. In healthy neurons, tau proteins stabilize microtubules; however in Alzheimer's the tau protein becomes hyperphosphorylated and detaches from the microtubules, resulting in them collapsing. The tau proteins gather and clump into neurofibrillary tangles within the neurons. The amyloid plaque outside the neuron, and the tau tangles within the neuron disrupts normal cell function and blocks signal transport, causes oxidative stress and eventually leads to neural synapse break down and necrosing. The brain attempts to defend itself using microglia and astrocytes however the response becomes chronic and toxic; as the release of inflammatory cytokines causes additional damage to the healthy neurons, therefore increasing necrosis and resulting in shrinkage of the brain. In the cholinergic system, the cholinergic synapse is damaged due to excessive amyloid plaque and tao tangle deposition, causing a disruption in transmission of signals. (Guo et al., 2020)

SIGNS	**SYMPTOMS**
Wandering aimlessly	Delusion
Confusion with places, times and familiar people	Increased anxiety
Forgetting names of family members, loved ones and everyday objects	Loss of reality
Personality changes - apathy, loss of inhibition, poor judgement	Difficulty concentrating
Difficulty doing day to day tasks alone (changing, eating)	Memory loss
Trouble with words (inability to find the right words, understanding conversation)	Dementia
Misplacing items	Paranoia
Difficulty sleeping	Emotional distress
Trouble understanding visual images and spatial awareness	Frustration
Social withdrawal	Anger
Restlessness	Aggression
Agitation	Depression
Sundowning	
Mood swings	
Repeating sentences, words or questions	

SIGNS	SYMPTOMS
Wandering aimlessly	Delusion
Confusion with places, times and familiar people	Increased anxiety
Forgetting names of family members, loved ones and everyday objects	Loss of reality
Personality changes - apathy, loss of inhibition, poor judgement	Difficulty concentrating
over and over	
Continuously repeating tasks over and over	

Alzheimer's disease has 4 main stages:

(i) **First Stage** is preclinical, in which patients experience mild cognitive impairment (MCI) and preclinical signs of neural damage in the hippocampus and cortex, without any disruption to day to day functions.

(ii) **Second Stage**, mild symptoms of cognitive deterioration begins to appear, such as mild impairment of attention and memory, as well as difficulty recognizing familiar places, and confusion with timings.

(iii) **Third Stage**, the disease progresses to the cerebral cortex, resulting in greater memory impairment, reduced impulse control, difficulty identifying familiar people and challenges with reading, writing and communicating.

(iv) **Fourth Stage**, the most severe symptoms are seen; progressive cognitive and functional decline, inability to identify familiar people, including family members, difficulty doing day to day tasks independently and experiencing difficulties swallowing and urinating, which in severe cases, can lead to death. This is caused due to the widespread of the disease to the entirety of the cerebral cortex (Breijyeh et al., 2020).

Diagnosis:

(i) Blood and imaging tests rules out other possibilities for the diagnosis (such as vitamin B12 deficiency, hypothyroidism, chronic infections or medication side effects) and guarantees that the disease is stemming from a neurological issue. Tau and amyloid beta protein levels in the blood can act as bio-markers to detect Alzheimer's.

(II) Physical and neurological exams can be used to identify cognitive impairment and its severity, to exclude other neurological diseases (such as Parkinson's, multiple sclerosis and

Creutzfeldt-jakob disease) and to help guide further tests such as cognitive testing and brain imaging. Physical and neurological exams include:

- Reflexes
- Coordination
- Balance
- Muscle tone and strength
- Sense of sight and hearing
- Ability to get up from a seated position and walk across the room

(iii) Lab tests helps rule out any other problem that could cause memory loss and confusion such as blood tests for thyroid-stimulating hormone (TSH) for thyroid disorder and serum vitamin b12 levels for low vitamin levels and kidney function tests to check for kidney problems. Newer blood tests can measure beta-amyloid and tau protein levels however they're not accessible everywhere and may not be covered by insurance

(iv) Mental status and neuropsychological testing may be given to you to evaluate memory and thinking skills. Longer forms of the test can give more detail about the patient's mental status and function which can be compared to other patients to similar age groups and education levels, and to aid diagnosis and use it as a starting point and follow future symptoms.

(v) Brain imaging is used to identify visible changes related to conditions other than Alzheimer's that could cause similar symptoms such as: strokes, tumors or injuries. Specific brain changes caused by Alzheimer's disease can be detected by newer imaging tests, such as neurofibrillary tangles and amyloid plaques.

Brain structure imaging includes:

- **Magnetic resonance imaging (MRI)** uses a powerful magnetic field and radio waves to create detailed images of the brain. They may show shrinkage in certain regions of the brain, as a result of Alzheimer's. They can also be used to eliminate other possibilities of conditions that may be causing these symptoms. MRI's are usually done before beginning certain medicinal treatments to monitor possible side effects. MRI's are usually better than CT scans to evaluate dementia.

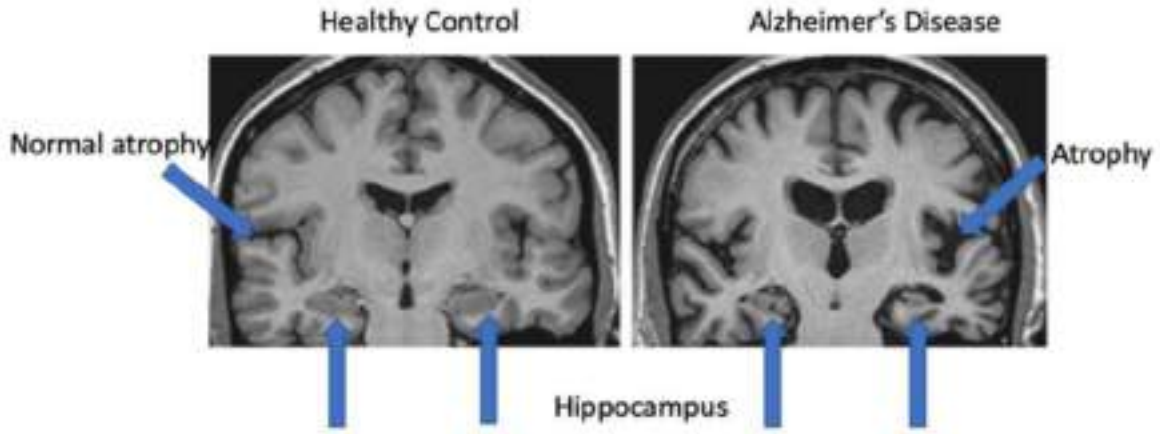

Figure 1 showing the difference between a brain with and without Alzheimer's (Dementia Services Information and Development centre, 2022) (Last accessed 11/8/2025)

- **Computerized tomography (CT)** produces cross sectional brain images by using a specialised x-ray machine; and is used to rule out tumors, strokes and brain injuries.
- **Positron emission tomography (PET)** scans can capture images of the disease process. During a PET scan, a low-level radioactive tracer is injected into the blood stream to reveal a specific region in the brain. PET imaging includes:
    - **Fluorodeoxyflucose (FDG) PET Imaging** shows areas of the brain in which nutrients aren't being used properly for energy (metabolism). In regions with low metabolism, we can find patterns to help distinguish between Alzheimer's

and other dementia types.

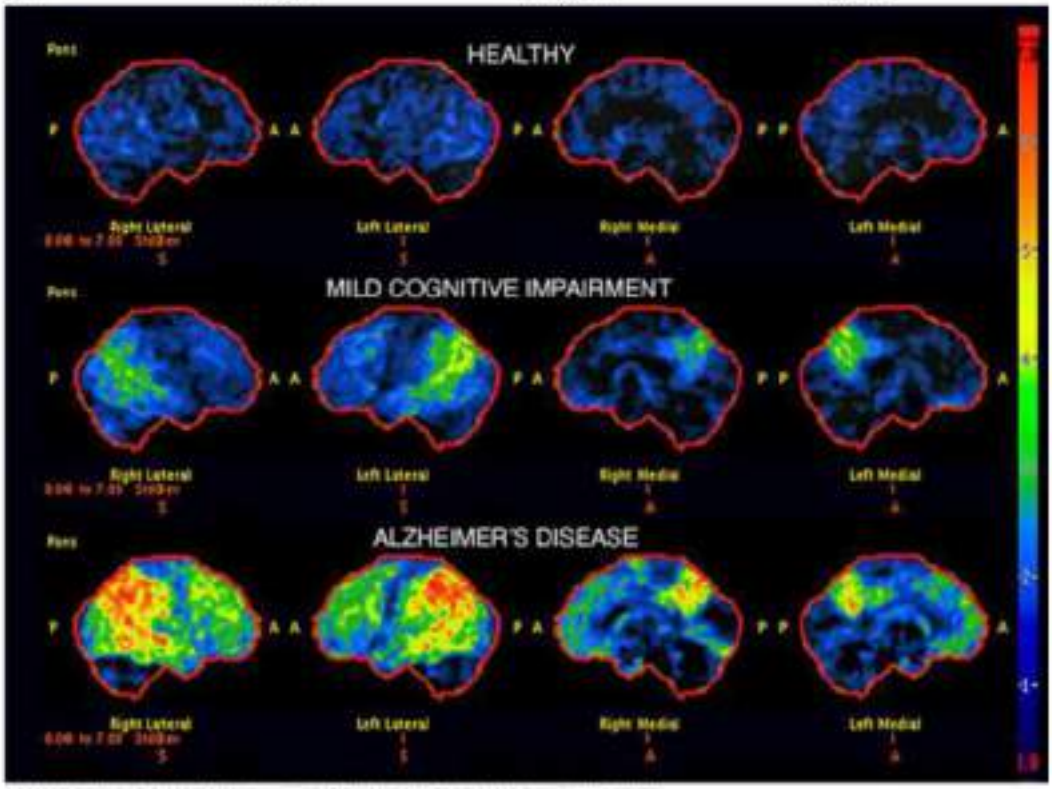

Figure 3 showing an FDG PET scan of a healthy patient, a patient with mild cognitive impairment and a patient with Alzheimer's.

- **Amyloid PET imaging** can detect amyloid plaques in the brain. This is usually used for research purposes however if a patient is expressing early-onset dementia symptoms, it may be used on them.
- **Tau PET imaging** measures neurofibrillary tangles in the brain
- If symptoms are developing quickly, and dementia is present in a patient of young age, other tests may be used to measure the presence of amyloid and tau in the cerebrospinal fluid.

(Mayo clinic, 2024, Last accessed 9/8/2025)

Current Alzheimer's Treatment

Current Alzheimer's treatments are symptom dependent, to foster the patients' need to limit the advancement of neurocognitive symptoms. Treatments include:

(i) Medicinal: There are four main drugs (donepezil, memantine, galantamine, rivastigmine) that have been approved, split into two main categories: Anticholinesterase inhibitors are used to increase the overall acetylcholine concentrations in the brain, which is a

neurotransmitter responsible for enabling communication between certain neurons, and involved in cognitive ability. Anti-glutaminergics are used to stabilize glutamate levels through a noncompetitive blocking effect in the NMDA (N-methyl-D-aspartate) receptors. These drugs are used to slow down the progression of AD and to regulate current cognitive functions. These treatments help patients diagnosed with AD to improve the quality of life for themselves and their loved ones, as well as to preserve their autonomy; however these treatments are only temporary and only focus on improving the symptoms, rather than the cause. As a result, higher dosages are imperative, which risk leading to secondary complications. (Passeri et al., 2022)

(ii) **Cognitive Interventions**: Cognitive interventions have been known as cognitive stimulation, cognitive training, and cognitive rehabilitation. Cognitive stimulation is a wide variety of tasks aimed to improve the general executive and relational functioning of the patient (i.e., reminiscence therapy, reality orientation therapy). Cognitive therapy focuses on a specific mental function, such as attention, executive functions, language, and memory by completing a set of standard activities to enhance or maintain its normal functioning for as long as possible. Cognitive rehabilitation is an approach made specific to the patient which sets realistic goals to aid the patient and their families in everyday life. (Zucchella et al., 2018)

(iii) **Deep brain stimulation:** Deep brain stimulation influences brain delivery by delivering electric impulses from an implanted impulse generator connected to electrodes implanted in a different region of the body. So far, three different locations have been tested as a target for the improvement of cognitive activities and memory: the nucleus basalisis of Meynert, the fornix, and the ventral capsule/ ventral striatum region (Majdi et al., 2023)

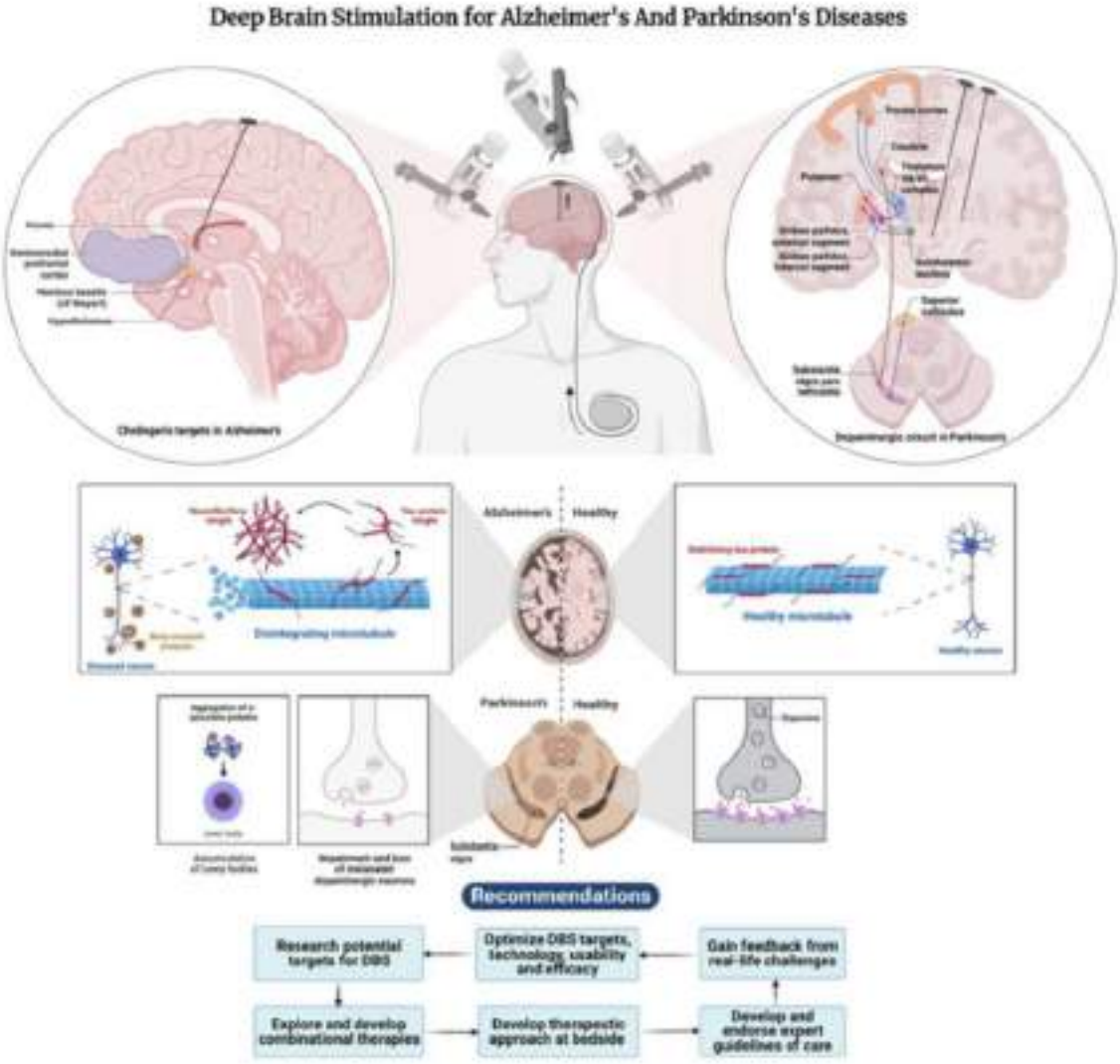

Figure 4 showing the process of a deep brain stimulation (MDPI, 2023)(Last accessed, 11/8/2025)

What is neuroplasticity?

Neuroplasticity is the ability of the brain to alter its activity in response to internal or external stimuli by rearranging its functions, structure or connections. This process enables adaptation to various experiences and situations and is a necessity for memory, learning and neurological recovery. Structural neuroplasticity involves physical alterations within the neural circuits such as axonal sprouting, formation of new dendritic spines, and in some cases, the formation of new neurons (neurogenesis); a careful and complex process which can include the specialisation, formation and incorporation of new neuron cells or initiation from neural precursor cells. Unlike structural neuroplasticity, functional neuroplasticity involves the change in the way that the neural circuits are arranged to perform specific functions. The proliferation and strengthening of synapses improves the communication and transmission of information amongst the neurons, leading to functional changes within the neuronal circuits. (Marzola et al., 2023).

In AD, the accumulation of neurofibrillary tangles and amyloid-beta plaques damages the neural circuits and synapses, leading to the loss of neuronal communication; leaving the brain with fewer intact neuronal circuits to sustain essential cognitive functions such as memory and learning (Jahan et al., 2024). A high correlation has been found linking the loss of neuronal circuits and the level of cognitive impairment in Alzheimer's (Koch et al., 2022). Neuroplasticity can help slow down cognitive decline by allowing the brain to reorganize the remaining neuronal circuits, and undergo neurogenesis, thereby allowing cognitive function to be maintained or regained (Jahan et al., 2024). Given that AD is a progressive disease, it is imperative to intervene at an early stage to maximize the reduction of cognitive decline. The extracellular matrix is a specialized network that holds together the brain cells and sends signals to help the brain cells undergo neurogenesis. Changes in the ECM due to Alzheimer's becomes a limitation as it becomes damaged due to the inflammation, restricting the body's ability to undergo neurogenesis, reorganize neural circuits and recover cognitive functions; which is why neuroplasticity-based interventions are needed to enhance the brain's natural ability to repair itself (Jahan et al., 2024).

Neuroplasticity-based interventions:

Neuroplasticity-based interventions aim to maintain and recover the cognitive function of a patient experiencing Alzheimer's. Examples of interventions include:

(i)Transcranial Direct Current Stimulation (tDCS), an intervention which uses a weak current, usually around 2mA to stimulate the brain, and affect the spontaneous activity of the cerebral cortex, and maintains the resting membrane position. This causes changes in the frequency of spontaneous neural activity, leading to the activation of the NMDA receptor. The electrode placement influences the effectiveness of tDCS: anodal stimulation causes depolarization (when the neuron's electrical charge becomes more positive) which enhances cortical excitability (how easily neurons can activate and transport information, and cathodes stimulation causes hyperpolarization (when the neuron's electrical charge becomes more negative) causing a decrease in cortical excitability. tDCS also induces changes in the regional blood flow in the brain to counteract abnormal neural synchronization which is seen in Alzheimer's disorder. tDCS is a portable, cheap device, and uses low intensity currents, so can be done as an out-patient procedure without the use of anaesthesia (Saxena et al., 2021).

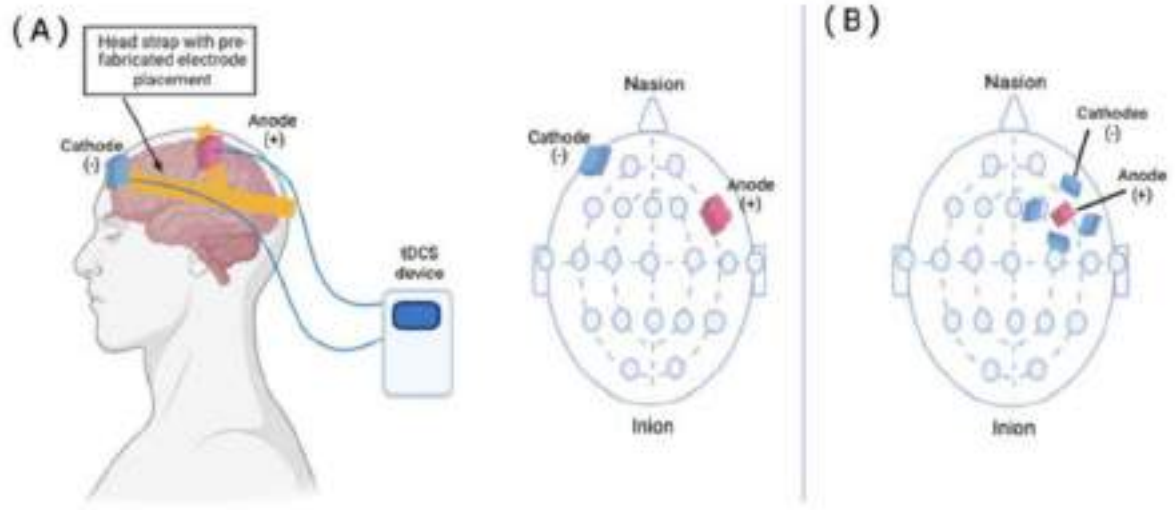

Figure 5 showing the placement of the electrodes (Sloane et al., 2024)

(ii) Repetitive Transcranial Magnetic Stimulation (rTMS) uses high or low intensity magnetic fields to stimulate the brain tissue and alter cortical excitability. rTMS administers recurring TMS pulses to a particular area in the brain. High frequency (>1Hz) increases cortical excitability and low frequency (<1Hz) decreases cortical excitability. The repetitive magnetic pulse stimulates the nerve cells, promoting neuroplasticity.

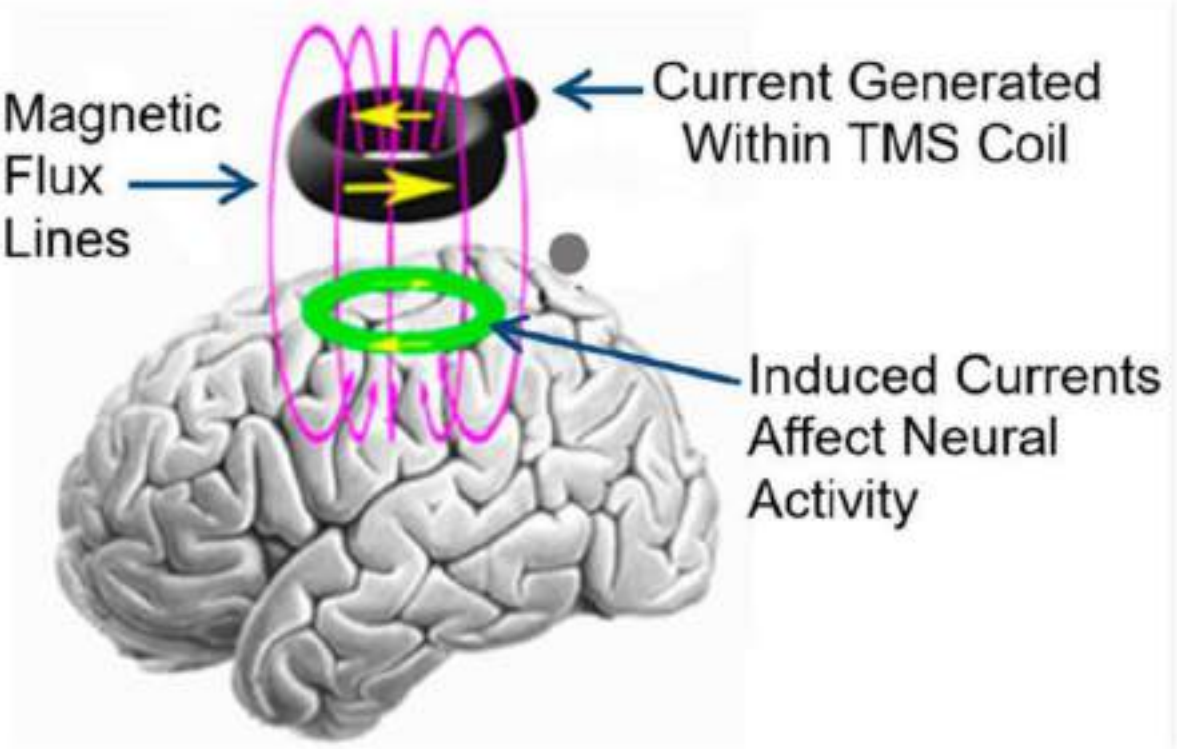

Figure 6 showing how TMS induces electrical currents (Tubbs et al., 2024)

(iii) Computerized Cognitive Training (CTT) is a digital method where people can do interactive brain exercises from their own devices. It uses structured "drill-and-practice" on regulated tasks, usually without any explicit training in memory or cognitive abilities. The game-like nature is often seen as rewarding, making patients motivated to complete their treatments. The repeated cognitive activities promotes the strengthening and the formation of neural circuits, allowing the brain to reorganize and adapt, boosting cognitive maintenance (Li et al., 2022).

However, recent models have stimulated a modelled synergistic plasticity taking place across a dendritic tree and within individual branches in the span of milliseconds, and others used a limited "pool of receptors" to portray different heterosynaptic behaviours as a result of the competitions (Chater et al., 2024).

Limitations:

This research was conducted under certain limitations. As I am a high school student, I was unable to conduct any primary research and had no access to any laboratories. Additionally, the time I had for research was limited to three weeks. This research paper is purely based off of secondary resources and existing literature.

Conclusion:

Alzheimer's disease is a progressive neurodegenerative disorder which leads to cognitive decline, and as a result, a loss of independence. Current treatments are symptom dependent and only target the effect rather than disrupting the disease progression. Neuroplasticity-based interventions on the other hand, focus on helping the brain regain its ability to reorganize and form new neuronal circuits, which can help slow down the rate of cognitive decline. Early intervention is imperative as it maximizes the effectiveness of the interventions before the neurological damage becomes irreversible. Ongoing research into these interventions is needed to create more reliable and effective interventions to guarantee positive outcomes, to improve quality of life for the patient and the patient's loved ones.

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Research Title: Is asteroid BENNU the to key for unlocking our knowledge about extraterrestrial life?

Rengin Yarali

Research Question:

Can Asteroid BENNU's Composition of Organic Compounds Provide Critical Evidence for Panspermia and Extraterrestrial Beings

Aims and Objectives

Aim 1: Compare the organic compounds found on BENNU with those essential for life on Earth.

Aim 2:Explain how BENNU is the right source for evidence for Panspermia and the existence of extraterrestrial beings with the SETI and WISE data.

Aim 3: Explain how extraterrestrial beings can exist with SETI and WISE data.

Aim 4: How life may have started in space with the panspermia theory and how the foundings of BENNU may be the evidence.

Aim 5: Draw a conclusion, based on secondary research to decide whether the foundings of OSIRIS-REx mission are actually a proof or not.

Study Design:

1. Method: Secondary research

This research is going to depend on information and knowledge from existing literature. Because it is not possible to access to the equipments needed or can not conduct a primary research, this study will be using secondary information on OSIRIS-REx mission, panspermia and extraterrestrial beings.

2. Purpose: Applied scientific research

The study is applied scientific research, it seeks to utilize existing knowledge to address real-world questions. Specifically the possibility of life's origin via panspermia and the role of asteroids like BENNU in transporting organic material.

3. Depth of Scope: Exploratory Research

This study investigates emerging and speculative topics (e.g., extraterrestrial life, asteroid-borne organic compounds), it uses an exploratory approach to synthesize available evidence.

4. Type of Data: Mixed Research

This research uses both qualitative and quantitative approaches. With data collected from BENNU asteroid and the literature that has been written about extraterrestrial beings and panspermia.

5. Timeframe: Cross-Sectional Research

The analysis will focus on data available at a fixed point in time without longitudinal tracking.

Introduction

On September 8, 2016 NASA launched its first spacecraft the *Origins, Spectral Interpretation, Resource Identification, and Security-Regolith Explorer*, or as shortened OSIRIS-REx, to collect samples from asteroid BENNU -before 1999 RQ36- and be delivered to Earth . After a 7 year journey covering nearly 4 billion miles, the spacecraft successfully delivered the samples to Earth on September 24, 2023 (1). Preliminary research of the samples has revealed a treasure throve of hydrated clay minerals and organic compounds, including amino acids and polycyclic aromatic hydrocarbons that moulded during evaporation of a late-stage brine that existed early in the phase of Bennu's parent body (2). These discoveries are a key to revolutionizing our understandings of prebiotic chemistry and potentially if the biological and chemical seeds that is needed for our existence came from outside. Following the OSIRIS-REx mission scientists found exactly "amino acids – 14 of the 20 that life on Earth uses to make proteins –, all five nucleobases that life on Earth uses to store and transmit genetic instructions in more complex terrestrial biomolecules, such as DNA and RNA, including how to arrange amino acids into proteins." explained Glavin's team. They also found exceptionally high amounts of ammonia in the samples. Ammonia is an important compound for biological life, it can react with formaldehyde ,which was also detected in samples- and formes complex molecules (e.g., amino acids) in the right conditions (3).

This study examines whether Bennu's organic inventory provides empirical support for panspermia - the hypothesis that life's precursors originated in space and if it provides a justifying proof for the "Fermi Paradox". The "Panspermia Hypothesis" It further evaluates whether these findings can meaningfully advance our understanding of the origin of life not just on Earth, but across planetary systems. By examining the OSIRIS-REx findings ,SETI, WISE missions and panspermia- the hypothesis of whether the life supplies came from and if it originated from space- and finding extraterrestrial being missions this research will determine what the findings mean.

Justification

The search for extraterrestrial life stands as one of humanity's most profound scientific pursuits, driven by the fundamental question: Are we alone in the universe? While technological limitations and the vast distances of space present significant challenges, the study of asteroid Bennu's returned samples offers an unprecedented opportunity to investigate life's cosmic origins. Asteroid Bennu represents a particularly promising source of evidence due to its unique organic composition findings.

Bennu is a B-type carbonaceous asteroid, has been identified as chemically similar to CI and CM chondrites, which are known to contain abundant prebiotic organic compounds (4). Other reasons that Bennu is picked for this research and OSIRIS:

- Unlike most other asteroids -which are in the belt between Mars an Jupiter- Bennu's orbit is relatively close to Earth's and even crossing it.
- Bennu is just the right size and speed which makes it possible to get samples. It has a diameter of 492 meters -a bit larger than the height of the Empire State- and rotates every 4.3 hours.
- Bennu is really old. Old that some compounds found inside it may be older than our Solar System itself.
- It is well preserved which makes it possible to collect rocks and dust (5)

If we analyse the data that comes from it correctly we may find great proofs of life outside our planet.

Inclusion & Exclusion Criteria

Inclusion Criteria	**Exclusion Criteria**
Sources of information(research papers,academic journals, books, etc) written in English	Sources of information(research papers,academic journals, books, etc) written in English
Research papers from 2016-2025/maximum dated back 9 years	Research papers older than 9 years/published before 2016
Sources of information including: 1. Peer reviewed journal articles 2. Academic papers 3. Institutional reports	Sources of information including: 1. non-reviewed journal articles 2. Websites like WIKIPEDIA 3. Non-reviewed blogs
Studies addressing 1. BENNU asteroid and its foundings 2. Panspermia theory	Studies unrelated to 1. BENNU asteroid 2. Panspermia theory 3. Extraterrestrial hypothesis

3. Extraterrestrial beings and potential life outside of earth	
Papers discussing the findings on BENNU asteroid mean the life comes from space or can it proof any potential life outside of earth	Papers which do not include any of the criteria my research aims to have
Data consisting of BENNU asteroid's composition of organic compounds and space mission	Studies unrelated to panspermia or extraterrestrial hypothesis
Studies including that only are free and does not need any institutional login.	Studies that demand money or an institutional login
Studies including the full research paper not only abstract.	Studies that only have an abstract

Boolean String

("Asteroid Bennu" OR "1999 RQ36" OR" OSIRIS-REx" OR "the Origins, Spectral Interpretation, Resource Identification, and Security-Regolith Explorer")
AND ("organic compounds" OR "prebiotic molecules" OR "amino acids" OR "nucleotides" OR "nucleobases")
AND (Panspermia OR Lithopanspermia OR " Directed Panspermia" OR " Radiopanspermia" OR Galactic Panspermia")
AND ("extraterrestrial life" OR "extraterrestrial being" OR "astrobiology" OR "biosignatures")

Limitations

1. **Reliance on Secondary Data**: The research is based entirely on previously published literature and mission data. This restricts the ability to verify results independently or conduct new experiments to test hypotheses about organic synthesis or biological markers on BENNU.
2. **Theoretical Constrains of Panspermia:** Panspermia still remains as a speculative hypothesis. While it offers a great mechanism for distributing life's building blocks, it does not address how life originated only how it might be

transferred. Therefore, the link between Bennu's chemistry and actual extraterrestrial life is indirect at best.

3. **The Lack of Evidence**: The lack of evidence about extraterrestrial beings existence makes the research seem like a sci-fi topic.

Ethical Considerations

1. **Space trash**: If sent more spacecrafts for this search, the possibility of them crashing in space increases. Even now with all the satellites we sent our orbit has become a trashcan.
2. **Financial Opportunity**: Scape or the search of universe has been one of the most expensive fields and the search for life outside is a far more expensive topic. In todays economy providing the needed financial support may result in some financial problems in other research fields.

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Table Of Content

RESEARCH PAPER
Is asteroid BENNU to key for unlocking our knowledge about extraterrestrial life?

1.1 Background on Asteroid Bennu

Bennu is a near-Earth object that approaches Earth every 6 years. Its rocks are believed to be formed nearly 4.6 billion years ago on a primeval world that was ultimately destroyed by a giant collision (1). It is a carbonaceous B-type asteroid, exhibiting a hydration feature in the 3 μm region, spectrally similar to ones aqueously altered CI- and CM-type chondrites (2). It is just the right size and speed, which makes it possible to get samples. It has a diameter of 492 meters, a bit larger than the height of the Empire State, and rotates every 4.3 hours. Due to its composition and old age, Bennu is considered a time capsule of the early solar system, potentially containing preserved organic materials, water-bearing minerals, and molecular precursors to life (3).

1.2 OSIRIS-REx Mission and Key Discoveries

Launched on September 8, 2016, the Origins, Spectral Interpretation, Resource Identification, and Security-Regolith Explorer's (OSIRIS-REx) mission was to collect samples -dust, rocks, etc- from asteroid Bennu's surface (101955) -formerly named 199RQ36- and deliver them to Earth. After a 7-year journey and approximately 4 billion miles, it successfully landed on Earth on the 24th of September, 2023 (4). The samples from the OSIRIS-REx mission revealed a rich inventory of water-rich minerals, amino acids, organic molecules, and a history of saltwater that could have served as the "broth" for these compounds to interact and combine (5). These mind-blowing discoveries can be a foundation that Bennu has retained the chemical building blocks necessary for life, preserved throughout the solar system's history, and the life outside may be real, now with its proofs.

1.3 The Question of Life's Cosmic Origins

The detection of these molecules and organic compounds on the samples of Benny has brought up the question itself: How did these organic molecules get there? Did our life come from space? Is there anybody out there? With these findings, this essay explores the evidence, theoretical frameworks, and scientific implications surrounding Bennu as a potential vector of panspermia and a model for understanding potential extraterrestrial life.

2. Theoretical Framework

2.1 The Panspermia Hypothesis

"The panspermia hypothesis is the philosophical proposition that the precursors of life are present in space and able to initiate life on reaching a suitable environment (especially the Earth)."-Mitton. It proposes that the building blocks of life, or even maybe life itself, exist throughout the universe and were delivered the Earth via celestial bodies (e.g., asteroids, interstellar dust). This idea, with roots in ancient Greek philosophy, evolved significantly in the 20th century through the work of scientists such as Arrhenius, Hoyle, and Crick (6).). The four proposed mechanisms of panspermia are lithopanspermia, accidental panspermia, directed panspermia, and radiopanspermia.

- "Lithopanspermia is the transport of microorganisms between planets as hitchhikers within rocks ejected into space by impacts" - Fajardo-Cavazos. "The interplanetary transfer process of microorganisms is divided into three separate stages: (i) impact-mediated ejection (launch) of rocks from the surface of the "donor planet" (ii) space transit and (iii) atmospheric entry and deposition on the "recipient planet". Each phase of interplanetary transfer is rife with its particular hazards to the survival of life" -Chukwudiegwu- (7).

- Accidental Panspermia: : The Gold Garbage Theory is a more modern name for the Cosmic Garbage Hypothesis, which was proposed by Thomas Gold in 1960". According to him, extraterrestrial beings may have accidentally seeded Earth with life by dumping their waste products on the planet, and while dumping these products, extraterrestrial beings might have carelessly left some of their native microbiota to escape. This idea later turned, or we can say renamed as accidental panspermia (7).

- Directed Panspermia: Sometimes referred to as "Planetary Seeding", Directed panspermia is the proposed "deliberate transmission of microorganisms to a lifeless planet with the aim of initiating life" -Sivula. This process could be done by a robotic interstellar life-seeding mission (8). A simple opening mechanism, such as thermal expansion, could release the microbiotics when the right condition is given without any need for electronic components. Moreover, genetic modifications could be made to the organic compounds that will be sent, with evolving for extreme radiation tolerance, or "evolutionary processes could be accelerated by a factor of ~1000 to facilitate terraforming, eventually that will result in Earth-like ecological diversity"- Subramanian (9).

- Radiopanspermia: First proposed by Arrhenius, radiopanspermia suggests that "microbial life can form and exist in space and that the radiation pressure from the sun can propel them into the gravity wells of planets" -Pasini (10).

Recent findings from Bennu, particularly the detection of complex organics, support the possibility of lithopanspermia. If life's building blocks were transported through asteroids to early Earth, there must be other planets around the cosmos that got these organic compounds.

2.2 Defining Life: Microbial to Complex Systems

While searching for extraterrestrial life or its biological residues, astrobiologists usually look for microbial beings and organic molecules. As these findings are the easiest to travel through the cosmos and are most likely to survive in the hard circumstances of interstellar travel. Before evaluating the evidence from Bennu, we must first define what are the major requirements for life. Life typically needs 3 key elements: liquid water, chemical elements (e.g., C, H, O, N, P, S), and an energy source, as we know from Earth. Yet the space conditions -as we know so far- are not suitable for any life to exist, with being highly radioactive and high, unstable temperatures, it makes any intelligent life to exist nearly impossible. Yet, some microorganisms, such as extremophiles on Earth, can survive in these extreme conditions (11). So, is it really impossible for any biological being to survive even in these circumstances?

3. Bennu's Organic Inventory

3.1 Detection of Prebiotic Molecules

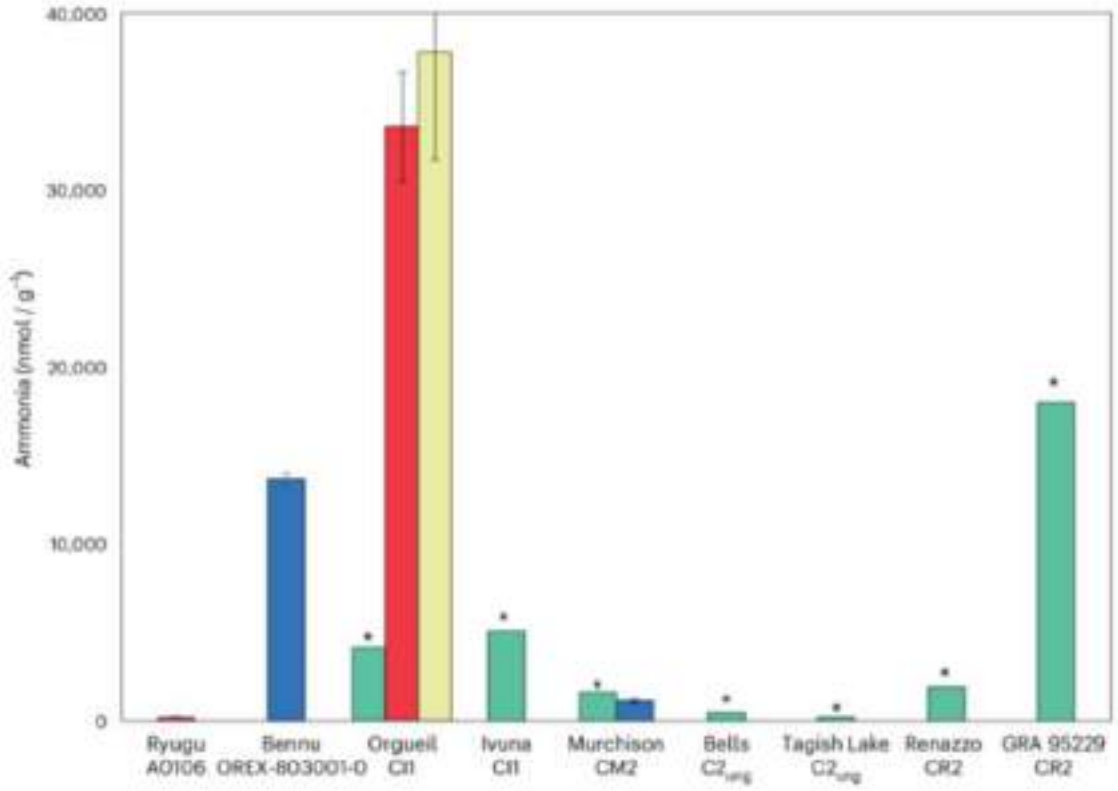
Organic matter in asteroids reveals clues about the early stages of Solar System chemistry and the origin of biomolecules that are essential for existence. Preliminary analyses of Bennu samples have revealed an astonishingly diverse array of soluble organic compounds, many of which are relevant to prebiotic chemistry. These analyses recorded the occurrence of salt minerals in the samples. Scientists identified 11 minerals' traces on the sample that leave behind traces of salts as crystals. Bennu's regolith is found to be exceptionally rich in water-soluble organics, including aliphatic amines, carboxylic acids, and aromatic nitrogen heterocycles. Moreover, "samples contain an arrangement of phases formed by precipitation from a fluid. The most abundant of these phases include sulfides, magnetite, and carbonates (10, 5, and 3 vol.%, respectively, by X-ray diffraction of a bulk sample), although concentrations differ between individual millimetre-sized asteroidal particles" -McCoy. These compound findings are highly significant because it is a residue of one of the 3 major needs of life on Earth. The preservation of these compounds without major signs of thermal degradation or terrestrial contamination supports the idea that Bennu has maintained much of its original chemical makeup since the formation of the solar system. In addition to these findings the samples also revealed a mix of biological compounds that include: 14 of 20 amino acids that are needed for like, all 5 nucleotides that life on Earth uses to store and

transmit genetic instructions in more complex terrestrial biomolecules (e.g., DNA and RNA) and also exceptionally high abundances of ammonia. (12; 4). These detections from samples may be proof that life has originated from outside of Earth, and they could have contributed to life's molecular precursors.

3.2 Molecular Diversity and Structural Complexity With Chondrites

In their comparative analyses, Glavin and his team defined the differences between the astromaterials before. Bennu shares strong chemical similarities with CI and CM chondrites, a stony (non-metallic) meteorite that has not been modified by either melting or differentiation of the parent body. But the real findings are in the differences. Bennu's aggregate samples had a higher mass-weighted average total of C and N than previous studies of chondrites. Despite the mineralogy and elemental compositions being similar to CI chondrites, isotopic data -especially for hydrogen and nitrogen- align more closely with less altered type-2 chondrites (e.g., Tagish Lake and Tarda). Compared to Ryugu and Murchison samples, Bennu contains a similarly wide range of soluble organic matter (SOM). Bennu's molecules have a lower mass range and carbon oxidation state than Murchison's. Ryugu's sulfur-rich chemistry so far aligns with the new samples from Bennu's nitrogen-rich composition with reflecting low-temperature aqueous processing on Bennu's parental body. Another discussion is the abundance of N-heterocycles, a cyclic compound with a divalent carbon atom bonded to at least one nitrogen atom- in Bennu samples ($\sim$5 nmol g^{-1}), these are 5 to 10 times more abundant than reported in Ryugu and Orgueil meteorites. The presence of water-extracted ammonia abundance that was measured in Bennu is 12 times higher than in Murchison and 75 times higher than in Ryugu (Table 1). Additionally, the presence of ammonium salts and carboxylic acids, like ones seen in comet 67P, supports the idea that Bennu retained ancient, nitrogen-rich organics formed in space (13; 14). Altogether, Bennu appears to be a uniquely preserved chemical archive -less altered, more nitrogen-rich, and highly relevant to the study of life's molecular origins.

Table 1: Concentrations of free ammonia measured in the extracts of Bennu (sample OREX-803001-0), Ryugu (sample A0106) and selected CCs Data



(Glavin et al., 2025)

4. Bennu as a Vector of Life: Survivability of Organics in Harsh Space Conditions

Another important question is how the organics were able to survive in the harsh space conditions if we take the panspermia hypothesis as possible. Several experiments and space missions have been conducted to analyse and demonstrate the range of microorganisms and organic compounds that can endure the vacuum, temperature fluctuations, and radiation exposure of the space environment. As mentioned before in this paper, part 2.2: There are 3

major key elements for life: liquid water, chemical elements (e.g., C, H, O, N, P, S), and an energy source, as we know from Earth. But in these conditions in the darkness of the cosmos, it is not possible to find any of these conditions easily.

Research conducted in the extreme conditions of International Space Station (ISS) studied the survival capacities and assessed the panspermia hypothesis. One of the samples, after 18 months of exposure, Bacillus pumilus SAFR-032, exhibited 10-40% survivability when the UV given was masked. However, when in the time these spores were exposed to UV light (above 110 nm), there was approximately a 7-log reduction in the viability, apart from a few spores. In a similar research, dried "Deinococcus" cell pellets, particularly ones in 500 µm thickness, remained viable even after 3 years of harsh space exposures due to a shadowing effect. Deinococcus radiodurans, after 1 year of exposure to outer space during the Tanpopo mission, showed signs of molecular modifications (e.g., DNA damage), oxidative stress response, and increased expression of metal transporter proteins. Its survival under near-space conditions was recently linked to pre-exposure growth conditions. Similarly, *Bacillus pumilus* SAFR-032 exhibited elevated levels of resistance-related proteins like superoxide dismutase when derived from space-exposed spores. These spores also produced first-generation offspring with significantly enhanced UVC resistance (~4000 J/m^2) compared to ground controls. In addition, elevated radiation levels on the ISS are associated with increased DNA damage. *D. radiodurans* demonstrates exceptional DNA repair via homologous recombination (HR), supported by 10 HR-related genes — a number comparable to those found across other ISS microbial genomes. These organisms also share core genes for recombination and repair (rec, ruv, rad, uvr) and at least one gene related to non-homologous end-joining (NHEJ). Notably, all ISS strains, including *D. radiodurans* and *B. pumilus*, encode the LexA repressor, a key regulator in the SOS DNA repair pathway (15).

In another study complementary to ISS experiments, provides a comprehensive review of how "environment of space is characterized by factors that stress organisms in ways that cannot be mimicked on Earth, such as microgravity (weightlessness), intense ionizing radiation, high vacuum, pressure, space magnetic fields and extreme temperatures"-Prasad et al.,. The factors given would not arise on Earth's surface. Experiments show that the environment of space had clear, sharp effects on genetics, mutation scale, gene expression, epigenetics, metabolite production, and metabolic pathways. It also had an effect on altering the shape, structure, function, physiology, and growth behaviour of organisms (16).
These studies both give examples of how some bacteria and organisms could survive in harsh space conditions. The given samples are also very similar to Bennu samples that were conducted. This means Bennu possesses both the environmental conditions and mineralogical structure which is needed to preserve complex organic molecules -and potentially life-bearing material.

5. Challenges

5. Challenges

While Bennu's organic inventory offers profound insights, several caveats must be acknowledged. Despite all the studies, experiments, and samples in this research, there is a significant challenge: none of the findings constitutes concrete proof. The presence of organic compounds -even if they are the ones essential for life- does not automatically imply biological origin. This truth complicates the findings of Bennu's key to finding extraterrestrial life. Moreover, space missions require substantial funding, and SETI (Search for Extraterrestrial Intelligence) demands even greater resources. Securing adequate financial support for such a speculative search, especially in the absence of solid evidence, is a major challenge. Finding enough financial opportunities for a search like this, when there is no solid proof, is also a big challenge. Furthermore, despite being theoretically possible, the panspermia hypothesis still remains theoretical. Without direct observation of biological activity or replication, Bennu's data, while promising, stops short of definitive proof. For now, all we can do is assume. These limitations must be acknowledged when initiating research on cosmic life.

6. Conclusion

Asteroid Bennu stands as one of the most promising keys to unlock the mystery of life's cosmic origins. With OSIRIS-REx missions findings we are now as close as we are closer than ever to answering questions that have haunted humans since ancient times: Where did we come from? Are we alone? Bennu's chemical findings, when examined through the panspermia hypothesis, do not offer certainty, but they offer something bigger: the possibility. It shows that essential life compounds are not just on Earth but also across the cosmos. Despite challenges that could be faced, the implications are immense. If even the potential for life's ingredients to travel across space exists, then so does the potential for life itself and maybe even everywhere.

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BUSINESS & ECONOMICS

What would it take for a new e-commerce platform in the food delivery industry in the UAE to be successful while being more ethical to riders?

Saif Hilal

What would it take for a new e-commerce platform in the food delivery industry in the UAE to be successful while being more ethical to riders?

Business concept: YallahYum

My idea is to form YallahYum, an e-commerce platform for food delivery services in the UAE. YallahYum will differentiate itself from its competition by focusing on delivery rider welfare and sustainability, which is often overlooked by the existing companies in the UAE. In today's market, consumers are increasingly inclined to support businesses with higher ethical standards and sustainable practices, making YallahYum's commitment to rider wellbeing and sustainability a strong driver for customer loyalty and trust.

Overview:

The online food delivery industry in the UAE has seen rapid growth during and post Covid-19. In the UAE, the industry is valued at $720.7 million, and is expected to grow to $1799.1 million by 2033, with a CAGR of 10.2%.

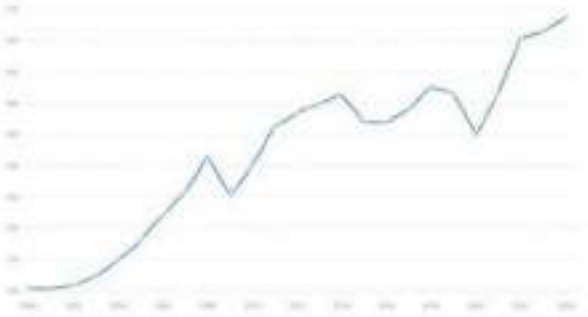
UAE Online Food Delivery Market Size, Share, Trends and Forecast by Platform Type, Business Model, Payment Method, and Region, 2025-2033, https://www.imarcgroup.com/uae-online-food-delivery-market (accessed 12/08/2025).

In the industry, there are four main companies, Talabat, Careem, Zomato, and Deliveroo. Out of the four, Talabat is the largest, with a market share of 70% as of 2024, followed by Deliveroo at 12% market share.

Why did it rise?

The rise in people's disposable incomes (shown by a rise in GDP) has resulted in the increased use of e-commerce platforms for food delivery, driven by the growing middle class in the UAE. Thus, making delivery fees (ranging from 5-10AED per delivery) become a price point that many people afford.

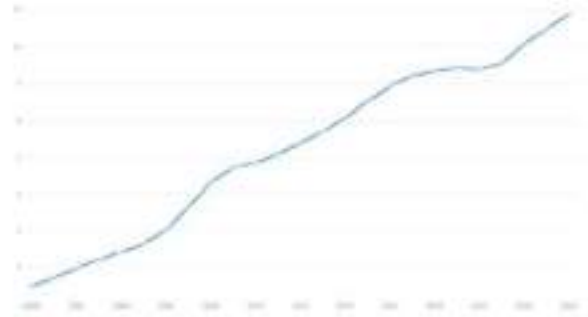
GDP growth of UAE from 2000-2024:



GDP (current $US) – United Arab Emirates, https://data.worldbank.org/indicator/NY.GDP.MKTP.CD?locations=AE (accessed 10/08/2025)

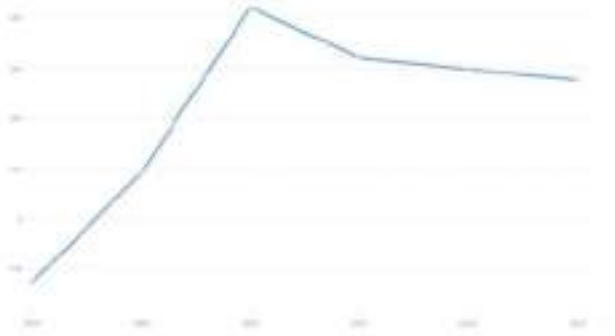
Moreover, the rise in demand for online food delivery in the UAE is also a result of UAE's growing population. With a plethora of people moving to the UAE, shown by the positive value of net migration (besides 2019), there is a larger population of people who demand food delivery services. The rise in demand results in a further rise in the food delivery industry's growth in the UAE.

UAE population (2000-2024):



Population, total – United Arab Emirates, https://data.worldbank.org/indicator/SP.POP.TOTL?end=2024&locations=AE&start=2000 (accessed 12/08/2025)

Net migration (2019-2024)



Net migration – United Arab Emirates, https://data.worldbank.org/indicator/SM.POP.NETM?end=2024&locations=AE&start=2019 (accessed 12/08/2025)

Why will YallahYum focus on ethics?

After interviewing riders from other companies, they had expressed their concerns about rider safety due to the extreme heat, and the financial risks associated with their job. One rider said, "I had an accident once and hurt my leg and lost two weeks and didn't make enough money that month.", indicating that compensation isn't given to riders, even when injured, further emphasizing the financial risks that the riders have to bear.

Furthermore, the issues that riders have was a reoccurring issue as in May of 2022, a strike done by Talabat and Deliveroo riders as a result of poor pay and rising fuel prices indicated that something needed to be done. Riders even claimed to "pay for fuel from their own pockets". Aljazeera, Dubai: Deliveroo riders strike for better pay and work conditions, https://www.aljazeera.com/news/2022/5/2/dubai-deliveroo-riders-strike-for-better-pay-and-work-conditions (accessed 08/08/2025)

What actions will YallahYum do to fulfill the needs of riders and the environment?

YallahYum will focus on rider welfare and improve ethical standards in this industry. To ensure that YallahYum can claim it is an ethical company, YallahYum will offer compensation to injured riders for however long it is required before they are able to resume delivery. YallahYum will take the requisite insurance protection for its riders to allow for their treatment in case of injury. This solution helps fix the main financial burden that the riders face when they happen to be in an accident.

YallahYum will also focus on sustainable practices. By ensuring that suppliers of the bikes that riders use are electric bikes (which are charged through solar), YallahYum is

able to show their use of sustainability and positive contribution towards the environment, further differentiating itself from the market.

How to market YallahYum?

Product:

YallahYum is an e-commerce platform, hence the way it is designed should be relatively similar to that of its competition, as the main differentiator is not done through its application. With this in mind, YallahYum is an application that is downloadable on both Laptops and phones and includes lists of restaurants (in the UAE) that customers can order from.

Gamification through adding a points-based system grounded on the number of orders customers have placed can help influence consumer behavior and keep them retained, as if you get 50 Yum points, you can get a free meal of up to 50AED (non-inclusive of delivery fees).

Price:

YallahYum can also use means of price to market itself. With the main competitors having a delivery fee ranging from 7.5-10AED, due to the additional costs of adequate insurance that YallahYum aims to pay, YallahYum's delivery fee will be at the higher end of the range, at 10AED. Although this could make YallahYum seem overpriced, consumers will know that the additional cost results in better rider welfare. This could have a counter-active effect when compared to traditional economic theory, as the higher price could incentivizes consumers to order through YallahYum, due to its positive impact on riders, instead of the simple reason of getting food.

Promotion:

YallahYum's promotion is the main form of marketing which can help portray YallahYum's main objective of changing the ethics of the industry.

One medium YallahYum will employ is their use of TikTok advertisements. With many people in the UAE spending lots of time on their phone (the resident average is around 8 hours 11 minutes, daily), using social media platforms as a form of advertising is one of the best ways to obtain a large number of stakeholders, which are essential to obtain for YallahYum's growth. Moreover, it targets the younger generation of consumers, who are considered to care more about working conditions when making decisions when compared to the previous generations.

Marija Hladni, Track and Visualize Your TikTok Ads Metrics with Databox, https://databox.com/track-and-visualize-your-tiktok-ads-metrics-with-databox (accessed 08/08/2025)

Another medium that YallahYum will use is a forty-five-second-long advertisement through YouTube. This will not only increase viewership of YallahYum however, it will also convey the ethics of the company itself. In the advertisement, the videos used will be of YallahYum riders being appreciated and joyful, to further imply that YallahYum's priorities is not just to deliver food, but to enrich the community as well. This advert can help YallahYum retain customers, as the ethical and passion conveyed through this medium of promotion helps portray the differentiation between YallahYum and the rest of the market.

Placement:

YallahYum will use placement of cloud kitchens to create a reputation of quick deliveries. By having one cloud kitchen in every major district in the UAE (e.g. Al Barsha, Business Bay, Al Maryah Island), YallahYum is able to reduce delivery times, as the distance covered by riders will be reduced. As a result, consumers will view YallahYum as a better alternative, as they are not only more ethical, but they are also faster at delivering food.

SWOT analysis of opening YallahYum:

Strengths:

With YallahYum being rider oriented, one key strength would be YallahYum's ability to scale a large and efficient delivery fleet in a short span of time. Based on interviews conducted, and recent strikes, it is clear that riders are not satisfied with the benefits given by existing companies, thus making it easier for riders to switch to YallahYum, which promises sufficient benefits.

Another strength YallahYum has is their emphasis on ethics. With YallahYum building its reputation on rider's wellbeing, it causes there to be distinction between itself and the market, and causes consumers to think that by using YallahYum, they are also doing good for the riders, thus causing more people to use YallahYum.

Weaknesses:

Access to adequate capital is an area of weakness for YallahYum, as it will be a new company in a market with established competition. This weakness can be addressed by the growing number of funding avenues focusing on start-ups that operate sustainable and ethical businesses. Banks such as FAB have allocated funding to sustainable and ethical businesses.

AB to Provide Over AED500 Billion (USD135 Billion) in Green Finance by 2030, Increasing Sustainable Commitment by 80%, https://www.bankfab.com/en-ae/about-fab/group/in-the-media/fab-to-provide-over-aed500-billion-usd135-billion-in-green-finance-by-2030 (accessed 12/08/2025)

Opportunities:

With its sustainable and ethical business model, YallahYum can expand market share within the UAE and expand its operations to other countries across the middle east. There is a growing demand for employment in the younger populations and YallahYum's business model will attract part-time workers due to its incentives.

Threats:

One threat to YallahYum's opening would be the competitive nature of the e-commerce industry for online food delivery. With the high monopolistic power that Talabat has, even if YallahYum differentiates itself from Talabat, consumers may still not be inclined to switch over. This could be a result of inertia or even brand loyalty, due to Talabat's points system, Talabat Rewards'. This threat can be mitigated by launching similar customer loyalty programs called Yum points that can be utilized for discounts.

Conclusion:

In conclusion, YallahYum is a business which focuses on ethical and sustainable business practices. With its central focus being on rider wellbeing and sustainability, although YallahYum is entering a competitive market, the differentiation that YallahYum possesses would help mitigate the competitive advantages that other companies in the

industry possess. Thus, YallahYum could help revolutionize the food delivery industry in the UAE, by turning its focus away from convenience, and towards enriching the community.

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The Impact of Political Instability on Foreign Direct Investment in Kenya

By Yash Karia

Abstract

Foreign direct investment (FDI) plays a critical role in shaping Kenya's economic trajectory. ..As a key gateway to East Africa, Kenya has attracted substantial international investment. However, political instability, including disputed elections, mass protests and constitutional crises has repeatedly disrupted investor confidence. This paper explores the connection between political events and FDI trends from 2009 to 2023. Through an annual timeline analysis the paper demonstrates that political stability is a core prerequisite for sustainable economic growth.

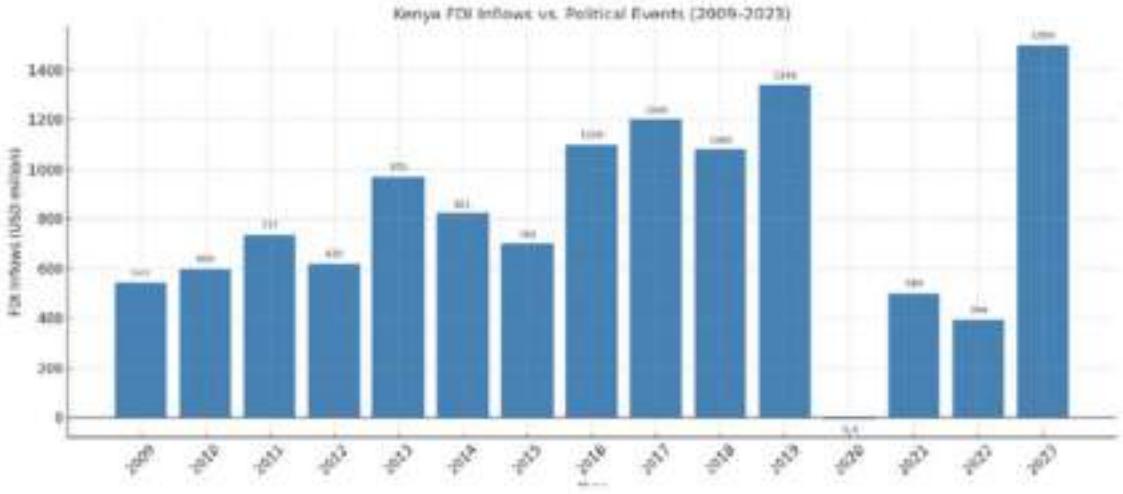
Introduction

Foreign Direct Investment (FDI) furnishes nations entry into worldwide marketplaces, technical proficiencies, and funding. Principal domains such as infrastructure, agriculture, energy, ICT and finance observe FDI assistance in Kenya. Political conditions, however, exert a heavy influence upon the FDI inflow. Political instability diminishes investor confidence, postpones project implementation, and incites capital flight. This instability includes election related violence, policy uncertainty, together with social movements for example Mandamano.

Methodology

- **Quantitative analysis:** FDI figures were collected from credible courses such as the world bank, UNCTAD, CEIC Data, Central Bank Of Kenya , Kenya National Bureau of Statistics
- **Qualitative analysis:** Media reports, government briefings, independent economic assessments

Analysis and Findings



2009

FDI inflows were recorded at $543 million, a modest recovery following the devastating 2007 2008 post election violence. Investor confidence was still low, but the establishment of a coalition government and steps toward reconciliation created the beginnings of a more stable business environment.

2010

With the new constitution passed via referendum, Kenya saw a boost in global perception. FDI inflows climbed to approximately $600 million, reflecting renewed investor optimism in Kenya's institutional reforms, increased rule of law and democratic progress.

2011

FDI rose further to $737 million . The relative political calm and focus on infrastructure development, especially Chinese funded projects, made Kenya more attractive. The country's role as a regional ICT and logistics hub also began taking shape.

2012

A year of political tension buildup ahead of the 2013 elections. FDI inflows dipped slightly to $620 million as investors adopted a "wait and see" approach, anticipating possible instability during the next election cycle. Uncertainty reduced long term investment commitments.

2013

Kenya held its first peaceful elections under the new constitution, leading to a sharp jump in investor confidence. FDI surged to $970 million. The peaceful transition of power was celebrated globally and sectors like real estate, telecom and energy received strong inflows.

2014

FDI dipped slightly to $821 million. Although the country remained politically stable, the rollout of devolution introduced fiscal and legal complexity at the country level. Investors remained active but more cautious, particularly in sectors like Reliant and National Coordination.

2015

Terrorist attacks, especially the Garissa University massacre, introduced major security concerns. FDI reduced to $700 million. Tourism and retail were the hardest hit, while infrastructure and energy retained foreign interest due to long term project momentum.

2016

This pre-election year was relatively calm with renewed momentum in infrastructure, transport and energy. FDI inflows climbed to $1.1 billion. Many investors capitalised on the last window of political stability before the upcoming elections.

2017

Despite disputed presidential elections and the Supreme Court's nullification of results, FDI surprisingly rose to $1.2 billion. This suggests that projects already in motion continued due to earlier approvals, even as new investment decisions were paused. However, delays and disruptions were evident, especially in hospitality and services.

2018

The handshake between President Uhuru Kenyatta and opposition leader Raila Odinga restored political calm. FDI inflows were stable at $1.08 billion with increased interest in ICT and banking. The symbolic reconciliation reassured both domestic and international markets.

2019

FDI peaked at one $1.34 billion, fuelled by optimism around economic growth, Vision 2030, infrastructure projects and improved relations with development partners. However, rising debate around the Building Bridges initiative began to introduce policy uncertainty, especially concerning governance and fiscal policy.

2020

This was a turning point. With the onset of COVID-19 and escalating political tension surrounding BBI, Kenya recorded negative FDI inflows of -$5.4 million, meaning more capital left the country than entered. Many foreign projects were delayed, downsized or cancelled. The economy shrank, job losses mounted, and investor confidence was severely shaken.

2021

Recovery efforts were underway, but political campaigns for the 2022 elections had begun and investors remained cautious. FDI inflows recovered slightly to $500 million, supported by essential sectors like health and telecoms, but well below pre-pandemic levels.

2022

Elections were marked by rising tension, inflation and the Mandamano protests over the cost of living. FDI declined further to $394 millon. Investor interest weakened due to perceived political and economic instability. Several large infrastructure and logistics projects were delayed.

2023

Kenya experienced a peaceful post election transition and the new government made strong efforts to improve fiscal policy and restore investor confidence. As a result, FDI rebounded to $1.5 billion, the highest in the 15 year timeline. Investors responded positively to reforms, renewed IMF support and a shift in tone toward business friendly governance.

Social and Economic Consequences

Political instability and related FDI fluctuations had wide reaching effects across Kenya society and economy:

1) Employment and livelihoods

- Sectors such as construction, manufacturing and IT, often funded by FDI, faced job cuts during periods of unrest.
- In 2020 alone, due to political and pandemic induced instability, over 1.7 million Kenyans reportedly lost jobs or income sources (KNBS, 2021)

2) Currency and inflation

- Instability often caused the Kenyan shilling to weaken, making imports more expensive.
- Inflation surged, especially during and after election cycles. (e.g. 2017, 2022)

3) Public infrastructure

- Major Chinese funded projects slowed or posed in years like 2017 and 2022.
- Policy uncertainty and legal delays reduced momentum in large scale development.

4) Investor sentiment

- Delayed approvals, regulatory ambiguity and street protests discouraged long term planning by foreign firms.
- Local investors posed hiring or expansion during unrest.

5) Youth and informal sector

- Over 70% of Kenya's youth work in the informal sector - most vulnerable to FDI related slowdowns.
- Political instability often disrupted supply chains & consumer demand, affecting daily earnings.

Conclusion

FDI is not just a financial metric, it is a mirror reflecting investor perception of a country's political stability. Kenya's case between 2009 and 2023 shows clear evidence that political violence, protests and uncertainty harm its investment inflows. Meanwhile, stability, such as in 2013 or post-handshake, drives capital into the country, boosting economic development. To secure future investment, Kenya must prioritize democratic transparency, judicial independence and peaceful transitions of power.

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What investment strategies convert companies like BlackRock from small start-ups to leading financial institutions?

Hashir Rizwan Khan

Introduction:

From humble beginnings in 1988 and after 37 years of sheer persistence, BlackRock has managed to establish itself as one of the largest and most trusted asset-management firms in the entire world, managing over 11 trillion dollars worth of assets despite ferocious competitors like JPMorgan and Vanguard, while having a whopping value of 155.7 billion dollars as of 2025.

But what exactly are the features possessed by the firm that have allowed it to become one of the most trusted and fast-growing companies with expanding horizons, day-by-day? As a result, this research highlights and carries out an in-depth analysis of investment strategies used by asset-management companies, especially like BlackRock, to scale their path towards unprecedented success while also addressing some key gaps within those strategies. These include the firm's high involvement in sustainable index funds such as the S&P 500, which help its clients gain a passive income; its goal of connecting the public to 'private markets'; and its disciplined and structured approach towards understanding and meeting client goals, coupled with the use of its newly powered risk management technology known as 'Aladdin. 'Major weaknesses have also been highlighted while one of them has been also worked out in detail. Using a hypothetical scenario and simulation.

The driving force behind success:

From the very start of the long road towards success, BlackRock's main aim has remained simple and been defined by the idea of an **"economic democracy"**, a type of democracy in which private markets linked to ownership of assets like infrastructure are not just available for the 'elite investor', but also for the common people of society.

BlackRock's strategy here is to connect the common man to both the private and public markets, helping one to start investing faster while crafting retirement plans for the near future. Larry Fink, the CEO of BlackRock, believes that this way the confidence of the general population in the economic growth can be uplifted while also making them feel a part of it. (BlackRock Inc, 2024b)

Sole strategies and synopsis:

Historically, the cornerstone of BlackRock's strategy has been a disciplined approach to investments (BlackRock Investment Stewardship,2025). This literature review analyzes the historical strategies employed by BlackRock across different time periods.

1988–2000 (Technology and Trade):

During this period, BlackRock's main focus was **bond management** and **MDS (mortgage-backed securities)** while taking on advisory assignments. Alongside this, it was during this period that BlackRock created the new **'Aladdin's (Asset, Liability, Debt, and Derivative Investment Network)** Technology' to manage portfolios and carry out risk-management tasks. It was the first time BlackRock started expanding their operations worldwide while offering Aladdin to clients like Microsoft for use in return for high-profit margins, additionally helping it enlist on the New York Stock Market during the 1990s (BlackRock, 2025).

So, what was the differentiating factor in Aladdin from other investment technologies? It was the ability of it to remain ahead of upcoming market changes or transitions by identifying different occurring scenarios; it was the ability of BlackRock to adapt Aladdin's capabilities with changing time periods to ensure it delivers up-to-date, accurate data so that investors can always make vigilant decisions, helping enhance portfolio growth. (Macq.O, 2022)

According to the Hedge School of Applied Economics, the use of Aladdin was also a pivotal factor in the firm's growth, allowing it to study market trends, carry out risk management, and diversify portfolios, although there were some critics who strongly opposed this strategy and questioned BlackRock's immense control over the market because of this and whether they addressed climate change concerns. In response, BlackRock started working more closely with companies while adapting their strategies to bring about positivity. (School of Hedge, 2025)

2000–2012 (Acquisition and Growth Investment):

In the early 2000s, BlackRock expanded its reach into **corporate acquisitions** and **direct investments in high-potential businesses** to improve them for profitability (BlackRock, 2025). A major milestone occurred in 2007, when BlackRock bought the Quellos fund-of-funds business for a value of $1.7 billion (Herbst-Bayliss, S., 2007).

Before the acquisition, BlackRock used Aladdin to analyse Quellos' present-time portfolios and assess their performance under all kinds of market scenarios while determining valuation and risk. After the acquisition, BlackRock ensured regulatory compliance, standardized reporting, and improved real-time monitoring of client portfolios. This strategic move enabled better transparency for institutional clients and allowed for greater customization of portfolio strategies. Moreover, this acquisition helped BlackRock close strategic gaps in its alternative's platform—particularly in hedge funds, private equity, and real estate services for high-net-worth clients. (Private Equity Wire, 2007)

As Harris.S from WealthBriefing, 2008, stated, BlackRock added $21.9 billion in assets under management (AUM) and achieved a $44 million increase in base advisory fees in Q4 2007. It was also a period of growing influence for the firm as it was called upon by governments to help them solve

the existing economic problems, although some argued this gave the firm too much control, making it 'too big to fail' with influence over financial markets controlled by one man, Larry Fink. (Vanity Fair, 2010)

2012-2025(Modernized Investment Strategies):

Since the past decade or so, BlackRock has mainly focused on investing more into **index funds** and **ETFs** while also giving the vast majority of its clients access to private markets. This has led the firm to have crossed ETF investments by 390 billion dollars, accumulating about 50 billion AUM, while private markets have done 212 billion as of 2024 (BlackRock Inc., 2024). Furthermore, having a large stake in these kinds of funds also plays a major role in assisting BlackRock in growing its financial influence over big organizations.

To explain this, we can take a case study example of Shopify, a giant Canadian e-commerce company that, in May 2024, proposed a new directory to be set up while presenting the idea of giving away stock options as incentives for the company's leading executive. Consequently, BlackRock voted against the proposal with a belief that companies should explain how these actions of giving rewards to executives can benefit investors in the long run. Seeing no explanation coming their way, BlackRock concluded that this action would reduce the ownership value of existing investors and has no major benefit for them either. Although the proposal passed in the end, it was a strong signal to Shopify that if things went on as they were, investor opinions might change on the company, which could risk a considerable amount of loss. (BlackRock Investment Stewardship, 2025)

Moreover, new ideas such as **tokenization of assets** (assets in the form of tokens or currency) have been proposed to increase the public's control over them and also serve as a strong testament to the CEO, Larry Fink's mission to create an 'economic democracy,' as mentioned above, in which each individual can feel that they are a part of the economic growth and own hard assets like infrastructure for better gains and margins (BlackRock Inc., 2024b).

Gaps and Loopholes:

But still,the most important concern here for the firm is that the main loopholes and gaps as a result or outcome of their investment strategies need to be identified. However this topic hasn't been covered with detail throughout the research but ,it is something that needs to be addressed and for the least identified:

1.One of the main strategies of the firm which makes is slowly making it lose confidence in front of capitalist investors is the firm's growing outreach and control alongside the other "Big Two"(Vanguard and State Street) of the passive funds such as the iShares MSCI EAFE ETF (EFA) where the fund has a massive amount of control which in turn leads to it having a greater percentage of proxy voting power that in turn leads to a 'concentration of control' scenario where other individual investors are bound to have less influence on a company of firms proposed strategies, incentives or ideas.

Here's a table which shows the Big Three's control over passive index fund in the market as of 2016:

Table 1: The Top 15 U.S. Asset Managers (Equity), June 2016

Name	Total AuM (Equity)	AuM in Passive Index Funds (Equity)	Share of Passive Index Funds (Equity)
BlackRock	*2,644*	*2,166*	*81.3%*
Vanguard	*2,270*	*1,839*	*81.1%*
State Street	*1,377*	*1,275*	96.9%
Fidelity	1,004	170	16.9%
Invesco	377	85	22.5%
T. Rowe Price	337	30	8.9%
BNY Mellon	247	14	6.9%
Capital Group	838	0	0%
Wellington Mgmt.	476	0	0%
JP Morgan Chase	342	0	0%
Affiliated Managers	336	0	0%
Franklin Templeton	297	0	0%
Goldman Sachs	254	0	0%
Dimensional F. Adv.	245	0	0%
Legg Mason	204	0	0%

Here, the claim is proved that the three funds each control more than 80% of passive funds present in the market.

2.Secondly, another problem is the firm's practice of securities lending where shares are lended out generally to short sellers so that additional income can be generated. Although the practice has served to be beneficial in good times, an increase in it(which can be seen as the amount of securities tripled from 40bn$ to 120bn$ for BlackRock in just two years from 2012-2014) can risk a rising indemnification figure which shows that more and more of these securities are being lended and can cause more potential risks to awaken. This practice furthermore even risked the firm being labelled as a bank which needs tighter monitoring because of its ability to fail the entire financial system by the FSB although this label was contested and eventually not put into action.

However, this can still serve as a warning sign for the firm that although things can go well in good-times with loans repaid and investment goals achieved, during times of crisis, this practice can trigger drying up liquidity and securities being unable to be gained back leading to complete failure and serious losses.(Fichtner, J., Heemskerk, E. M., & Garcia-Bernardo, J. 2017)

Furthermore, even the collateral's given by the borrower can lose in value during times of financial stress as BlackRock also invests them in different index funds which although have a historically stable market performance, can still lose a lot in value in case of a market crash.

3.In addition, another potential concern here are BlackRock parting ways with NZAMI (Net Zero Asset Managers Initiative), which may point to tensions towards the firm's position on its ESG (Environmental, Social, and Governance) policy, which may disillusion ESG-oriented clients on its climate commitments. (Jessop, S., & Kerber, R., 2025).

Possible Solutions:

Hypothesis: Although BlackRock has well-structured systems in place to work on its lending practices, this hypothesis can be used by other smaller firms or banks with less capable tech, the idea is that if they adopted a diversified collateral framework (60% cash,40%stocks) with a >15% market-drop liquidation trigger, while collaborating with the borrower and giving it permission to

sell and reinvest with help from Alladin then loan default losses would be significantly lower safeguarding the borrower from full default and even help in making profits.

1.Lending securities Hypothetical Scenario:

Hypothetical Securities Lending Scenario

Initial Lending Conditions:

- **Borrowed/Lent Amount:** $2,500,000
- **Collateral Value at Start:** $2,750,000
- **Collateral Type:** $652/share equivalent IVV shares
- **Term:** 2 years
- **Expected Total Growth (2 years):** +12.6%
    - Annualized ≈ 6.3% per year

Year 1 — Pre-Crash Value (No Shock Yet):

Value=2,500,000×(1+0.063) =2,657,500

End of Year 1 — Market Crash of 18%:

Loss=0.18×2,657,500=478,350

Loss compared to the original borrowed amount:

2,500,000−2,179,150=320,850(≈12.83%)

Year 2 — Weak Recovery (+4% after crash):

2,179,150×1.04=2,266,316

Approximately **9% below** the original $2.5M — net loss after two years.

Contingencies BlackRock can put down to maintain repayment progress while keeping the borrowers risk at bay?

Proposed Contingency Solution for BlackRock's Securities Lending

To reduce losses in the event of a market downturn, BlackRock can diversify the collateral it takes from borrowers across multiple asset classes.

Collateral Composition:

- **60%**: Cash Amount (in currency)
- **40%**: Stocks or ETFs (liquid market instruments)

Contingency Clause:
If there is a **market decline of more than 15%** in any given year affecting the collateral's value:

1. **Immediate Liquidation of Cash Portion** — BlackRock liquidates 60% of cash amount portion of collateral to secure value before further decline.
2. **Retain Other 40% as Loan Collateral** — Stocks remain pledged against the outstanding loan. (But can be sold if market falls beyond mentioned trigger as stocks will lose value and borrower still has to pay the 40% in full value)
3. **Borrower Supplement Requirement** — The lender must provide borrower with two options:

   Either borrower pledges another 10-15% collateral.

   accepts restrictions on credit lines.

However, after the fall the lender will allow the borrower to **sell and reinvest** with existing securities using help from tech-platforms like Aladdin and BlackRock's Investment Departments.

4. **Time period-**The time should be doubled as of the previous agreement considering market conditions so that the market is given time to regrow and the borrower can pay back the other leftover 40% without having to risk collateral.
5. **Fall-limit-**These clauses apply only if the market experiences a fall till 20%, but if the fall continues till 25-30% or more than that then 100% of the collateral can be liquidated.

Advantages of This Approach:

- **Liquidity Protection**: Cash can be liquidated quickly, locking in value before deeper declines.
- **Borrower Relationship**: Allows time for the borrower to rebuild collateral instead of triggering full loan default, maintaining trust and long-term business.
- **Win-win Scenario:** The borrower can be saved from default in correlation to acceptable terms if loss is till 20-25% but if it goes beyond, the firm can avoid bigger losses by locking 100% of the collateral.

SO, in the aforementioned scenario, this would happen:

Loan left off to pay after collateral liquidated:

2,750,000*(0.6) =1,650,000

2,500,000-1,650,000$=850,000$

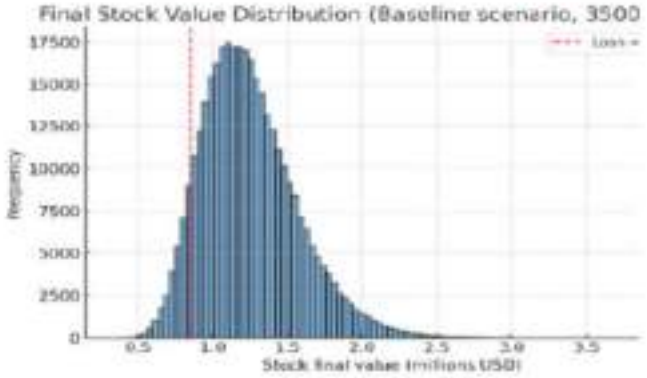
Use of Aladdin:

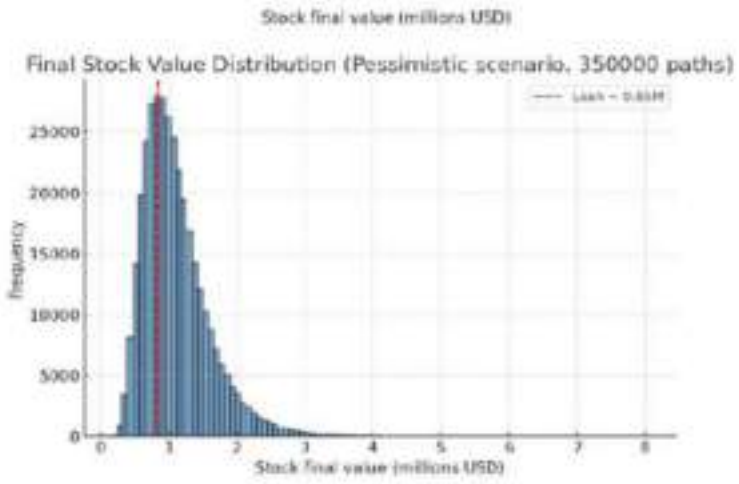
Here Blackrock as we know it needs immediate liquidity while borrower wants to stay away from complete default so as the solution presented above goes, BlackRock's Aladdin can come into use to

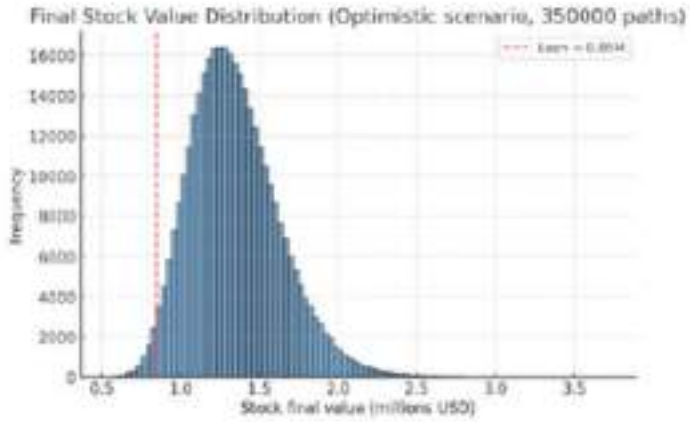
test the collateral before it being granted whether how will different parts of the collateral will perform under harsh market conditions .BlackRock can access its performance then giving loan to the borrower and in case of market fall, the borrower can be allowed to sell fallen existing securities ,reinvest them while taking Aladdin's suggestions on what market stock is set to rebound into account so that smart and stable investments can be made helping pay off the existing loan and even making a profit.

Final judgement:

To test the reliability of my hypothesis a Monte Carlo test was run considering different simulated paths while remaining loan to pay after liquidation was 850,000$ after the 15%+ trigger mentioned and here are the results:







(The **x-axis** = Final collateral amount (in millions of USD).

Success Rates (probability stock ≥ $850k after cash liquidation)

- **Baseline (μ=6.3%, σ=18%) → 91.6%** success
- **Pessimistic (μ=0%, σ=30%) → 65.4%** success
- **Optimistic (μ=10%, σ=15%) → 97.9%** success

Percentiles of Final Stock Value (USD)

- **Baseline**
  - Median ≈ $1.21M
  - 1% worst-case ≈ $667k
- **Pessimistic**
  - Median ≈ $1.01M
  - 1% worst-case ≈ $375k
- **Optimistic**
  - Median ≈ $1.31M
  - 1% worst-case ≈ $802k

It is important to note that the success rate can be approximated in the 90's and cannot be a 100% for sure as in the hypothesis given, there are also many gaps such as lack of keeping external factors in mind while also being summed-up by the fact that the Monte Carlo simulation has its own systemic errors. Moreover, the hypothesis can be improved by taking legal structure and laws for collateral framework in view to design a better framework, a more complex hypothesis with a real-life case scenario while adding 1 or 2 external variable other than market fall can also be designed while also going out and testing it with different types of simulations.

Methodologies:

The research is more inclined towards a qualitative research method, although some quantitative data has been gathered. Information has been gathered from reliable sources such as BlackRock's history page to find out about their investment strategies over different time periods. The use of BlackRock's technology, Aladdin, has been explained by analysing the article from the School of Hedge, which not only argues about the benefit of Aladdin to BlackRock but also ethical concerns over its use and BlackRock's adaptability to a climate-sensitive era. The factors that differentiate Aladdin have been taken from a KPMG report in 2022.

Private Equity Wires, which is a credible source due to its specialized focus on the private equity industry, reports on acquiring Quellos, which has been considered to point out the strategies used by the firm to improve Quellos's portfolios, while WealthBriefing provides credible, double-checked quantitative data of the growth. An article from Vanity Fair has also been analysed to peek into BlackRock's growing influence over financial markets and economies. In addition, the value at which Quellos was priced is inculcated from Reuters report on the acquisition, while its weakening stance on ESG has also been presented as an observation of its exit from NZAMI by Reuters.

To explain the investment strategies of the past decade, their contribution in numbers to the firm's growth, and potential risks associated with them, a highly reliable and detailed article from the US Securities and Exchange Commission, which has sufficient expertise in this field of economics historically, has been used. Most importantly, the letter of the CEO, Larry Fink, has also been critically evaluated to find out the driving force behind BlackRock's growth and connect the strategies of the past decade to it, while ideas to refurbish the public's economic control have also been given, but in comparatively less detail. Furthermore, a testament to BlackRock's proxy voting power has also been given in detail by presenting a case study from this year's Annual BlackRock Investment Stewardship (BIS) Report.

In addition to this, a detailed article from The American Review has considered to identify the potential gaps and weaknesses in BlackRock's Investment Strategies.

The reason why most of the methodology is qualitative is because although quantitative data has been used to back up the research findings and present BlackRock's growth factors as a result of their strategies is because the qualitative research framework helps address the main aim of the research which is analyze BlackRock's most crucial strategies which helped them scale-up to become a financial powerhouse and as most of the major data present on BlackRock's investment tactics is qualitative in itself.

Moreover, there were also some limitations to the research as one can see, there is no major strategy of BlackRock which played a pivotal role in helping them grow since 2012,instead a few most important collective strategies and ideas have been listed such as passive investing and 'tokenization of assets' which have played a significant role than most other to assist BlackRock in increasing its revenue and AUM. In addition to this, as the company was not listed on the IPO during the first period till 1999-2000, growth of the firm in terms of its AUM at the time has only been considered and compared with the following two periods.

Findings and Discussion:

The main findings of this research have been given below:

(It is important to note that the company's growth from 1988-1999 is not included as back then it was not enlisted as an IPO and hadn't disclosed the market figures which is why data from 1999 and onwards has been collected)

(***x-axis*** *represents stock price in USD while the* ***y-axis*** *represents the time period from late 1999's till today)*

BlackRock's **stock growth in value**:

1988-1999: Undocumented due to no presence on IPO

2000-2012: +966.11%

2012-2025: +480.02%

Although we have no records about its growth in value from 1988-1999, we can still calculate **growth in AUM**:

1988-1999: +6.011% (2.7 billion dollars-165 billion dollars)

2000-2012: +2.198% (165 billion dollars-3.792 trillion dollars)

2012-2025: +205.5% (3.792 trillion dollars-11.584 trillion dollars)

From this we can conclude that the period of the lowest growth in total for BlackRock is the one of the past decades, while the era from 1988 to 2012 has been a winning spree. The first period, till the dawn of the 2000s, can be considered as the period of the highest accelerated growth by value, although the period where BlackRock really managed to establish itself, expand its influence, and set itself apart from rivals was indubitably the one from 2000 to 2012.

This analysis, in the end, tells us that the most significant investment strategies were the ones BlackRock implemented from its founding till 2012. These include:

1. **BlackRock's Aladdin Tech:**

According to the School of Hedge and KPWG, Aladdin was something that played a pivotal role in BlackRock's success because of its reliable nature for investors, helping them make the right decisions and setting itself apart from competitors by always remaining ahead of market trends by always predicting them ahead of time.

2. **Corporate Investment:**

This was one of BlackRock's most tactical moves, which allowed the firm to carry out analysis of not only high-potential businesses like the Quellos Fund of Funds but also failing companies using their Aladdin Tech while also making sure to find out how these businesses and their portfolios would perform under different market conditions. This was followed by investment to acquire these kinds of businesses, improve their already existing systems, and increase transparency while triggering growth in return for high profitability.

On the other side, three gaps of BlackRock's investment strategies have also been listed. The two Major ones are regarding:

1.The firm's growing outreach and control of the majority of passive funds in the market

2.The firm's lending practices.

3.It's stance on its ESG policy.

After this,a hypothesis was conducted and tested using a Monte Carlo simulation on the solution to BlackRock's lending practices t.It is to be considered that variables were kept simple and no external factors like taxes of any other loan-fees was taken seriously into account while 1.05 million different simulated paths were run giving the results mentioned.

Conclusion:

To conclude, this research offers a valuable insight for financial analysts and investors to get a broad and clear idea of what actually have been the major strategies that helped an asset-management firm like BlackRock to transform itself into a market giant even while having to face fierce competition while also getting a good idea of the existing weaknesses in these strategies. This

research basically breaks down BlackRock's timeline of existence into three periods while not only explaining but also carrying out an analysis of the different strategies they used during each period but also mentioning some of the major existing gaps which are a part of their strategies and their outcomes. These mainly include their use of tech systems like Aladdin their investments into companies with growth potential alongside other stable investment strategies into index funds and ETFs, and the private markets, even furthermore carrying out an analysis of their growth during different time periods while pointing out the strategies that helped them to scale up the most by using that data. The research also presents a hypothetical scenario as a possible sustainable solution to the weakness in BlackRock's lending practices while also testing it using the Monte Carlo simulation Future research should focus on presenting alternatives to cover the leftover-weaknesses mentioned within these given strategies or work on improving them in detail while considering government and company policies or maybe a comparative analysis of growth between BlackRock and any other asset-management firm like Vanguard which can help analysts or investors better understand the dynamics related to BlackRock's growth and how it affects competitors.

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To what extent does AI shape productivity and drive economic prosperity?

Kian Makanji

Abstract

This study investigates how artificial intelligence (AI) investment affects labour productivity and economic prosperity across 10 high-income countries from 2014 to 2023. Using OLS regression models with country fixed effects, it analyses the relationship between AI venture capital investment, labour productivity and GDP per capita using several control variables. Despite AI's current lack of statistical significance, which may reflect the J-curve phenomenon, this report suggests that investment in human capital and infrastructure could help unlock AI's long-term growth potential.

Introduction

Artificial intelligence (AI) refers to a machine's ability to perform cognitive functions such as perception, problem-solving, linguistic interaction and creativity (UNESCO, 2022). AI's popularity surged following the release of generative AI tools like 'ChatGPT', and global AI adoption may "reach 378 million users by 2025" (Marr, 2025). Additionally, forecasts predict that global AI markets will grow from "$189 billion in 2023 to $4.8 trillion by 2033" (UNCTAD, 2025).

This rapid expansion suggests that AI may play a fundamental role across all sectors: streamlining lives, boosting productivity and enhancing public services. However, concerns around labour disruptions, inequality and data privacy have sparked debates within academia and policy.

This study explores AI's evolving role in the global economy by using econometric analysis to assess whether increased investment correlates with higher productivity and economic prosperity.

Literature Review

The relationship between AI, productivity and prosperity has become a prominent theme in economic literature. Many studies suggest that AI can enhance labour productivity, leading to higher GDP growth and greater prosperity.

Forecasts are optimistic, with McKinsey estimating that generative AI could "add $2.6 trillion to $4.4 trillion annually to the global economy" (Chui et al., 2023). The OECD also anticipates productivity increases at both firm and national levels in G7 economies, especially within the UK and US (OECD, 2025). The UK government reinforces this by predicting "£146.5 billion GDP increase by 2035" (GOV.UK, 2025).

However, several sources have alluded to the potential drawbacks of AI. The IMF warns that AI adoption benefits only large firms able to afford it. This may enable them to become more productive, profitable and dominant than their competitors, so this contributes to a rise in industrial concentration (Brynjolfsson and Unger, 2023). The Economist adds that productivity gains may disproportionately favour high-skilled workers, potentially exacerbating inequality (Economist, 2025). Additionally, PwC estimates that "326 million jobs globally will be at risk by 2030" (PwC, 2017).

Conversely, the IMF also highlights AI's potential to promote inclusion through low-skill workforce training (Brynjolfsson and Unger, 2023). While the OECD notes how AI can improve accessibility for disabled individuals, further reducing inequality (OECD, 2024).

Another key debate is whether AI augments or automates human roles. MIT Sloan argues that while AI boosts efficiency, human oversight remains essential for productivity gains with specific roles (Dell' et al., 2023).

We should also consider the privacy and ethical concerns as the OECD warns about the risks of AI handling sensitive data, particularly in medical roles. Moreover, personal information may be mishandled or privacy breaches may occur due to faults within the AI training datasets. The OECD recommends policies that promote transparency and continuous monitoring of AI systems to mitigate these risks (OECD, 2024).

Overall, while AI may boost long-term productivity and prosperity, it also poses risks to inequality, labour markets and ethics so well-designed, inclusive policies may be required to maximise AI's benefits and mitigate harm.

Methodology

This study investigates the relationship between AI investment, productivity and economic prosperity. The hypothesis is that greater AI investment enhances productivity through automation, decision-making improvements, and efficiency gains, which boosts overall prosperity.

Panel data was compiled from 10 high-income, innovation-led countries (Australia, Canada, China, France, Germany, Japan, South Korea, Sweden, United Kingdom and United States) from 2014 to 2023. This geographically diverse sample enabled cross-national insights into how AI influences economic outcomes over time.

The independent variable was AI venture capital investment (measured in millions of USD), which serves as a proxy for a country's commitment to AI development, and this was sourced using OECD data (2025). Labour productivity and economic prosperity were the two dependent variables used. Labour productivity was measured using GDP per hour worked (PPP), sourced from the OECD (2024) and the ILO (2025). Economic prosperity was captured through GDP per capita (PPP), obtained from IMF datasets (2025), reflecting the broader living standards and economic well-being of citizens.

To reduce omitted variable bias and improve the robustness of my analysis, my control variables were: mean years of schooling (Our World in Data, 2018), gross fixed capital formation percentage (Worldbank.org, 2015), R&D expenditure percentage (Worldbank.org, n.d), internet users percentage (World Bank Open Data, 2025), government expenditure percentage (IMF, 2022), corporate tax rate percentage (OECD, 2024) and M1 money supply (USD) (Board of Governors of the Federal Reserve System (US), 1959).

Using this data, I constructed multi-variable Ordinary Least Squares (OLS) regression models within Python. I initially visualised the relationships between my variables using scatter plots created by the

Seaborn library. I then ran OLS regressions using the Statsmodels library which also incorporated my control variables. To account for unobserved heterogeneity, such as cultural, political, geographical differences, I introduced country fixed effects. Through creating dummy variables for each country, I allowed for country-specific intercepts within the models. I then replotted my scatter plots including the regression lines using Matplotlib and model performance was evaluated using R-squared values, AI investment coefficients and their statistical significance (p-values).

Finally, I tested alternative model specifications, including models with fewer control variables and ones introducing a one-year lag for AI investment. This aimed to capture the delayed economic effects from AI investment.

Data

Figure 1: Summary Statistics by Variable

Variable	Minimum	Maximum	Mean	Standard Deviation
AI_VC_Investment_Lagged_MillionUSD	8.18	117,347.34	7,428.16	17,835.28
AI_VC_Investment_MillionUSD	8.18	117,347.34	8,197.21	17,942.77
Capital_Formation_pctGDP	16.57	43.38	25.11	6.50
CIT_Rate_pct	19.00	46.10	27.71	5.67
GDP_per_Capita_PPP	13,910.91	74,112.92	52,138.76	13,303.63
Gov_Expenditure_pctGDP	18.51	61.70	40.70	9.72
Internet_Users_Pct	47.90	97.60	87.39	10.21
M1_USD	189,201,292,138.85	244,835,700,000,000.00	12,971,145,586,060.00	41,863,862,043,086.50
Mean_Education_Years	7.44	14.30	12.43	1.72
Productivity_GDP_per_hour_PPP	10.30	83.96	62.92	20.71
RnD_Expenditure_pctGDP	1.70	5.20	2.80	0.84

Figure 2: Summary Statistics by Country and Variable

Variable	Country	Minimum	Maximum	Mean	Standard Deviation
AI_VC_Investment_Lagged_MillionUSD	Australia	17.52	1,979.59	448.44	601.98
AI_VC_Investment_Lagged_MillionUSD	Canada	60.16	4,799.31	1,394.39	1,471.55
AI_VC_Investment_Lagged_MillionUSD	China	116.18	52,863.58	23,613.65	16,126.30
AI_VC_Investment_Lagged_MillionUSD	France	32.08	2,651.42	872.18	994.87
AI_VC_Investment_Lagged_MillionUSD	Germany	85.89	6,038.06	1,631.76	2,047.60
AI_VC_Investment_Lagged_MillionUSD	Japan	50.63	1,842.11	833.74	649.86
AI_VC_Investment_Lagged_MillionUSD	South Korea	15.63	4,311.03	1,194.43	1,604.32
AI_VC_Investment_Lagged_MillionUSD	Sweden	8.18	5,871.39	1,028.78	1,842.34
AI_VC_Investment_Lagged_MillionUSD	United Kingdom	84.43	8,466.55	2,802.29	3,082.26
AI_VC_Investment_Lagged_MillionUSD	United States	5,589.28	117,347.34	40,463.95	32,626.72
AI_VC_Investment_MillionUSD	Australia	44.76	1,979.59	521.23	687.93
AI_VC_Investment_MillionUSD	Canada	146.35	4,799.31	1,595.22	1,804.75
AI_VC_Investment_MillionUSD	China	2,843.04	52,863.58	25,613.61	14,049.74
AI_VC_Investment_MillionUSD	France	45.44	2,651.42	1,071.35	1,007.79
AI_VC_Investment_MillionUSD	Germany	85.89	6,038.06	1,923.67	2,014.22
AI_VC_Investment_MillionUSD	Japan	98.60	1,842.11	1,005.82	647.29
AI_VC_Investment_MillionUSD	South Korea	38.27	4,311.03	1,424.10	1,381.04
AI_VC_Investment_MillionUSD	Sweden	8.18	5,871.39	1,229.79	1,828.85
AI_VC_Investment_MillionUSD	United Kingdom	201.89	8,466.55	3,169.99	2,937.95
AI_VC_Investment_MillionUSD	United States	15,984.99	117,347.34	46,417.33	30,943.74
Capital_Formation_pctGDP	Australia	22.84	26.88	24.24	1.47
Capital_Formation_pctGDP	Canada	22.58	24.39	23.17	0.62
Capital_Formation_pctGDP	China	40.45	43.38	41.70	0.81
Capital_Formation_pctGDP	France	20.96	23.65	22.08	1.11
Capital_Formation_pctGDP	Germany	19.76	21.71	20.75	0.75
Capital_Formation_pctGDP	Japan	24.76	25.26	25.39	0.48
Capital_Formation_pctGDP	South Korea	28.96	32.17	30.69	1.23
Capital_Formation_pctGDP	Sweden	22.69	25.55	24.29	0.88
Capital_Formation_pctGDP	United Kingdom	20.42	21.59	21.10	0.39
Capital_Formation_pctGDP	United States	16.57	18.25	17.70	0.48

Variable	Country	Minimum	Maximum	Mean	Standard Deviation
CIT_Rate_pct	Australia	30.00	30.00	30.00	-
CIT_Rate_pct	Canada	25.95	26.69	26.39	0.30
CIT_Rate_pct	China	25.00	25.00	25.00	-
CIT_Rate_pct	France	25.83	46.10	35.48	7.56
CIT_Rate_pct	Germany	29.71	30.06	29.88	0.10
CIT_Rate_pct	Japan	29.74	36.99	30.72	2.30
CIT_Rate_pct	South Korea	24.20	27.50	25.74	1.66
CIT_Rate_pct	Sweden	20.60	22.00	21.46	0.64
CIT_Rate_pct	United Kingdom	19.00	25.00	20.00	1.89
CIT_Rate_pct	United States	25.75	39.08	32.38	6.94
GDP_per_Capita_PPP	Australia	56,681.07	61,533.17	58,721.66	1,796.44
GDP_per_Capita_PPP	Canada	53,377.74	57,606.96	55,813.07	1,268.17
GDP_per_Capita_PPP	China	13,910.91	22,676.97	18,187.56	2,935.23
GDP_per_Capita_PPP	France	50,756.26	55,601.96	53,481.64	1,403.87
GDP_per_Capita_PPP	Germany	59,638.82	63,395.80	61,914.56	1,406.40
GDP_per_Capita_PPP	Japan	42,952.69	46,314.96	44,512.46	985.96
GDP_per_Capita_PPP	South Korea	43,964.23	54,103.27	49,060.50	3,428.90
GDP_per_Capita_PPP	Sweden	57,140.91	63,402.08	60,655.60	2,024.43
GDP_per_Capita_PPP	United Kingdom	48,616.31	54,960.32	52,789.83	1,914.91
GDP_per_Capita_PPP	United States	63,144.98	74,112.92	68,221.68	3,803.02
Gov_Expenditure_pctGDP	Australia	36.74	44.37	38.45	2.57
Gov_Expenditure_pctGDP	Canada	38.37	52.36	42.22	4.01
Gov_Expenditure_pctGDP	China	28.89	35.40	32.76	1.72
Gov_Expenditure_pctGDP	France	53.34	61.70	57.93	1.79
Gov_Expenditure_pctGDP	Germany	44.50	51.13	46.78	2.73
Gov_Expenditure_pctGDP	Japan	36.69	44.52	39.36	2.86
Gov_Expenditure_pctGDP	South Korea	18.51	26.68	21.29	2.93
Gov_Expenditure_pctGDP	Sweden	47.49	51.24	48.84	1.13
Gov_Expenditure_pctGDP	United Kingdom	38.73	49.96	42.21	3.71
Gov_Expenditure_pctGDP	United States	35.01	44.57	37.18	3.43

Variable	Country	Minimum	Maximum	Mean	Standard Deviation
Internet_Users_Pct	Australia	84.00	97.10	91.10	5.39
Internet_Users_Pct	Canada	87.10	94.60	92.17	2.29
Internet_Users_Pct	China	47.90	77.50	62.53	11.03
Internet_Users_Pct	France	78.00	86.80	82.98	2.96
Internet_Users_Pct	Germany	84.20	92.50	88.28	2.96
Internet_Users_Pct	Japan	82.90	93.20	89.15	3.37
Internet_Users_Pct	South Korea	87.60	97.60	94.63	3.44
Internet_Users_Pct	Sweden	88.20	95.70	92.94	2.36
Internet_Users_Pct	United Kingdom	90.40	96.30	93.56	2.37
Internet_Users_Pct	United States	73.00	93.10	86.52	7.08
M1_USD	Australia	383,420,000,000.00	1,043,365,333,333.33	687,890,860,606.06	257,720,696,113.32
M1_USD	Canada	525,977,100,000.00	1,151,969,040,000.00	809,774,000,800.00	236,110,907,016.14
M1_USD	China	5,360,972,854,819.47	9,766,718,506,998.45	7,850,982,525,369.53	1,602,299,966,477.12
M1_USD	France	645,911,715,794.88	2,234,400,000,000.00	1,323,004,349,308.92	497,818,443,957.91
M1_USD	Germany	1,915,200,000,000.00	3,420,000,000,000.00	2,591,220,000,000.00	521,668,174,225.72
M1_USD	Japan	3,871,113,070,000.00	7,029,023,400,000.00	5,323,242,333,500.00	1,129,823,158,000.00
M1_USD	South Korea	389,056,920,000.00	999,119,068,000.00	673,335,647,600.00	197,607,793,375.31
M1_USD	Sweden	189,201,292,188.85	462,000,000,000.00	313,859,072,435.52	92,948,035,194.41
M1_USD	United Kingdom	1,752,385,580,000.00	3,215,511,090,000.00	2,447,427,051,000.00	511,238,115,992.27
M1_USD	United States	33,776,800,000,000.00	244,835,700,000,000.00	107,602,860,000,000.00	90,214,392,756,295.40
Mean_Education_Years	Australia	12.17	12.87	12.53	0.26
Mean_Education_Years	Canada	13.66	13.87	13.79	0.08
Mean_Education_Years	China	7.44	8.04	7.81	0.22
Mean_Education_Years	France	11.23	11.77	11.54	0.20
Mean_Education_Years	Germany	14.04	14.30	14.19	0.10
Mean_Education_Years	Japan	12.59	12.68	12.64	0.04
Mean_Education_Years	South Korea	12.02	12.72	12.44	0.26
Mean_Education_Years	Sweden	12.29	12.74	12.56	0.17
Mean_Education_Years	United Kingdom	12.89	13.49	13.28	0.22
Mean_Education_Years	United States	13.22	13.91	13.54	0.25

Variable	Country	Minimum	Maximum	Mean	Standard Deviation
Productivity_GDP_per_hour_PPP	Australia	65.98	70.75	67.96	1.43
Productivity_GDP_per_hour_PPP	Canada	56.94	62.91	58.83	1.84
Productivity_GDP_per_hour_PPP	China	10.30	18.02	14.26	2.70
Productivity_GDP_per_hour_PPP	France	81.10	83.96	82.59	1.09
Productivity_GDP_per_hour_PPP	Germany	77.94	83.79	81.36	2.12
Productivity_GDP_per_hour_PPP	Japan	47.38	53.02	49.25	1.12
Productivity_GDP_per_hour_PPP	South Korea	40.21	50.96	45.94	4.01
Productivity_GDP_per_hour_PPP	Sweden	75.94	82.82	79.23	2.17
Productivity_GDP_per_hour_PPP	United Kingdom	68.66	72.62	70.94	1.36
Productivity_GDP_per_hour_PPP	United States	74.62	83.62	78.89	3.56
RnD_Expenditure_pctGDP	Australia	1.80	1.90	1.85	0.05
RnD_Expenditure_pctGDP	Canada	1.70	1.90	1.75	0.08
RnD_Expenditure_pctGDP	China	1.90	2.60	2.16	0.22
RnD_Expenditure_pctGDP	France	2.20	2.30	2.22	0.04
RnD_Expenditure_pctGDP	Germany	2.90	3.20	3.04	0.11
RnD_Expenditure_pctGDP	Japan	3.10	3.40	3.27	0.11
RnD_Expenditure_pctGDP	South Korea	4.00	5.20	4.56	0.46
RnD_Expenditure_pctGDP	Sweden	3.10	3.50	3.33	0.13
RnD_Expenditure_pctGDP	United Kingdom	2.30	2.90	2.62	0.29
RnD_Expenditure_pctGDP	United States	2.70	3.60	3.14	0.35

Results

Full Model with Lagged AI Investment Results

This model uses lagged AI investment alongside all seven control variables to capture delayed effects and isolate AI's specific impact on productivity and prosperity.

For Model 1 (Labour productivity), the regression results reveal an overall strong fit with an adjusted R-squared value of 0.991. This indicates that the model explains 99.1% of the variation in productivity across countries and years. However, the coefficient for lagged AI investment is positive ($2.616e^{-5}$) but statistically insignificant ($p=0.430$), indicating that a robust link may not be evident once controls are included.

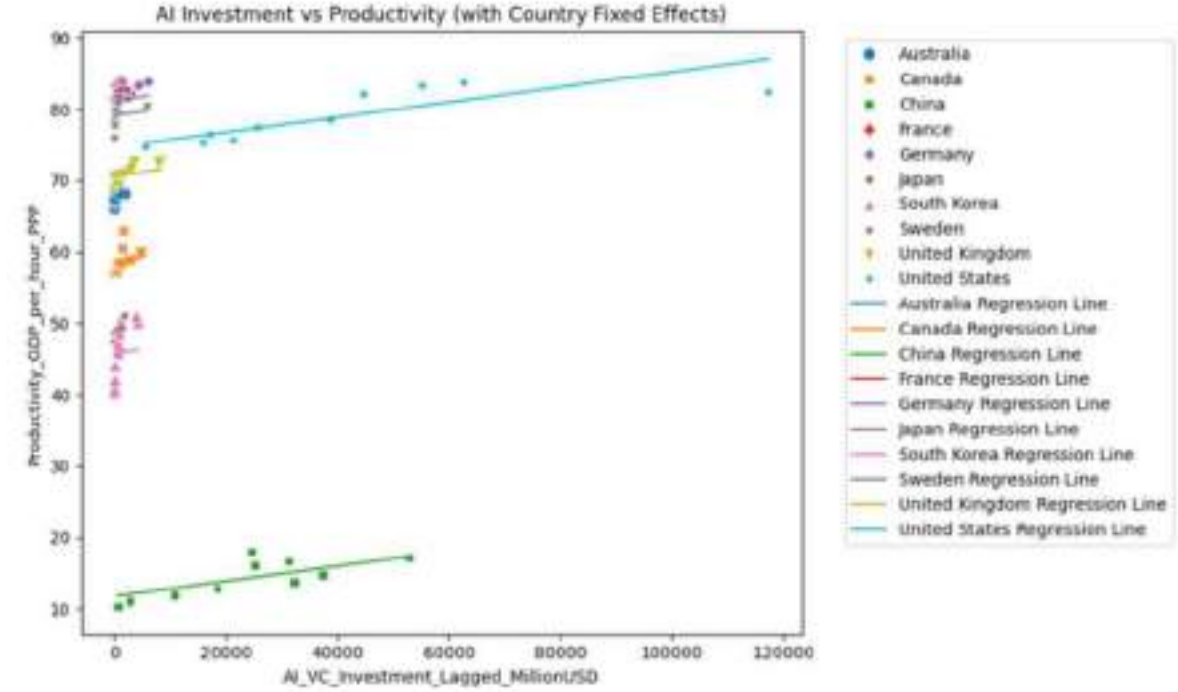
Similarly, the results from Model 2 (GDP per capita) also indicate a strong model fit, with an adjusted R-squared value of 0.982. Again, the coefficient is positive (0.0359) but statistically insignificant ($p=0.232$). This further reinforces that while AI venture capital investments are positively correlated with productivity and prosperity, its impact is not statistically significant when controlling for other economic factors and fixed effects.

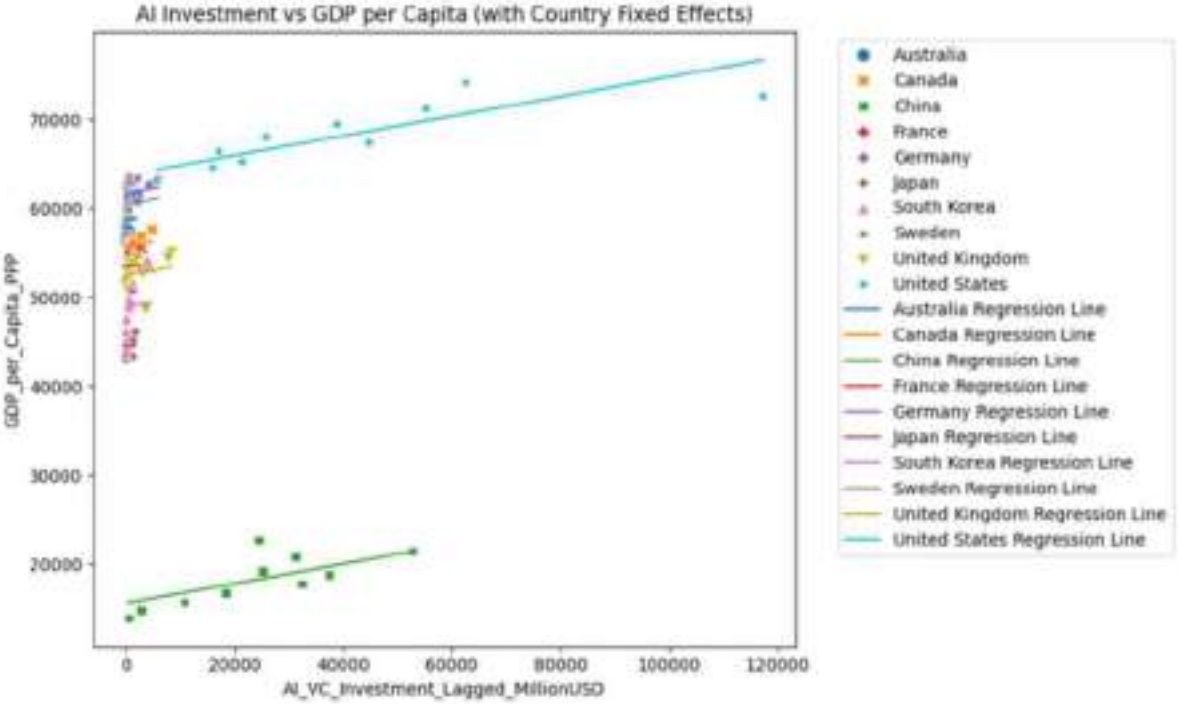
Figure 3: Full Model Results Tables

```
=== Model 1: AI Investment vs Productivity (with Country Fixed Effects) ===
                            OLS Regression Results
==============================================================================
Dep. Variable:     Productivity_GDP_per_hour_PPP   R-squared:                       0.992
Model:                                    OLS   Adj. R-squared:                  0.991
Method:                         Least Squares   F-statistic:                     958.6
Date:                        Thu, 07 Aug 2025   Prob (F-statistic):           1.44e-86
Time:                                16:29:50   Log-Likelihood:                -204.75
No. Observations:                         100   AIC:                             433.5
Df Residuals:                              88   BIC:                             464.8
Df Model:                                  11
Covariance Type:                    nonrobust
==============================================================================
                                 coef    std err          t      P>|t|      [0.025      0.975]
------------------------------------------------------------------------------
const                          2.6841      8.332      0.083      0.003      2.024      3.344
AI_VC_Investment_Lagged_MillionUSD  3.616e-05   3.3e-05      0.792      0.431   -3.95e-05   9.18e-05
Mean_Education_Years           5.8542      0.421     13.900      0.003      5.017      6.691
Capital_Formation_pctGDP      -0.9927      0.044    -22.315      0.003     -1.081     -0.904
RnD_Expenditure_pctGDP        -3.0234      0.439     -6.886      0.003     -3.896     -2.151
Internet_Users_Pct             0.0305      0.050      0.537      0.592     -0.083      0.143
Gov_Expenditure_pctGDP         0.4334      0.077      5.609      0.003      0.279      0.586
CIT_Rate_pct                   0.0415      0.068      0.610      0.544     -0.094      0.177
M1_USD                      1.811e-14   1.29e-14      1.410      0.162   -7.42e-15   4.36e-14
Canada                        -28.6125      1.136    -26.922      0.003     -30.821     -26.404
China                          -3.5439      1.023     -3.463      0.001      -5.577      -1.510
France                         13.7561      2.096      5.635      0.003      9.611      18.901
Germany                         1.2142      1.135      1.070      0.288      -1.042      3.471
Japan                         -13.3914      0.761    -18.063      0.003     -14.865     -11.918
South Korea                     1.8584      1.131      1.681      0.096      -0.337      4.038
Sweden                         12.3784      1.344      9.206      0.003      9.700      15.041
United Kingdom                 -2.5464      1.008     -2.527      0.013      -4.549      -0.544
United States                   0.9272      1.398      0.667      0.506      -1.855      3.689
==============================================================================
Omnibus:                        5.188   Durbin-Watson:                   1.078
Prob(Omnibus):                  0.075   Jarque-Bera (JB):                7.031
Skew:                          -0.133   Prob(JB):                       0.0297
Kurtosis:                       4.271   Cond. No.                     5.64e+15
==============================================================================

Notes:
[1] Standard Errors assume that the covariance matrix of the errors is correctly specified.
[2] The condition number is large, 5.64e+15. This might indicate that there are
strong multicollinearity or other numerical problems.
```

```
=== Model 2: AI Investment vs GDP per Capita (with Country Fixed Effects) ===
                            OLS Regression Results
==============================================================================
Dep. Variable:     GDP_per_Capita_PPP   R-squared:                       0.984
Model:                            OLS   Adj. R-squared:                  0.982
Method:                 Least Squares   F-statistic:                     482.5
Date:                Thu, 07 Aug 2025   Prob (F-statistic):           1.31e-73
Time:                        16:29:50   Log-Likelihood:                -885.19
No. Observations:                 100   AIC:                             1794.
Df Residuals:                      88   BIC:                             1826.
Df Model:                          11
Covariance Type:            nonrobust
==============================================================================
                                 coef    std err          t      P>|t|      [0.025      0.975]
------------------------------------------------------------------------------
const                       1027.7543    294.462      3.490      0.001     432.636    1622.872
AI_VC_Investment_Lagged_MillionUSD     0.0359      0.030      1.204      0.232      -0.023      0.095
Mean_Education_Years        5046.6101    379.827     13.287      0.000    4291.783    5801.437
Capital_Formation_pctGDP    -485.6554     42.119    -12.100      0.000    -565.181    -405.727
RnD_Expenditure_pctGDP      -3052.5517    395.965     -7.709      0.000   -3839.449   -2265.655
Internet_Users_Pct            137.1014     51.930      2.642      0.010      33.961     240.242
Gov_Expenditure_pctGDP        -52.9088     49.614     -0.739      0.450    -151.152      85.334
CIT_Rate_pct                   38.3706     61.416      0.299      0.766    -103.683     180.421
M1_USD                      1.605e-11   1.15e-11      1.386      0.169   -6.97e-12    3.91e-11
Canada                      -9168.2309    997.846     -9.188      0.000   -1.12e+04   -7185.222
China                       -3195.1396    922.823     -3.462      0.001   -5029.157   -1361.123
France                       2636.4019   1891.437      1.393      0.165   -1102.359    6375.363
Germany                     -1565.7674   1023.939     -1.471      0.145   -3540.571     529.036
Japan                       -8668.4701    668.617    -12.995      0.000    -1e+04   -7359.935
South Korea                  2091.5972    892.583      2.107      0.038     319.047    4064.147
Sweden                       7720.4641   1211.048      6.370      0.000    5311.733    1.01e+04
United Kingdom              -7941.3287    908.918     -8.737      0.000   -9747.607   -6135.050
United States                3446.0400   1253.421      2.749      0.007     955.129    5936.951
==============================================================================
Omnibus:                        6.212   Durbin-Watson:                   1.312
Prob(Omnibus):                  0.045   Jarque-Bera (JB):               10.078
Skew:                          -0.462   Prob(JB):                      0.00648
Kurtosis:                       4.547   Cond. No.                     5.64e+15
==============================================================================

Notes:
[1] Standard Errors assume that the covariance matrix of the errors is correctly specified.
[2] The condition number is large, 5.64e+15. This might indicate that there are
strong multicollinearity or other numerical problems.
```

Figure 4: Full Model Scatter Diagrams





Reduced Model without Lagged AI Investment Results

This simplified model included fewer control variables to better assess the direct relationship between AI's influence on productivity and prosperity.

For Model 1 (Labour productivity), the regression results demonstrated a very strong model fit, with an adjusted R-squared value of 0.991, showing that model accounts for 99.1% of the variation in productivity across countries and years. AI investment showed a positive, statistically significant coefficient ($6.874e^{-5}$, p=0.023), indicating a strong link between AI investment and productivity growth.

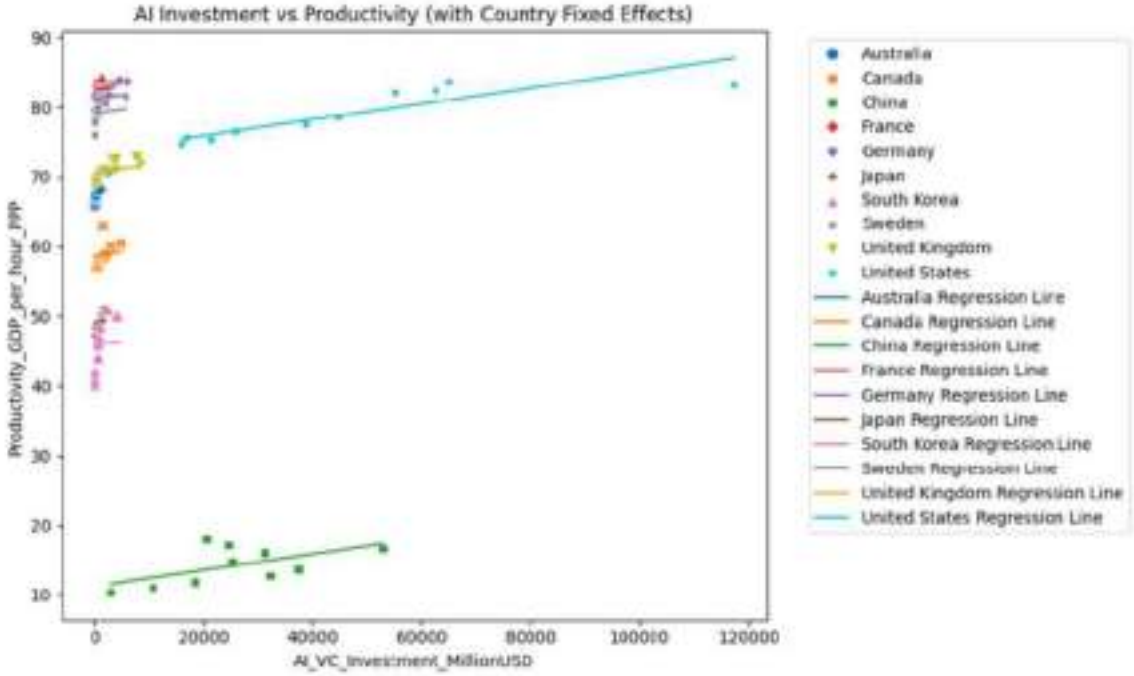
Similarly, the results in Model 2 (GDP per capita) revealed a significant positive correlation between AI investment and GDP per capita (adjusted R^2=0.980). There is also a highly significant positive coefficient for AI investment (0.0635, p=0.031), suggesting that AI investment may be a meaningful predictor of both productivity and prosperity when fewer controls are included.

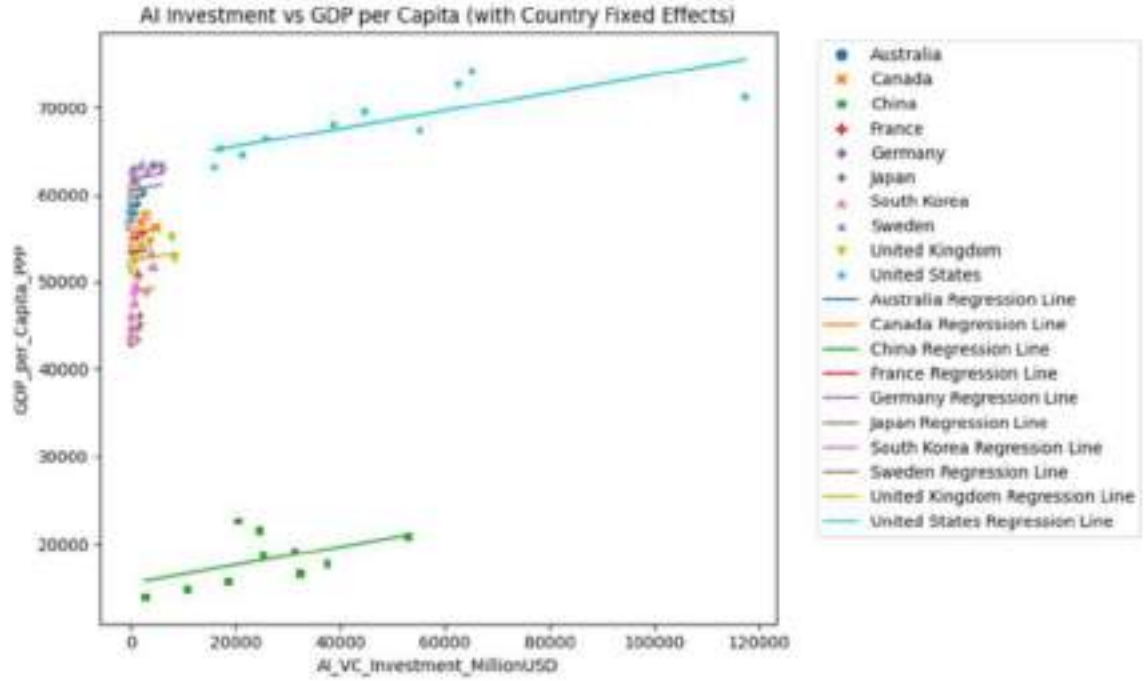
Figure 5: Reduced Model Results Tables

```
=== Model 1: AI Investment vs Productivity (with Country Fixed Effects) ===
                            OLS Regression Results
==============================================================================
Dep. Variable:     Productivity_GDP_per_hour_PPP   R-squared:                       0.992
Model:                                       OLS   Adj. R-squared:                  0.991
Method:                            Least Squares   F-statistic:                     1145.
Date:                           Thu, 07 Aug 2025   Prob (F-statistic):           1.88e-89
Time:                                   16:33:09   Log-Likelihood:                -201.21
No. Observations:                            100   AIC:                             424.4
Df Residuals:                                89   BIC:                             453.1
Df Model:                                    10
Covariance Type:                       nonrobust
==============================================================================
                                 coef    std err          t      P>|t|      [0.025      0.975]
------------------------------------------------------------------------------
const                         -6.8311      0.415    -16.459      0.000      -7.656      -6.006
AI_VC_Investment_BillionUSD  6.874e-05   2.97e-05      2.311      0.023    9.65e-06       0.000
Mean_Education_Years          6.0988      0.172     35.391      0.000       5.756       6.441
RnD_Expenditure_pctGDP       -3.4998      0.381     -9.174      0.000      -4.474      -3.934
CIT_Rate_pct                  0.1255      0.067      1.871      0.065      -0.008       0.259
M1_USD                     2.313e-14   1.15e-14      2.007      0.048    2.31e-16    4.6e-14
Canada                       -15.4169      1.025    -15.036      0.000      -17.454      -13.380
China                        -23.1453      0.920    -25.160      0.000      -24.973      -21.317
France                        22.7636      0.901     25.266      0.000       20.973       24.554
Germany                        9.2302      0.666     13.862      0.000        7.907       10.553
Japan                        -12.7592      0.608    -20.979      0.000      -13.968      -11.550
South Korea                   -9.1439      0.627    -14.592      0.000      -10.389       -7.899
Sweden                        19.2436      0.731     26.323      0.000       17.791       20.696
United Kingdom                 3.9867      0.979      4.071      0.000        2.041       5.933
United States                  5.1585      1.241      4.150      0.000        2.688       7.628
==============================================================================
Omnibus:                        3.637   Durbin-Watson:                   0.896
Prob(Omnibus):                  0.162   Jarque-Bera (JB):                4.062
Skew:                          -0.464   Prob(JB):                        0.130
Kurtosis:                       3.981   Cond. No.                     4.83e+15
==============================================================================

Notes:
[1] Standard Errors assume that the covariance matrix of the errors is correctly specified.
[2] The condition number is large, 4.83e+15. This might indicate that there are
strong multicollinearity or other numerical problems.
```

```
=== Model 2: AI Investment vs GDP per Capita (with Country Fixed Effects) ===
                            OLS Regression Results
==============================================================================
Dep. Variable:     GDP_per_Capita_PPP   R-squared:                       0.982
Model:                            OLS   Adj. R-squared:                  0.980
Method:                 Least Squares   F-statistic:                     499.8
Date:                Thu, 07 Aug 2025   Prob (F-statistic):          2.72e-73
Time:                        16:33:08   Log-Likelihood:                -889.58
No. Observations:                 100   AIC:                             1801.
Df Residuals:                      89   BIC:                             1830.
Df Model:                          10
Covariance Type:            nonrobust
==============================================================================================
                                 coef    std err          t      P>|t|      [0.025      0.975]
----------------------------------------------------------------------------------------------
const                      -3780.4045    405.163     -9.331      0.000   -4585.416   -2975.393
AI_VC_Investment_MillionUSD     0.0630      0.029      2.187      0.031       0.006       0.121
Mean_Education_Years         5339.3183    168.222     31.740      0.000    5005.061    5673.572
RnD_Expenditure_pctGDP      -3703.8433    381.237     -9.715      0.000   -4461.353   -2946.333
CIT_Rate_pct                   43.4501     65.440      0.664      0.508     -86.577     173.478
Hi_USD                      1.764e-11   1.12e-11      1.568      0.120   -4.71e-12    4e-11
Canada                     -8788.1048   1000.916     -8.780      0.000   -1.08e+04   -6799.307
China                      -1.413e+04    898.037    -15.732      0.000   -1.59e+04   -1.23e+04
France                      2285.4764    879.498      2.599      0.011     537.932    4033.021
Germany                      -44.6126    649.990     -0.069      0.945   -1336.128    1246.903
Japan                      -8420.2048    593.827    -14.180      0.000   -9600.127   -7240.283
South Korea                 2438.4200    611.715      3.986      0.000    1222.955    3653.885
Sweden                      8894.4811    713.641     12.464      0.000    7476.491    1.03e+04
United Kingdom             -5497.5287    956.017     -5.750      0.000   -7397.111   -3597.944
United States               5291.9980   1213.493      4.287      0.000    2790.813    7613.183
==============================================================================
Omnibus:                        4.470   Durbin-Watson:                   1.241
Prob(Omnibus):                  0.107   Jarque-Bera (JB):                5.804
Skew:                           0.046   Prob(JB):                       0.0549
Kurtosis:                       4.177   Cond. No.                     4.83e+15
==============================================================================

Notes:
[1] Standard Errors assume that the covariance matrix of the errors is correctly specified.
[2] The condition number is large, 4.83e+15. This might indicate that there are
strong multicollinearity or other numerical problems.
```

Figure 6: Reduced Model Scatter Diagrams





Discussion

My OLS regression results demonstrate that AI investment was positive but insignificant within the full model. However, the reduced model highlighted that AI investment became significant, suggesting a more direct and robust link with economic performance when fewer control variables were included. The lack of significance in the full model may reflect the productivity J-curve effect (Brynjolfsson, Rock and Syverson, 2021). This may be due to initial AI investments taking time to integrate into workflows, thus delaying productivity gains.

A key limitation of this study is the small sample size due to the limited AI investment data available. Therefore, incorporating broader measures of AI adoption or longer time series data may better capture the delayed productivity effects common within technological diffusion.

The consistently positive AI investment coefficient across all models, further reinforces the J-curve theory and that we are within the transitionary phase, as the impact will be non-linear or delayed (OECD, 2025). This also aligns with the view that significant macroeconomic benefits from AI require time, reskilling and organisational adaptation (Chui et al., 2023). Consequently, policymakers should anticipate the short-term disruptions that lie ahead and prioritise further investment in infrastructure and human capital to progress up the J-curve.

Conclusion

In conclusion, this research project has enhanced my understanding of the nuanced relationship between AI investment, productivity, and economic prosperity. The results indicate that while AI investment is positively correlated with labour productivity and GDP per capita, its statistical insignificance in the full model aligns with the productivity J-curve hypothesis. This suggests that the transformative economic effects of AI are still emerging, and the benefits of investment may only materialize over time as organisations adapt and integrate these technologies.

The findings highlight the importance of strategic investment in human capital, digital infrastructure, and reskilling programs. AI adoption alone is unlikely to generate maximum productivity gains; complementary efforts in workforce development and organisational change are essential to navigate the transitional period effectively. Moreover, without these measures, short-term gains may disproportionately favour large firms or high-skilled workers, potentially exacerbating inequality.

Looking forward, AI raises important considerations about privacy, ethics, and societal impacts. As AI systems increasingly process sensitive personal and business data, risks of privacy breaches and misuse of information intensify. Ensuring transparency, robust data governance, and continuous monitoring of AI systems will be critical to safeguarding public trust. Additionally, AI's automation of complex tasks may redefine the nature of work, necessitating broader educational reforms and adaptive skill development to prepare the workforce for the future economy.

Emerging AI technologies—such as autonomous systems, generative AI, and AI-driven decision support—could redefine work processes and accelerate innovation across sectors including healthcare, finance, logistics, and creative industries. However, these advancements require proactive management of societal impacts, including workforce displacement, ethical dilemmas, and privacy concerns. Countries and firms that invest strategically in human capital, AI literacy, and regulatory frameworks will be best positioned to harness AI's full potential while mitigating risks, ultimately shaping an economy that is more productive, equitable, and resilient in the face of technological disruption.

To fully unlock AI's transformative potential as a catalyst for sustainable and inclusive growth, targeted investment on reskilling the workforce and investing in infrastructure are essential. Therefore, by proactively managing this technological shift, we can harness AI's full capabilities of strengthening economies and promoting greater equity, turning disruption into an opportunity for all.

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Kian Makanji is an exceptional student, combining intellectual curiosity with academic excellence across Economics, Maths, Further Maths, and Physics. Kian's creativity, problem-solving ability, and collaborative nature ensure he thrives in challenging academic environments by demonstrating precision, insight, and technical mastery. He is academically gifted, intellectually curious, humble, and intrinsically motivated. Kian is a kind, mature, reflective and collaborative young person whose academic achievements are matched by his personal qualities.

LITTLE NEST, A STRATEGIC LAUNCH INTO THE MODERN BABYWEAR MARKET

Anca-Maria Onita

INTRODUCTION

Today, creating a baby and children's clothing brand involves more than simply designing adorable outfits, it also entails attending to the actual demands of contemporary parents. Little Nest is founded on the idea that children's clothing should provide more than just design, it should also offer comfort, safety, and thoughtful options. For infants and toddlers ages 0 to 4, our brand sells clothing produced from certified organic, hypoallergenic, UV protective, and sustainable fabrics. This essay explores the business strategy behind Little Nest, focusing on the 4Ps of marketing: product, price, place and promotion. It includes market analysis, consumer behaviour analysis, and real-world data, along with a SWOT analysis to assess how this brand can enter and grow within the babywear market.

OUR PRODUCTS AND WHY THEY MATTER

Our product line includes essentials such as onesies, bodysuits, hats, sleepwear, and seasonal outerwear, all designed to be worn comfortably and washed repeatedly without losing quality. With features like fold-over mittens, flat seams, and temperature regulating fabric, every item of clothing is also designed with usefulness in mind, providing parents with simplicity without compromising comfort or style.

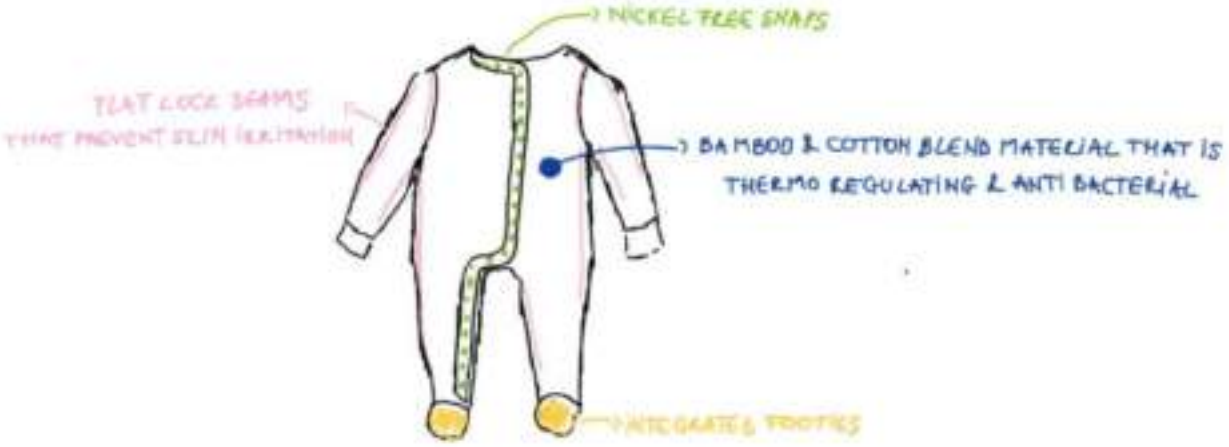
Every piece in the Little Nest line is crafted from carefully selected fabrics, including bamboo and organic cotton, which are renowned for their natural softness, breathability, and skin friendly qualities. These textiles are ideal for infants with sensitive or allergy prone skin, as they avoid harsh dyes, synthetic fibres, and chemical treatments. Dr. Adarsh Vijay Mudgil, a board certified dermatologist, highlights in his book *"The Skincare Bible"* (2020) that organic cotton is an excellent fabric choice for babies because it is grown without synthetic pesticides and harsh chemicals, thereby reducing the risk of irritation and allergic reactions.[1] Our dedication to safety goes beyond just the materials we use, our apparel is UV-protective, which helps protect sensitive skin from damaging sun exposure, particularly in warmer climates.

[1] Mudgil, Adarsh Vijay. The Skincare Bible. London: Pavilion Books, 2020.

Little Nest is more than simply a clothing company, it's an answer to the increasing demand from consumers for eco-friendliness, transparency, and thoughtful design. According to Fiona McDonald, a leading analyst in the retail sector, the UK childrenswear market began recovering in 2022, reaching a value of £6.8 billion, largely due to the full return to schools without pandemic related restrictions.[2] In such a growing market our brand addresses a rising need: parents who want safe, clean, and stylish options for their children. Our products offer them exactly that: comfort, trust, and quality they can feel.

We specifically cater to a modern demographic: parents aged 25 to 40, many of whom are educated, working professionals, and first time parents. This group engages in parenting communities, is quite active on the internet, and is thoughtful about the decisions they make for their kids. Aesthetics, sustainability, environment and health are important to them, and Little Nest reflects these values in every aspect of design and service.

LITTLE NEST DESIGN AND FABRIC CONCEPTS



[2] McDonald, Fiona. "UK Childrenswear Market Report 2023." Mintel, 2023. Accessed July 30, 2025. https://store.mintel.com/report/uk-childrenswear-market-report-2023

PRICING WITH PURPOSE

With niche companies like Frugi, Mini Rodini, and Little Green Radicals setting the standard for premium, eco-friendly clothing priced between £12 and £22 per piece, the market for organic and ethically made babywear is gradually expanding. In order to reflect the true value of certified organic textiles, safe dyes, and ethical labour practices, our brand prices most products between £10 and £20. This strategy is designed to ensure affordability for middle class families who prioritise ethical consumption, while maintaining the quality and style they expect from premium products.

Studies show a consumer willingness to pay a premium price for ethically produced apparel. For example, Ellis, McCracken & Skuza (2012) reported that consumers were prepared to pay up to 25% more for organic cotton garments.[3] More recent research confirms similar trends, with over 28% of consumers indicating a willingness to pay up to 15% more for naturally coloured cotton apparel (2024).[4] These findings validate our pricing strategy: with an average production cost of approximately £5.50 per onesie, including organic materials, ethical labor, and eco-friendly packaging, our £16 retail price supports a healthy gross profit margin of around 65%. This margin enables sustainable marketing, continuous product development, and a high quality customer experience aligned with our brand values.

FINANCIAL PLANNING 3 YEARS TIME

The purpose of the financial planning is to reveal the way in which the business will develop during a period of 3 years and give the investor an overview of potential further developments (example: possible increase in the number of shops, development of new products etc.).

All the data is collected via market research (example: collection of offers from suppliers, collection of data via online customer surveys, rent offers from the pilot stores locations, data collected from competitors etc.).

The scenario is based on a conservative approach, by which costs are estimated at a maximum level and prices at a minimum level.

Based on the level of profit achieved, the preliminary decision would be to further develop the line of products which can be tested on a segment of customers who are already familiar with the brand and quality of the products.

It is envisaged that the level of costs and revenue achieved in year 3 could represent a min/max level that could be achieved by the business with regards to costs and revenue.

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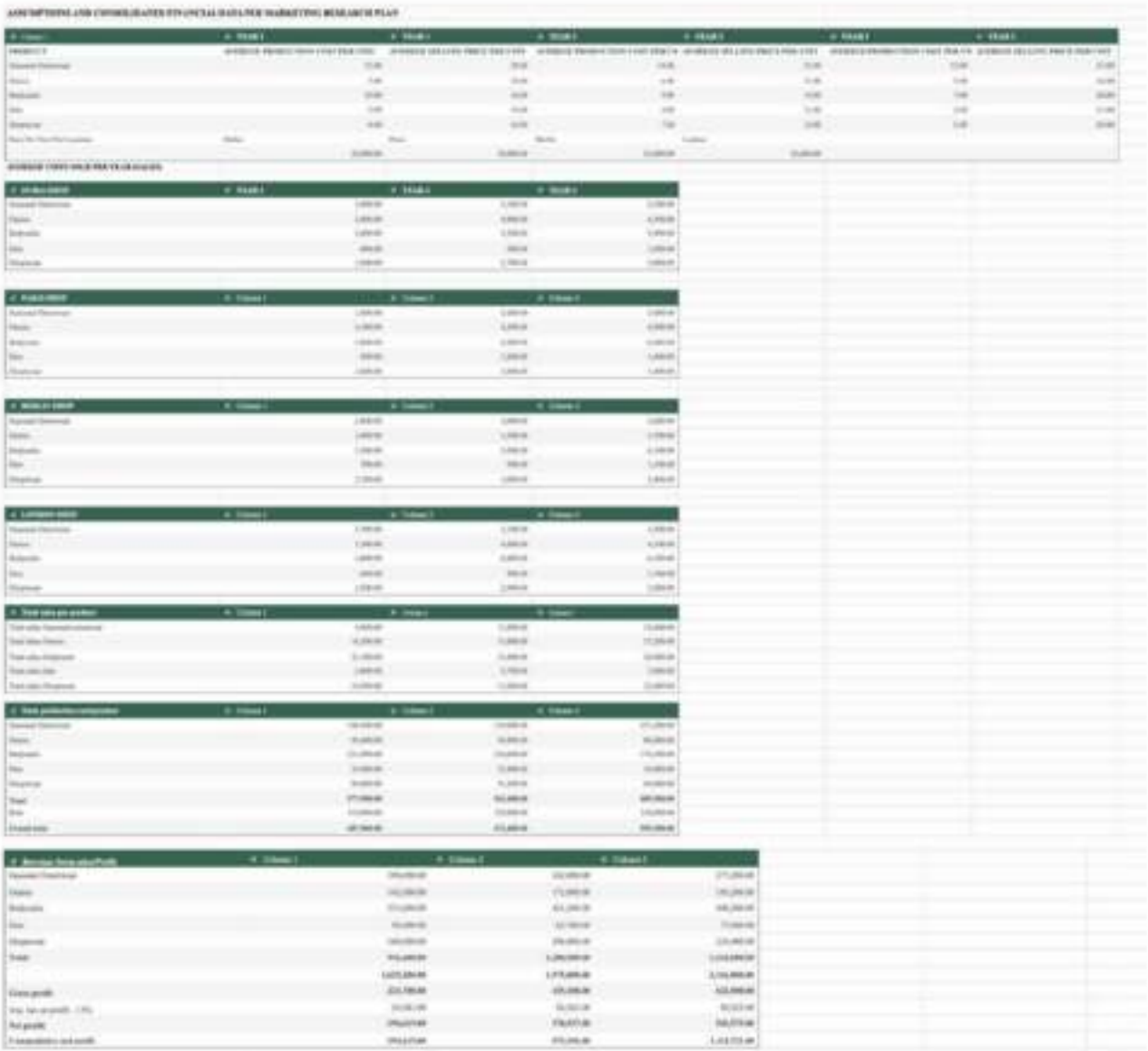
[3] Ellis, Nicole, Vicki McCracken, and Natalia Skuza. "Consumer Preferences for Organic Cotton Clothing: Willingness to Pay and Perceived Quality." Journal of Fashion Marketing and Management 16, no. 3 (2012). Accessed July 31, 2025. https://www.emerald.com/insight/content/doi/10.1108/13612021211246053/full/html

[4] Dishoja, A., N. Bharti, and A. Malik. "Consumers Willing to Pay More for Naturally Colored Cotton Clothing." World Review of Entrepreneurship, Management and Sustainable Development, 2024. Accessed August 1, 2025. Díaz-Méndez, M. and Sánchez-Fernández, R., The Influence of Fashion Retailers on Customer Psychology Using Visual Merchandising and Store Layout to Improve Shopping Decision, Journal of Theoretical and Applied Electronic Commerce Research, MDPI, 2023.



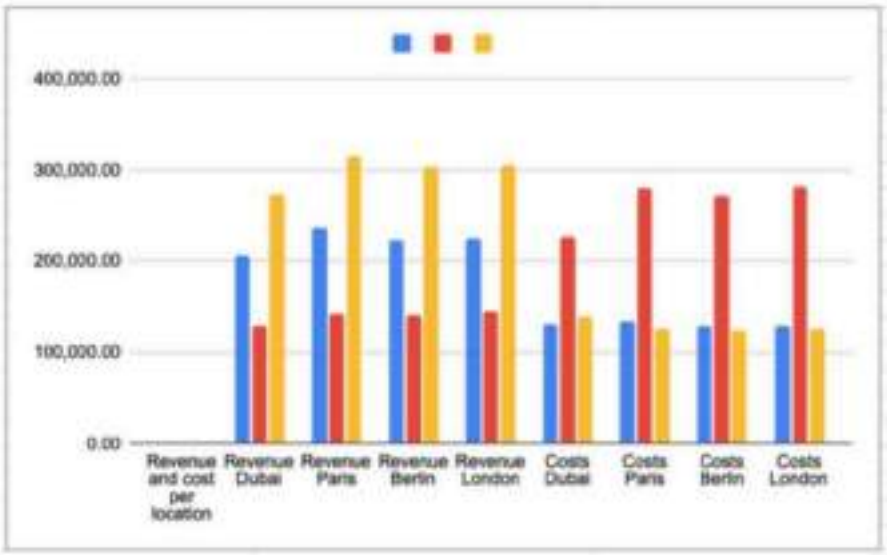
FOOTNOTE

The financial plan is based on maximum level of costs and minimum level of price as per market research

The dynamics of costs are based on the relationship developed with suppliers and increased volume of production

The dynamics of revenue are based on the customer satisfaction, formation of a loyal segment of stable clients as well as a margin of new clients aquired each year.

The maximum level of sales is set to be achieved in year 3.


400,000.00
300,000.00
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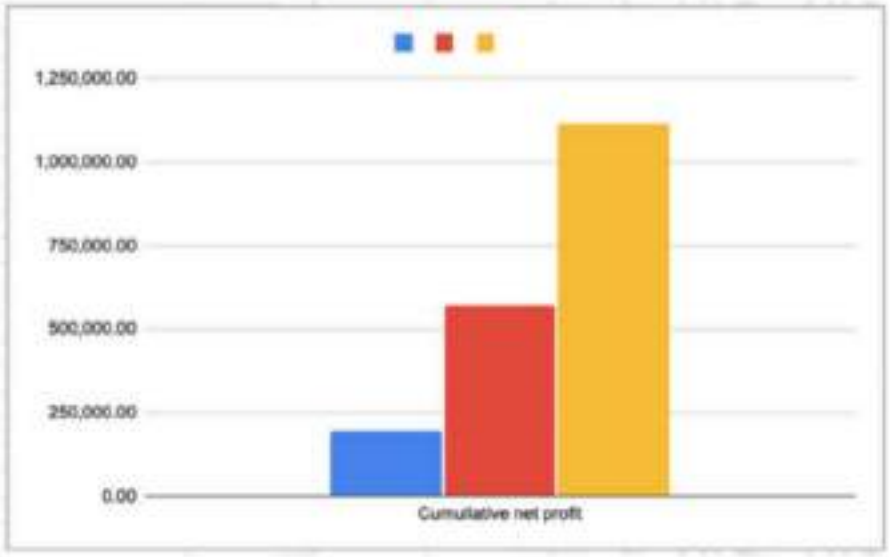
Revenue and cost per location
Revenue Dubai
Revenue Paris
Revenue Berlin
Revenue London
Costs Dubai
Costs Paris
Costs Berlin
Costs London


YEAR 1
YEAR 2
YEAR 3


1,250,000.00
1,000,000.00
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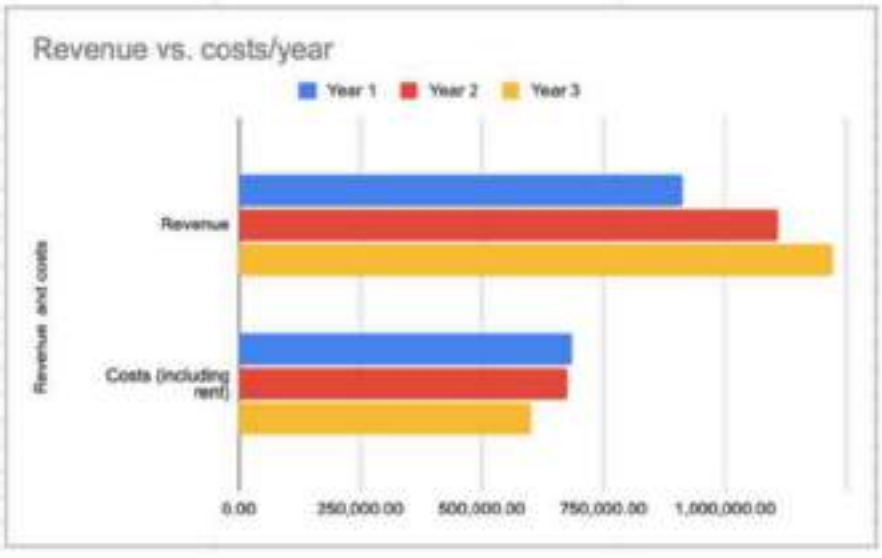
Cumulative net profit


Revenue vs. costs/year
Year 1
Year 2
Year 3
Revenue and costs
Revenue
Costs (including rent)
0.00
250,000.00
500,000.00
750,000.00
1,000,000.00

PLACING THE BRAND, THOUGHTFUL RETAIL LOCATIONS

Our physical distribution will start with flagship concept stores in four initial markets: the United Kingdom, Germany, France, and the United Arab Emirates. These stores will be situated in key cities such as London, Berlin, Paris, and Dubai. Based on demographic research, these locations were chosen because they have a large number of prosperous millennial parents who have a strong propensity for mindful consumption. Our brand will be tested in each of these locations, enabling us to monitor demand, improve our designs, and gather real time customer feedback before expanding.

The brand's identity will be reflected in these pilot stores' thoughtful design, which will use eco-friendly materials and captivating display formats that let parents learn about the backstories of each item of apparel. Research has shown that visual merchandising elements, such as product layout, window displays, mannequins, and lighting, not only enhance the shopping experience but also contribute to impulse purchases, customer loyalty, and a measurable increase in sales. In fact, an optimized store atmosphere can improve retailer profits by around 3.2%.[1] As we evaluate the performance of these pilot locations, we will expand to other cities through a combination of retail partnerships and pop-up stores in baby focused expos and premium shopping centers.

In parallel, our e-commerce platform will offer a seamless and user friendly shopping experience. Designed to reflect the same thoughtful aesthetic as our physical stores, the website will emphasize simplicity, trust, and transparency. Parents will be able to browse by age, fabric type, or function, with clear information about sourcing, care instructions, and the benefits of each garment. The platform's integration with Instagram and Facebook Shopping will facilitate seamless discovery-to-purchase experiences, particularly for clients who interact with us on social media.

LITTLE NEST STORE BANNER CONCEPT

[1] Diaz-Méndez, Maria, and Rocio Sánchez-Fernández. "The Influence of Fashion Retailers on Customer Psychology Using Visual Merchandising and Store Layout to Improve Shopping Decision." Journal of Theoretical and Applied Electronic Commerce Research (MDPI), 2023. Accessed July 31, 2025. https://phys.org/news/2024-05-consumers-pay-naturally-cotton.html .

PROMOTING THE BRAND

A key component of our brand's expansion is promotion. The behaviour of our target group is closely matched with our marketing strategy. Parents spend a lot of time on social media sites like Facebook, YouTube, and Instagram, particularly mothers between the ages of 25 and 40. Influencer marketing will therefore be a key strategy. We will collaborate with real, trustworthy influencers who are parents and can honestly talk about their experiences using our products. Parents looking for advice from approachable voices may find resonance in these partnerships' product placements, reviews, and behind-the-scenes footage.

We are also investing in emotionally powerful video content, drawing inspiration from campaigns like Nike's "Dream Crazier". A case study on Nike's emotionally driven campaigns, including the "Dream Crazier" ad featuring Colin Kaepernick, demonstrated strong emotional engagement and measurable brand impact. Research published by Kantar Millward Brown showed that Nike experienced a significant increase in online sales, up to 31% in the days following the ad release, along with notable improvements in brand sentiment and media coverage.[6] Many viewers reported more positive perceptions of Nike's values following the campaign. Inspired by these examples, our own video series, titled "Born Into Love" will feature real mothers and fathers sharing the joys and challenges of parenting. These videos will air during strategic morning and evening TV slots, and will also be displayed in high traffic spaces such as salons, pediatric clinics, gyms, and family cafés, ensuring strong brand visibility and resonance with our target audience.

To further support the credibility of our brand, we have incorporated interviews with relevant voices into our promotional content. One such interview is with Dr. Onita Cristina, medical school graduate and mother, who shared her experience with conventional babywear and why organic options are necessary. "As a medic, I often see rashes and sensitivities in newborns caused by synthetic fabrics and harsh chemicals in clothing," Dr. Onita said during our interview. "But as a mother, I know how hard it is to find safe, well made clothes that also look beautiful. Knowing that my child's skin is safe and that the brand is ethical makes me feel like I'm making a responsible choice."[7] Testimonials like these, grounded in both professional and personal insights, help convey trust and authenticity.

[6] Kantar Millward Brown. Emotionally Charged Ad Analysis: Nike–Kaepernick Campaign. 2018. Accessed July 31, 2025. https://www.kantar.com/campaigns/nike-kaepernick-campaign-analysis

[7] Onita, Cristina. Interview by Anca Onita. Bucharest, August 2, 2025.

SWOT ANALYSIS

STRENGTHS

- Use of certified organic, hypoallergenic, and UV-protective fabrics appeals to health-conscious and eco-minded parents.
- Strong alignment with Millennial and Gen Z values like transparency, ethical labor, and environmental responsibility.
- Positioned between £10–£20, making it affordable for middle-class families
- Emotionally resonant campaigns build strong customer connection and loyalty.
- Presence in both thoughtfully designed physical stores and seamless e-commerce experience

WEAKNESSES

- Use of premium materials and ethical production practices raises manufacturing costs, limiting price flexibility.
- As a new brand, Little Nest lacks brand recognition and established customer trust.
- The strong sustainability angle may not resonate with price-sensitive or less environmentally conscious consumers.

OPPORTUNITIES

- The organic babywear market is expanding, with increasing consumer demand for safe, ethical products for children.
- Growing influence of social media parenting communities and ethical influencers provides cost-effective visibility.
- Collaborations with boutiques and premium baby expos can rapidly expand physical presence.

THREATS

- Competitors offering cheaper, trend-driven babywear could draw away price-sensitive customers.
- Larger competitors may dilute consumer trust by adopting misleading "eco" claims.
- Ethical sourcing and organic certification can make the supply chain slower and more vulnerable to disruption.

CONCLUSION

In conclusion, Little Nest represents more than a clothing brand, it embodies a shift in how modern parents shop for their children: with care, consciousness, and intention. By aligning product design with core values such as sustainability, safety, and ethical production, Little Nest directly responds to the growing expectations of Millennial and Gen Z parents. The use of certified organic materials, combined with child focused features and UV protection, positions the brand as a trusted ally in early childhood care. Strategically priced to reflect quality while remaining accessible to middle class families, Little Nest balances ethical integrity with commercial viability. With a multi channel distribution model, flagship stores in key global cities and a seamless online experience, the brand is equipped to meet parents where they are, both physically and digitally. Promotion efforts grounded in emotional storytelling and authentic voices further build connection and brand trust. The alignment between market trends, consumer behaviour, and brand values is supported by real world data and expert testimony, making Little Nest well positioned to not only enter but thrive in the competitive babywear market. Ultimately, Little Nest is not just selling garments, it is offering peace of mind, practical comfort, and a brand philosophy that reflects the heartfelt priorities of modern parenting.

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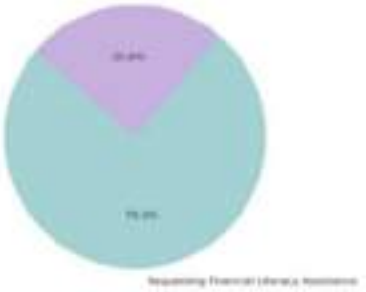
How can early financial literacy education be implemented effectively in Egypt to make young people more aware and responsible with money?

Mary Youssef

In a progressing world, financial literacy is not optional but essential for personal independence, economic stability, and long-term success. It helps both individuals and economies thrive. In today's digital financial landscape, those who cannot manage savings and liquidity risk fall into debt, miss investment opportunities, and are unprepared for emergencies. This issue is even greater in developing economies, where structured financial education is often overlooked and underfunded. In Egypt, only 27% of the population is financially literate (Klapper, Lusardi, and Oudheusden 2015). This is largely due to a lack of standardized early instruction, except for students in private international schools or those studying economics and business at universities. Many young people enter adulthood without the skills to manage their finances effectively because of a lack of guidance.

StackSmart is an educational initiative that aims to fill a gap in the Egyptian market by collaborating with schools to develop interactive digital tools and adapting content to local needs. The goal is to make financial literacy accessible and enjoyable for students. This paper examines how StackSmart can be implemented in Egypt to help empower the youth to become financially responsible citizens.

Before exploring StackSmart's strategy, it is important to define financial literacy. Financial literacy refers to the ability to understand and effectively use financial skills, including managing personal finances, budgeting, and investments. It requires analytical and practical application using critical thinking and discipline. Supporting this, a paper published by Cambridge University Press (*Fornero and Lo Prete 2023, 15*) emphasises the benefits of financial competence, highlighting its role in better retirement planning and reduced financial vulnerability, particularly for women. Furthermore, the authors contend that financial education fosters more informed public decision-making, including voting behaviour and policy comprehension. Reflecting these needs in the Egyptian context, youth widely feel disadvantaged. To better understand the local situation, I conducted a survey of 30 students from Alexandria, Egypt, from Collège Saint Marc (boys' school) and Saint Jeanne-Antide Institute (girls' school). The results showed 75% of students requesting assistance with financial literacy and essential skills not provided by schools. Additionally, 80% of female students were more insistent on learning financial skills to gain



independence in a country where women are considered inferior.

StackSmart's mission is encapsulated in "don't spend it, master it."Its approach is built on three key pillars: simplicity, uniformity, and interactiveness. Financial concepts can often be daunting, especially when they are first introduced. Students often struggle with complex financial concepts like inflation and interest rates; therefore, these concepts will be explained through simple scenarios and relatable analogies to make sure they are deeply understood. Additionally, standardising the curriculum ensures consistency in teaching quality across schools, making it easier for schools to implement without developing new material. Finally, by making learning interactive with games and quizzes, it will be more enjoyable and less dry. Studies often show that interactive learning helps stimulate the brain more and therefore increases the percentage stored in a person's long-term memory. For example, Okano, *Kaczmarzyk, and Gabrieli (2018)* showed that embedded quizzes and guided discussions not only make learning more engaging but also boost memory retention by up to 26% compared to passive methods.

To further distinguish StackSmart from competitors, I would hire recent graduate software engineers from Egypt. This ensures the website is well-maintained while remaining affordable, given lower salary expectations and average incomes. Notable competitors include HSBC & INJAZ Egypt, Mastercard & Ingiz, and FinGreen by QNET & Misr El Kheir Foundation. Despite many alternatives, StackSmart offers a distinctive, engaging, and accessible way to learn about money through a tailored, interactive program using age-appropriate modules designed for Egyptian schools. This approach simplifies complex financial concepts, aligns with national education goals, and provides students with practical skills often lacking in current curricula, setting StackSmart apart. While external, scholarship-based competitors primarily serve students with access to private education, school collaborations will enable StackSmart to achieve broader reach and deeper impact.

StackSmart's pricing balances affordability for Egyptian schools with sustainable revenue. Prices are set below competitors', with flexible payments and discounts for multiple subscriptions (economies of scale). INJAZ Egypt & Partner programs typically cost between EGP 100 and 850 per week. Therefore, I propose a pricing structure of EGP 200 per student per month for external sign-ups and EGP 100 per student per month for schools that partner with StackSmart.

StackSmart will use Social media campaigns, mainly on TikTok and Facebook, as a first launch, as renting a billboard would be very expensive and redundant if there were only one, given that Egypt is littered with Billboards. TikTok will be used because the majority of

students have access to it; however, in Egypt, parents and educators tend to have Facebook accounts and are addicted to scrolling Facebook. StackSmart will be advertised as a game to attract students, since advertising it as an educational platform will put students off.

StackSmart is well placed to succeed in Egypt's financial literacy sector for several reasons. Its curriculum is designed specifically for the local context, addressing cultural and economic realities that broad international programs often miss. By providing high-quality, ready-to-use materials for schools, StackSmart also makes life easier for teachers and helps ensure consistent learning experiences for students.. The interactive, gamified learning approach significantly enhances student engagement and retention. Collaborating directly with educators will make it more integrated and effective and will simplify adoption. However, as StackSmart is just a startup, it will not have adequate funding to help all of Egypt within a short period, and therefore, I will have to focus on cities like Alexandria and Cairo first, and then, as I retain more profit, I will invest it in more school partnerships, moving to more rural areas like Saiid and Assyout. Additionally, the lack of brand recognition may lead to speculation during the initial launch.

Looking ahead, StackSmart holds great promise for improving financial inclusion in Egypt, with significant partnership opportunities with public schools outside major cities to teach financial literacy. Securing funding from nonprofits, fintech companies, and corporate giving, and utilizing a blend of in-person and online tools. However, there are still some challenges. StackSmart will have to compete with bigger, well-known organizations like INJAZ and EBI. It may be difficult to set prices that benefit both the schools and the business, and changes in school policies could lead to further delays. On the tech side, ensuring the platform is secure and works reliably will help maintain people's trust and effectiveness.

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How can we improve the thermal performance of electromagnetic space debris collectors to make them safer and more efficient?

Zayan Zamir

Table of Contents

Research Proposal

Abstract

As Earth's orbit becomes more clogged with satellites and space junk, new clean-up strategies are an urgent need. Electromagnetic space junk collectors provide a glimmer of hope to clean up the mess by collecting metal shreds without coming into contact with them. But these systems generate a lot of heat from high electric currents in the coils - and in the vacuum of space, cooling is difficult. The question this paper answers is how thermal control systems can be designed to make such collectors safer and more efficient. By reviewing recent studies on space-based thermal management and electromagnetic actuator technologies, the present study identifies main thermal challenges and suggests solutions such as radiator integration, material optimization, and passive cooling techniques. Although supplementary in nature, this study fills a clear gap in existing literature by linking electromagnetic collection technology to thermal engineering required to make it operate efficiently in orbit.

Research Question

How can we improve the thermal performance of electromagnetic space debris collectors to make them safer and more efficient?

Aims and Objectives

This study's aim is to discover ways of improved thermal performance in electromagnetic debris collection systems via secondary research.
Learn about electromagnetic collectors and why they generate heat.

- Discover important thermal dangers with these systems.
- Determine how spacecraft typically handle heat in space.
- Evaluate which of those methods can be used on electromagnetic debris collectors.
- Provide your suggestions for more effective and safer operation.

Research Design and Framework

This is a secondary research study, drawing on existing sources of academic papers, journals, and open-source reports to yield data and information. The study uses sources from 2010 to 2025, with a focus on recent advancements in thermal control, electromagnetic technologies, and ADR technologies.
Framework:
The thermal performance problem is split into three parts:

- Heat Generation - electricity flowing through coils.
- Heat Transfer - transfer of heat within components.
- Heat Rejection - radiation to space.

Each part goes hand in hand with appropriate thermal measures. Priority is being given to the recognition of solutions which are light weight, reliable, and efficient for space.
Classification of research methods: Secondary Research
Because I will be using already existing studies, papers, and information rather than collecting new data yourself.

Classification based on purpose: Applied Research

Since the focus is on practical applications of autonomous AI to reduce space debris, not just theoretical concepts.

Classification based on depth of scope: Exploratory Research

Because this is a relatively new area and I'm investigating how AI might help, exploring possibilities rather than confirming established facts.

Classification based on type of data used: Quantitative Research

Most information will be quantitative, e.g., statistics regarding trash, AI performance metrics, and satellite data.

Classification by time frame: Cross-Sectional

Since my research will be contrasting current or recent studies and data rather than observing change over an extended period.

Boolean Search String:

(improve) AND ("thermal performance" OR thermals or "heat removal") AND (electromagnetic OR omnimagnet) AND ("space debris" OR "orbital debris") AND ("space debris collector" OR "space debris removal" OR "space debris mitigation" OR "space debris remover") AND (improvement OR efficiency OR safety OR safer)

Inclusion Criteria	Exclusion Criteria
Sources of information written in English	Non-English sources
Research papers, academic journals, and books published between 2010 and 2025	Publications older than 2010
Peer-reviewed journal articles, academic publications, and institutional reports	Non-peer reviewed sources such as blogs, opinion pieces, and general news articles
Studies specifically focused on: • Electromagnetic systems used for space debris collection • Thermal control technologies in spacecraft systems • Materials science relevant to heat management in aerospace applications • Engineering methods for increasing safety and efficiency in orbital systems	Studies unrelated to: • Space debris collection technologies • Electromagnetism in aerospace • Thermal performance in space environments
Case studies, experimental analyses, literature reviews, or theoretical models related to the research question	Papers focusing exclusively on unrelated spacecraft systems or atmospheric vehicles

Justification

Electromagnetic space debris collectors offer a low-contact, futuristic means of cleaning Earth's orbit. But there is a warning sign - they warm up. Pretty warm. Without making use of standard cooling technologies like fans or air flow, such systems must rely on the application of skilled thermal management methods normally assumed in design reports. It is not often that study papers cover keeping electromagnets actually cool enough to run safely and effectively. This piece fills the void by working through available thermal control methods and proposing how they can be applied to particular

electromagnetic trash collection systems. If these systems do heat and crash, they themselves may become debris - rendering this study not only important, but necessary.

My Own Research Limitations

One major limitation was that I couldn't do primary research. Since I'm not part of a space agency or lab, I didn't have access to real electromagnetic collectors or satellites to test. I also couldn't build a full prototype because making one that works in space conditions (like vacuum or extreme temperatures) is really complicated, expensive, and needs special equipment I don't have. So I focused on secondary research - reading papers, articles, and engineering reports. Even though I didn't do physical testing myself, I still got to learn a lot from professional experiments and real spacecraft designs. But it means I had to rely on what's already been published, which might not cover everything I wanted to explore.

Background:

Space trash - from decommissioned satellites to malfunctioning fragments of rockets - is a large threat to working satellites. Even a marble-sized piece traveling at orbital speeds has the ability to destroy a satellite upon collision. Singh et al. (2024) note that more than 36,500 tracked pieces of debris with sizes larger than 10 cm exist, and hundreds of millions smaller than that. Without cleaning up the garbage, the clutter looms to initiate the "Kessler Syndrome," in which collisions produce more debris, which create even more collisions.

To address this, scientists are researching Active Debris Removal (ADR). Possibly the most exciting technology under development is the electromagnetic collector. The machines use coils or magnetic fields to grab and divert the debris without coming into contact - especially convenient in microgravity where grappling or docking is dangerous. One example machine is the Omnimagnet that uses rotating magnetic fields to interact with non-magnetic conductive debris (Pham et al., 2021). But exciting as this is, this method has its drawbacks.

Heat is a significant restriction. Large currents induce resistive heating (Joule heating), which in vacuum can't be removed via air convection. Only conduction and radiation remain, which must be engineered with caution. If thermal issues aren't properly managed, systems fail or become hazardous themselves (Lv et al., 2024).

Research Essay:

Keeping Cool: Heat Control in Space Debris Capture

Literature Review: Current Technologies and Challenges

Engineers have proposed many debris-removal ideas, such as nets, harpoons, and robotic arms to physically grab large junk. Some approaches use the Earth's atmosphere (like drag sails) or the planet's magnetic field (tethers) to passively deorbit satellites. Electromagnetic concepts include mounting electromagnets on a "space tug" that slows or attracts metal fragments (Starr & Youngquist, 2017). NASA researchers have envisioned satellites using oscillating magnets to push or pull other spacecraft without fuel (NASA, 2017).

Several recent studies examine electromagnetic collection. For example, a student-led article by Turkmen (2023) proposed sending a rocket with a powerful electromagnet to sweep up ferromagnetic debris and dump it into the Moon's gravity well. However, this approach only attracts ferromagnetic materials like iron or nickel. Most satellites use aluminum and composites (non-magnetic), so onboard magnets would only catch a portion of the junk (Scudder, 2016).

In summary, magnets in orbit can safely slow or orient debris, but only metallic objects respond. Non-ferrous debris must be handled by other means such as nets or adhesives. Also, making a strong electromagnet requires heavy coils and lots of power, which itself creates thermal challenges. Any viable collector must balance these issues - it needs to be lightweight, catch many types of debris, and shed heat efficiently (Zinnecker, 2021; Bigdeli et al., 2025).

Overheating Issues in Electromagnetic Debris Collectors

Powerful electromagnets draw high electrical current to generate magnetic fields. That current causes Joule heating (I^2R losses) in the coils. If an electromagnet is driven too hard, its coil insulation can melt, leading to short circuits or even burned-out windings (Ersoy, 2025). In space this is especially problematic because there is no air for cooling. Heat can only leave the system by radiating from surfaces or conducting to a radiator, which can be slow (Lv et al., 2024).

Another issue is uneven heating: if one part of the collector heats up (like a coil or electronics), thermal expansion can warp structures or break seals. The heat could soften adhesives or coatings, causing leaks or delamination (James, 2022). NASA warns that power density is a big problem, especially when stacked electronics generate intense heat but may have no direct path to a cold surface (NASA, 2024).

If a collector fails thermally, it could become an additional debris hazard. A coil burning out might break loose bits or trigger thermal runaway, potentially causing an explosion in energized capacitors or batteries (Electronic Products, 2007). Preventing this requires both passive and active thermal controls, as well as heat-tolerant materials.

Thermal Control Solutions in Spacecraft Systems

Spacecraft routinely face extremes of temperature: full Sun can heat a panel to hundreds of °C, while shade can plunge it below –100 °C. As one aerospace blog explains, "for spacecraft, the heat in space is a much more challenging problem than the extreme cold" because excess heat is hard to get rid of. Over the

decades, many thermal management methods have been developed. Some are passive (no moving parts or power) and others are active (using pumps or electronics).

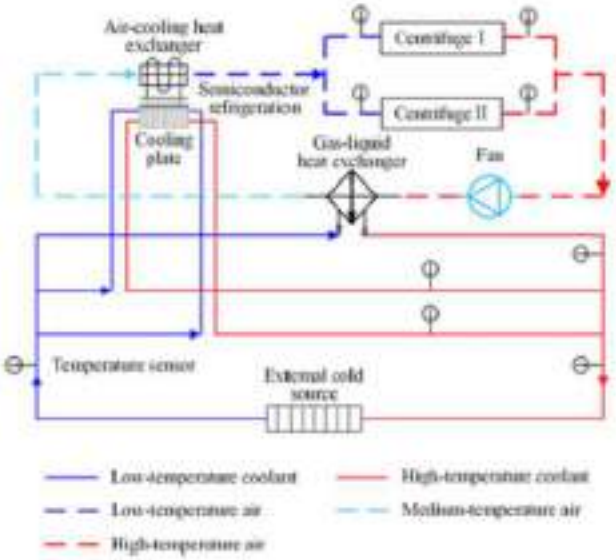

Figure 1. Basic layout of a thermal control system onboard a spacecraft. This shows how components like heat pipes, radiators, and temperature sensors work together to move and release heat. Adapted from Zhang et al. (2020).

This diagram shows the parts of a thermal control system used on spacecraft. You can see how heat is moved from hot components like coils through pipes and straps, and then released into space through radiator panels. It's basically like a radiator on Earth, except it doesn't have air - everything is done by radiation and conduction. This kind of system could be used in an electromagnetic debris collector to stop it from overheating while still keeping the design lightweight.

Common solutions for heat in spacecrafts include:

- **Radiators:** Flat panels coated in materials with high infrared emissivity. A radiator has a low solar absorptivity/high emissivity coating (often white paint or second-surface silvered tape) so it absorbs little sunlight but efficiently radiates waste heat away. Radiators are a simple way to dump heat into cold space. The drawback is that large areas are needed, and they must be oriented away from the Sun for effectiveness (Reid, 2020).
- **Multi-Layer Insulation (MLI):** Many spacecraft use MLI blankets (multiple layers of reflective film) to prevent unwanted heating. MLI traps heat inside, keeping hot components from soaking up solar radiation. It can protect instruments from overheating by reflection. However, MLI does not remove heat – in fact it inhibits radiation. Thus it is often used with radiators: heat is conducted to a panel, and MLI covers the rest of the satellite to block heating (NASA, 2012).
- **Heat Pipes:** These are sealed, fluid-filled tubes that conduct heat passively. A heat pipe has a liquid (like ammonia or water) that evaporates at the hot end, travels as vapor to the cooler end,

and condenses, releasing heat to a radiator. Heat pipes can move heat very efficiently from a hot magnet coil or battery to a radiator panel. They have no moving parts and very low thermal resistance. NASA's small-sat guide calls them "an efficient passive thermal transfer technology". For example, Redwire Space flew a flat "FlexCool" heat pipe on a 6U CubeSat (TechEdSat-10) in 2020 to cool its radio module (NASA, 2012).

- **Thermal Coatings and Surface Treatments:** Engineers paint or tape spacecraft surfaces to tune their optical properties. Matte black paint (high absorptivity and high emissivity) is used on surfaces meant to radiate heat. Matte white paint or silverized tape (low solar absorptivity, high emissivity) is used on radiators. Selecting the right coating on the magnet housing or radiators helps control how much heat is absorbed from sunlight and how much is emitted as infrared (Reid, 2020).
- **Phase Change Materials (PCM):** These materials (like certain waxes or salts) absorb heat by melting at a set temperature. A PCM unit stores thermal energy during a hot period (staying at its melting point) and releases it later as it solidifies. This smooths out temperature spikes. NASA has developed PCM panels for CubeSats to blunt peak heat loads. The downside is extra mass (for the metal container and PCM) and limited capacity (Sharp & Loftin, 1990).
- **Thermal Straps and Heat Spreaders:** Flexible conductive straps (often made of copper or graphite fibers) can spread heat from a hot spot to a radiator. A strap is simpler than a rigid heat pipe. For very high heat, advanced composites are used. NASA studies show that carbon-fiber–reinforced metal composites can conduct heat 2–3× better per weight than aluminum. These composites can act like built-in heat spreaders without extra plumbing (Sharp & Loftin, 1990).
- **Active Systems:** Though rarer on small satellites, active loops (circulating pumped coolant) or even miniature refrigeration can be used on large spacecraft. These systems can transport heat aggressively but add complexity, power draw, and potential points of failure (Ersoy, 2025).

In practice, a mix of methods is used. For instance, a collector might mount its electromagnet coil on a structure with embedded heat pipes leading to a radiator panel, and cover the rest of the vehicle in white insulation to reject heat. Any radiator must be sized for the worst-case heat load (from solar heating plus coil losses). As one study notes, selection of coatings and tapes is important because their optical properties degrade in orbit (e.g. darkening from radiation). Thermal engineers must account for this aging so the system still functions at end-of-life conditions (James, 2022).

Another example: consider a magnetic coil cooled by conduction to its mount. One might paint the mount with high-emissivity tape (like silvered FEP) and expose it to deep space. This draws heat out of the coil continuously. If additional cooling is needed, a miniature loop heat pipe could pump heat from the coil to an external radiator. For very transient peaks (say, activating the magnet in short bursts), a small PCM reservoir could absorb the burst energy without overheating the electronics (Sharp & Loftin, 1990).

No single solution is perfect, so Table 1 (below) summarizes the pros and cons of key methods.

Materials and Design Strategies for Thermal Management

Along with thermal systems, the choice of materials and structural design greatly affects heat handling. Some key strategies include:

- **High Thermal Conductivity Materials:** Using metals or composites that conduct heat well ensures hot parts don't stay hot. For example, copper or aluminum frames can spread heat from the coil. Even better are metal-matrix composites loaded with graphite fibers: NASA reports these can offer 2–3 times the conductivity per weight of pure aluminum. Such advanced composites act as built-in heat sinks without moving parts. Carbon-based materials like pyrolytic graphite sheets or carbon foam also conduct heat very efficiently and are lightweight (James, 2022; Sharp & Loftin, 1990).
- **Thermal Path Optimization:** Designers ensure that from the heat source (coil) to the sink (radiator) there is a good conductive path. This might mean mounting coils on metal plates, using thermal grease, or embedding heat pipes. Minimizing thermal resistance (avoiding air gaps or poor contacts) is crucial (Ersoy, 2025).
- **High-Temperature Components:** Some parts of a magnetic collector will still get hot, so choosing materials that tolerate heat prevents damage. For instance, high-temperature wire insulation, ceramics for coil formers, and stable alloys can survive higher operating temperatures. Also, electronic components (sensors, controllers) should be rated for the expected thermal environment
- **Modular and Redundant Design:** If one electromagnet overheats, another might take over. Using multiple smaller coils instead of one giant coil can reduce individual heating. Also, a modular thermal design (with separate radiators or heat pipes for each magnet) confines a problem to one area (Bigdeli et al., 2025).
- **Orientation and Spacecraft Attitude:** The spacecraft's orientation can be chosen to help cooling. For instance, the collector could deploy its radiator away from the Sun during operation. Some missions even plan on spinning slowly so that no one side gets too hot. Designing flexible thermal straps or rotating louvers can adapt to different attitudes (NASA, 2024).
- **Superconducting Magnets (in theory):** In concept, superconductors would eliminate Joule heating entirely. However, they require cryogenic cooling (e.g. liquid helium or cryocoolers), which adds huge complexity and weight. Research is ongoing into high-temperature superconductors for space, but currently this is beyond small satellite capabilities. If it becomes feasible, a superconducting collector would drastically reduce heat issues (Abbott, 2021).

By combining smart materials and layout with active/passive cooling, engineers can greatly improve a collector's thermal performance. For example, a design might bury heat pipes in a carbon-fiber composite boom to transport coil heat, while the outer shell uses multi-layer insulation and paint to control external heating.

Comparison of Thermal Control Methods

The table below compares several thermal management methods that could apply to an electromagnetic debris collector, listing their main advantages and drawbacks.

Method	Pros	Cons
Radiators	- Passive (no power needed) - Directly emit heat to space efficiently	- Require large surface area - Must face deep space (sunlight reduces effectiveness)
Multi-Layer Insulation (MLI)	- Excellent insulator (low heat loss) - Lightweight and passive	- Cannot remove heat, only trap it - Edges can "short" and leak heat
Heat Pipes	- Very efficient passive heat transfer - No moving parts - Proven in many spacecraft (e.g. Redwire FlexCool)	- Must be properly oriented (wick gravity limitations on non-zero-G) - Can freeze up if cold (solutions exist)
Thermal Coatings/Tapes	- Simple way to tune emissivity and absorptivity - Many pre-qualified materials (paints, FEP tapes)	- Properties degrade over time in orbit (darkening from atomic oxygen) - Doesn't remove heat itself
Phase-Change Materials	- Absorbs heat at fixed temperature (buffers spikes) - Passive thermal storage	- Adds mass for housing and PCM - Limited capacity (saturates)
Thermal Straps/Conduction	- Simple, can conform to shapes - Good for spreading heat between modules	- Generally heavier than heat pipes for same length - Less effective for long distances
Active Loops (fluid/pumped)	- Can move heat anywhere onboard - Can handle very high heat loads	- Complex (pump, piping) - Requires power - Potential leak points
Superconducting Cooling	- Virtually zero electrical heating if maintained - Strong magnetic fields possible	- Requires heavy cryocoolers or cryogens - Very complex and power-hungry

Table 1. Comparison of thermal control methods for an electromagnetic debris collector.
Table content synthesized from sources including Ersoy (2025), Reid (2020), and NASA technical references from 1990–2024.

Each method can be part of the solution. For example, a radiator panel coated in silver tape could pair with heat pipes to carry coil heat to it. Meanwhile MLI and surface paints regulate how sunlight affects the system. Table 1 shows why engineers must weigh trade-offs: a radiator is reliable but large, while a heat pipe is efficient but needs good startup/warm-up. A practical design will likely combine several approaches to cover different scenarios (sunlit heating, eclipse cooling, power-on bursts, etc.).

Conclusion and Recommendations

Electromagnetic space debris collectors hold promise for safer, fuel-free removal of orbital junk. They can gently tug or steer metallic fragments without contact. However, their Achilles' heel is thermal: the strong magnets and power electronics inside create a lot of heat that must be carefully managed. If overheated, the system could fail or even produce more debris.

This review has shown that improving thermal performance involves both how we cool and what materials we use. On the cooling side, tried-and-true spacecraft solutions should be applied: large-area radiators, high-emissivity coatings, multi-layer insulation, and heat pipes to transport the coil's waste heat. Where mass and volume allow, active elements like pumped loops or phase-change buffers can help during peak loads. The space around Earth (especially in LEO) is cold darkness, so any heat pipe or radiator should face away from the Sun as much as possible.

Material choices are equally important. Using high-conductivity metals or metal-matrix composites will spread heat out; carbon-based straps or graphite panels can link the magnet to the radiator. Coil insulation and structural parts should tolerate the highest expected temperature, so that even if cooling is momentarily insufficient, nothing melts or burns. Designing the collector with modular coils or multiple magnets can also spread the thermal load.

Based on current knowledge, the following recommendations seem most promising for next-generation electromagnetic collectors:

- **Integrate heat pipes or straps into the magnet support:** Attach pipes directly to the electromagnet coil form to whisk heat to side panels. As demonstrated in recent CubeSat thermal designs, flexible heat pipes (like Redwire's FlexCool) can effectively cool high-power components (NASA, 2012).
- **Use high-emissivity radiator coatings:** Cover exposed surfaces with second-surface silver tapes or white paints. These coatings reflect solar light but emit infrared heat, as NASA's thermal guide suggests (Reid, 2020).
- **Employ advanced conductive materials:** Wherever possible, make structural components from graphite-enhanced metal composites. These provide excellent thermal conduction (50–70% mass savings over pure aluminum) so heat can flow out quickly (Sharp & Loftin, 1990).
- **Add thermal isolation and storage:** Place multi-layer insulation around areas that should stay cool, and consider a small phase-change reservoir near the coil to soak up brief surges of heat (Sharp & Loftin, 1990).
- **Plan orbital attitude for cooling:** If the mission allows, schedule operations so that heat rejection systems (radiators) point away from the Sun during magnet operation (NASA, 2024)
- **Redundancy and monitoring:** Include multiple smaller coils or redundant circuits so a failure does not destroy the entire system. Monitor temperatures with sensors to throttle the magnet if it approaches danger (Bigdeli et al., 2025).

Limitations

The technology itself also has a few limitations. First, electromagnetic collectors can only pull in metallic or conductive debris, such as old satellite parts or broken tools made from certain metals. This means that plastic, paint flakes, or composite materials would not be affected, so other methods, such as nets or lasers, would still be needed for a full cleanup.

Another issue is that these systems can heat up very quickly, especially when the magnets are running at high power. If the heat is not managed well, it could damage the system or even turn it into debris. Additionally, adding cooling systems, such as radiators or heat pipes, takes up space and weight – and in satellites, every gram counts.

In summary, by borrowing the best practices of satellite thermal engineering, designers can make electromagnetic debris collectors much safer and more efficient. The physics of heat transfer in space is well understood. The challenge is integrating those solutions into a novel debris-collector design. With careful material choices, clever geometry, and established thermal hardware, it should be possible to use magnets in orbit **without burning up the spacecraft**. Future work could prototype such a system on a test mission, measuring coil temperatures and debris-capture performance. If successful, enhanced thermal designs would make these collectors credible tools in the fight against space junk.

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