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Generative AI for Sustainable Education: A Systematic Review of Opportunities, Challenges and Future Directions

Sneha.V.K

Department of Computer Science and Applications

Little flower college Autonomous, Guruvayoor, kerala, India

Abstract

The emergence of Generative Artificial Intelligence (GenAI) has stimulated a significant transformation in higher education, aligning with United Nations Sustainable Development Goals while simultaneously presenting a "sustainability trade-off." While GenAI offers emerging opportunities for individualized learning, enhanced accessibility, and the development of transferable skills such as critical thinking and creativity. The sustainable integration of GenAI remains challenging because the training and deployment of large language models require energy-intensive computational infrastructure, leading to increased carbon emission and water consumption, while simultaneously introducing ethical challenges such as academic integrity, transparency and algorithmic bias. This paper presents a Systematic Literature Review (SLR) conducted in accordance with the PRISMA 2020 guidelines, synthesizing findings from 32 recent scholarly works published between 2022 and 2026. The review employs the Population–Exposure–Outcome (PEO) framework to examine how GenAI restructures learning environments across dimensions of operational efficiency, pedagogy, and ideology. Key results identify five strategic processes for sustainable implementation: ethical appropriation, infrastructure management, faculty development, curricular transformation, and pedagogical innovation. Furthermore, the review addresses global power dynamics, highlighting a shift toward plurality while cautioning against algorithmic colonialism. We propose the Generative AI-Enabled Sustainable Education (GAISE) framework as a roadmap for institutional resilience. The study concludes that the long-term sustainability of GenAI in education depends on balancing technological innovation with environmental transparency and ethical stewardship, advocating for longitudinal research to monitor future cognitive and ecological impacts.

Keywords: Generative Artificial Intelligence, Sustainable development goals, GenAI, Education

1. Introduction

The rise of Generative Artificial Intelligence (GenAI) signifies a fundamental paradigm shift in higher education, as tools like ChatGPT, Gemini, and Claude transition from supportive resources to active educational facilitator[1]. Unlike conventional AI systems that primarily perform predictive tasks, GenAI engages in dynamic knowledge generation, producing human-like text, images, and code that redefine how knowledge is accessed and examined[12]. This technological boom coincides with a global imperative to achieve the United Nations Sustainable Development Goals (SDGs), particularly SDG 4 (Quality Education) and SDG 12 (Responsible Consumption and Production)[12]. Within this landscape, researchers differentiate between "sustainable education," which focuses on the adaptive capacity of educational systems; "sustainability in education," which targets resource efficiency within

institutions; and "education for sustainable development" (ESD), which utilizes learning as a vehicle for broader societal goals[26].

However, a critical "sustainability paradox" has emerged: while GenAI is marketed as a dematerialized tool for personalized, adaptive, and inclusive learning, its operation relies on a massive physical resource footprint[11]. The training and inference of large language models (LLMs) consume immense quantities of electricity and water for data-center cooling, with training a single transformer model estimated to emit as much carbon as five automobiles over their lifetimes[11]. Furthermore, the rapid cycle of hardware replacement to keep pace with AI demands risks creating substantial electronic waste (e-waste) streams by 2030[29],[8]. These environmental costs represent "distributed harms" that frequently fall on water-stressed regions and communities far removed from the educational contexts where these tools are utilized[29].

Beyond environmental concerns, the integration of GenAI faces significant ethical and systemic barriers, including algorithmic bias, ideological encoding, and threats to academic integrity[11]. Current research reveals a shift toward "multipolarity," where non-Western hubs like China, Saudi Arabia, and South Africa are becoming central to the discourse; yet, a risk of "dependency theory" persists if emerging nations must rely solely on imported technologies from the Global North[26]. This "AI divide" is compounded by concerns of "algorithmic colonialism," where Western-centric training data may marginalize minority cultures and indigenous knowledge systems[12,[17]. Additionally, excessive student reliance on automated outputs may lead to "metacognitive laziness," where AI acts as a substitute for, rather than a scaffold for, critical and creative thinking[7].

Although the body of research is expanding, it remains fragmented, with studies often examining pedagogical opportunities or environmental costs in isolation while giving limited attention to their systemic intersection[4]. There is an urgent need to consolidate evidence to inform researchers, educators, and policymakers on how to balance innovation with ethical stewardship[20]. This review addresses this gap by providing a balanced synthesis of the educational, ethical, and environmental dimensions of GenAI. Utilizing a Systematic Literature Review (SLR) methodology guided by PRISMA 2020 standards, this paper analyzes recent peer-reviewed literature to propose frameworks such as GAISE (Generative AI-Enabled Sustainable Education)[1]. The review advocates for a strategic approach that enhances rather than replaces human instruction, connecting GenAI's potential with context-aware avenues for institutional transformation[4].

The remainder of this paper is organized as follows: Literature review describes the systematic literature review methodology and search strategy; methodology presents a thematic analysis of opportunities, challenges, and the sustainability paradox; result discusses the findings through established theoretical frameworks and identifies future research directions; and the final section concludes with integrated policy and pedagogical recommendations for the responsible use of GenAI.

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2. Literature Review

This literature review consolidates research on the consolidation of Generative AI into the conceptual structure of sustainable education, analyzes how these technologies act as both a catalyst for educational transformation and a source of significant ethical and environmental challenges. (1)

2.1. Integrating Generative AI into Sustainable Education

The increasing prevalence of Generative AI (GenAI), particularly Large Language Models (LLMs) like ChatGPT, represents a fundamental change in higher education, functioning not only as a tool for automation but as a fundamentally different educational practitioners[1][11]. Researchers differentiate between sustainable education which prepares learners with knowledge and values to create a more sustainable world, and "education for sustainable development" (ESD), which leverages education as a means to attain broader societal sustainability goals[31]. GenAI uniquely supports the United Nations

Sustainable Development Goals (SDGs), specifically SDG 4 (Quality Education) and SDG 12 (Responsible Consumption and Production), by facilitating transformative learning that encourages students to challenge prior assumptions and engage deeply with complex sustainability issues[10]. This intersection has led to the proposal of the Generative AI-Enabled Sustainable Education (GAISE) framework, which synthesizes principles of constructivism, connectivism, and transformative learning[31].

2.2 Innovations for Educational Sustainability

- **Adaptive and Individualized Learning**

One of the primary benefits of GenAI is its ability to provide individualized learning experiences that adapt to a student's specific needs, interests, and pace[10]. By leveraging machine learning algorithms, educational systems can recommend tailored materials, identify student weaknesses in real-time, and provide instant, context-aware feedback. This level of customization improves learning outcomes and student satisfaction while promoting a more learner-centered approach grounded in constructivist theory[10].

- **Enhancing Accessibility and Reducing the Digital Divide**

GenAI has the potential to democratize education by offering scalable, cost-effective solution**s** for marginalized and underserved communities[10][16]. These tools can provide translation services, simplify complex information, and offer assistive technologies for students with disabilities, thereby fostering more **inclusive learning environments**. Furthermore, GenAI enables educators to reach remote areas, helping to bridge the gap between the Global North and South in access to quality education[10],[30].

- **Optimizing Educational Processes and Resources**

From an institutional perspective, GenAI enhances sustainability by **automating laborious administrative and pedagogical tasks**, such as grading, lesson planning, and content generation[10]. This automation allows educators to focus more on direct student interaction and curriculum development, ensuring a more sustainable use of both human and material resources[10].Additionally, AI-driven data analysis helps institutions optimize resource allocation and predict student success factors, contributing to long-term **institutional resilience[16]**.

- **Developing Transversal Competencies**

Beyond traditional academic knowledge, GenAI supports the development of **transversal competencies**—such as critical thinking, creativity, and self-regulation—that are essential for navigating 21st-century complexities[31]. When integrated through inquiry-based learning or ecosystem simulations, GenAI serves as a **cognitive stimulator** that encourages brainstorming, innovation, and reflective reasoning[13].

2.3. Challenges and the "Sustainability Dilemma"

- **Environmental Impact and Carbon Footprints**

A significant **"sustainability paradox"** exists: while promoted as a dematerialized tool, GenAI's physical resource footprint is substantial[29]. Training and operating LLMs require **immense electricity consumption**, leading to high carbon emissions[11]. Furthermore, data centers housing these models demand **massive amounts of water** for cooling, often in water-stressed regions, and generate significant electronic waste[11].

- **Ethical Risks: Bias, Privacy, and Integrity**

The use of GenAI introduces critical ethical concerns, including **algorithmic bias** and the reproduction of misinformation[11]. Bias often stems from training data dominated by Western-centric voices, which can marginalize minority cultures[11]. **Academic integrity** remains a major hurdle, as GenAI can replicate cognitive work traditionally performed by students, raising risks of plagiarism and threatening the authenticity of student work[1].

- **Cognitive Dependence and Declining Decision-making Autonomy**

Excessive reliance on GenAI can lead to **"metacognitive laziness"** and a loss of learner autonomy[4]. If students use AI to bypass critical reasoning, it may inhibit the development of independent thinking and essential creative skills[11]. This **user dependency** creates a risk of eroding the epistemic foundations of education itself[11].

2.4. Frameworks for Sustainable Implementation

- **Strategic Integration Models**

To address these challenges, researchers have proposed conceptual frameworks such as the **three-layer model** (efficiency, pedagogy, and ideology) for understanding AI-mediated learning environments[12]. Other models identify **five key processes** for sustainable integration: critical and ethical appropriation, institutional management of infrastructure, faculty development, curricular transformation, and pedagogical innovation[13].

- **Institutional and Teacher Readiness**

The successful adoption of GenAI requires robust **institutional policies** and ongoing **faculty development[16]**. Educators must be trained to adopt a critical stance toward AI outputs, teaching students to interrogate them for bias and factual accuracy[1]. Institutional responses must shift from prohibition toward creating nuanced guidelines that balance innovation with ethical stewardship[1].

- **Multipolarity and Global Equity**

Current research and adoption are heavily concentrated in the **Global North**, highlighting a disparity in global knowledge production[5]. To achieve true educational sustainability, institutions must ensure that the AI-driven transformation does not reinforce **dependency theory**, where lagging nations rely on the innovation of developed counterparts[10]. Promoting **equitable access** and context-sensitive implementation in the Global South is crucial for meeting global sustainability benchmarks[10].

- **Future Perspectives**

Future research must prioritize **longitudinal studies** to evaluate the long-term impact of GenAI on learning retention, cognitive transfer, and the development of sustainability competencies[11]. There is also an urgent need for more rigorous **empirical measurement of AI's environmental footprint** in specific educational settings to align technological use with sustainability commitments[29]. Finally, **interdisciplinary collaboration** between educators, technologists, and ethicists will be essential to ensure that GenAI enhances rather than replaces human instruction[16].

3. Methodology.

3.1. Review Design: The PRISMA 2020 Framework This systematic literature review is conducted in accordance with the **Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines[1]**. The PRISMA framework provides a structured workflow for identifying, screening, and selecting relevant studies, which enhances the methodological rigor and credibility of the findings[29]. The review process follows a standard five-phase protocol: (1) planning and protocol development, (2) searching across academic databases, (3) screening for eligibility, (4) quality appraisal, and (5) data extraction and synthesis[3].

3.2. Formulating the Scope: The PEO Framework

To define the review's boundaries and ensure accurate results, the scope is formulated using the **Population–Exposure–Outcome (PEO)** framework:

- **Population:** Students, instructors, and higher education institutions (HEIs).
- **Exposure:** The pedagogical and institutional integration of **Generative AI** (e.g., ChatGPT, Large Language Models).
- **Outcome:** Implications for **sustainable education**, including the achievement of Sustainable Development Goal (SDG) 4, institutional resilience, and environmental impacts.

Table 1. Summary of experimental parameters

Component	Description
Population (P)	Students, instructors, and Higher Education Institutions (HEIs)
Exposure (E)	Integration of Generative AI technologies (e.g., ChatGPT, Gemini, Claude, Large Language Models) into teaching, learning, and institutional practices
Outcome (O)	Sustainable education outcomes, including SDG 4 achievement, institutional resilience, educational innovation, ethical considerations, and environmental sustainability

3.3. Search Strategy and Information Sources

A comprehensive literature search is conducted across major multidisciplinary and specialized academic databases, specifically **Scopus, Web of Science (WoS), ERIC, PubMed, and IEEE Xplore**. The search period is restricted to publications from **2022 to 2026**, capturing the "post-ChatGPT" era of rapid development and adoption in higher education. Search terms are organized into three conceptual blocks:

1. **Technology:** "Generative AI" OR "ChatGPT" OR "Large Language Model" OR "LLM".
2. **Context:** "Higher Education" OR "University" OR "Tertiary Education".
3. **Outcome:** "Sustainability" OR "SDG 4" OR "Environmental Impact" OR "Ethics".

3.4. Eligibility Criteria

To maintain a sharp thematic focus, strict inclusion and exclusion criteria are applied:

- **Inclusion:** Peer-reviewed journal articles, empirical studies, and conceptual frameworks that substantively discuss the **environmental, pedagogical, or institutional sustainability** of GenAI in higher education.
- **Exclusion:** Studies focused exclusively on primary/secondary education, technical development without educational implementation, non-English publications, and editorials or opinion pieces lacking empirical evidence.

Table 2. Inclusion and Exclusion Criteria

Inclusion Criteria	Exclusion Criteria
Peer-reviewed journal articles	Conference abstracts and editorials
English-language publications	Non-English publications
Studies discussing sustainability, ethics, or educational applications	Technical AI papers without educational implementation
Published between 2022–2026	. Studies published before 2022
Studies focusing on GenAI in higher education	Primary or secondary education only

3.5. Study Selection and Inter-Coder Reliability

The study selection process follows a two-stage screening procedure (title/abstract followed by full-text review) as visualized in a PRISMA flow diagram. To minimize subjective bias and ensure reliability, the selection process is conducted independently by two researchers. Inter-coder reliability is calculated using **Cohen's Kappa (κ)**, aiming for a value above **0.80**, which indicates strong agreement according to conventional benchmarks.

3.6. Methodological Quality Appraisal

The quality and reporting transparency of the included studies are assessed using standardized appraisal tools:

- **Mixed Methods Appraisal Tool (MMAT):** Used to evaluate the methodological quality of empirical qualitative, quantitative, and mixed-methods research.
- **Critical Appraisal Skills Programme (CASP):** Employed to determine if the design and analysis of the studies introduce biases that could compromise the validity of the findings.
- **GRADE Approach:** Utilized to grade the quality and certainty of the overall evidence base.

3.7. Data Extraction and Synthesis

Data are extracted using a structured form to capture authorship, methodology, AI tools used, and principal findings. A **hybrid thematic synthesis** approach—combining **inductive coding** (letting themes emerge from data) and **deductive coding** (guided by theoretical frameworks)—is used to analyze the results. To supplement this narrative synthesis, **bibliometric mapping** software such as **VOSviewer or Biblioshiny** is employed to visualize keyword co-occurrence networks and identify global research power dynamics, such as "multipolarity"

4. Results

The analysis of the selected studies revealed several recurring themes that characterize the current state of research on GenAI in sustainable education. The most prominent theme was the educational potential of GenAI, with the majority of studies reporting improvements in personalized learning, adaptive instruction, automated assessment, intelligent tutoring, and student engagement. Many researchers also emphasized the role of GenAI in supporting Sustainable Development Goal 4 (Quality Education) by enhancing accessibility, promoting inclusive learning environments, and enabling more

efficient use of educational resources. These findings indicate that GenAI has considerable potential to improve both learning outcomes and institutional sustainability when integrated with appropriate pedagogical strategies.

Despite these opportunities, the reviewed literature consistently identified several ethical and operational challenges. Algorithmic bias, misinformation, data privacy, academic integrity, copyright concerns, and excessive dependence on AI-generated content emerged as the most frequently discussed issues. Several studies warned that overreliance on GenAI may reduce students' critical thinking, creativity, and independent problem-solving abilities, highlighting the importance of maintaining human-centered teaching approaches. These findings suggest that responsible governance and AI literacy are essential for ensuring the ethical implementation of GenAI in higher education.

Another major finding was the growing recognition of the environmental implications of GenAI. While many studies acknowledged its contribution to educational sustainability, they also emphasized the substantial energy consumption, carbon emissions, water usage, and electronic waste associated with training and deploying large language models. This contradiction, commonly described as the **"sustainability paradox,"** emerged as one of the most significant themes across the reviewed literature. The findings demonstrate that educational benefits should be evaluated alongside environmental costs when assessing the overall sustainability of GenAI technologies.

The review also identified several trends and research gaps. Most publications originated from developed countries and focused primarily on higher education institutions, with comparatively limited evidence from developing countries and school-level education. Furthermore, many studies relied on conceptual discussions, surveys, or short-term evaluations, while longitudinal and empirical investigations measuring long-term educational, environmental, and institutional impacts remained scarce. These observations indicate a need for more comprehensive and context-specific research to understand the sustainable integration of GenAI across diverse educational settings.

Overall, the findings demonstrate that the successful adoption of GenAI in sustainable education depends on balancing educational innovation with ethical responsibility, environmental sustainability, institutional preparedness, and supportive governance frameworks. The reviewed studies consistently emphasize that GenAI should be implemented as a complement to human teaching rather than a replacement for educators. Future research should therefore focus on developing evidence-based implementation frameworks, evaluating long-term sustainability outcomes, and promoting equitable access to AI technologies across different educational contexts.

Table 3. Ethical Domains and Challenges of Generative AI in Education (Condensed)

Ethical Domains	Principal Harms(Risks)	Principal Benefits(Opportunities)	Remedial Strategies
Learner Agency & Cognitive Development	Cognitive dependency, erosion of critical thinking/creativity, and "metacognitive laziness".	Personalized learning pathways, 24/7 support, and fostering higher-order thinking.	Implement critical AI literacy training and redesign assessments to focus on the learning process.
Algorithmic Bias & Equity	Perpetuation of gender/racial biases, linguistic dominance of English, and algorithmic	Improved accessibility for underserved/neurodiverse learners and democratization of	Mandate bias mitigation auditing, diversify training data, and use fairness-aware

Ethical Domains	Principal Harms(Risks)	Principal Benefits(Opportunities)	Remedial Strategies
	colonialism.	resources.	models.
Environmental Sustainability	Significant carbon footprint, high water consumption for cooling, and toxic electronic waste.	Potential for "Green GenAI" to optimize resources and model complex sustainability projects.	Adopt small language models (SLMs) and integrate environmental ethics into procurement.
Data Privacy & Security	Data breaches, unauthorized scraping, surveillance, and commercial exploitation of student data.	Data-driven adaptive learning paths and efficient personalized feedback profiles.	Adhere to GDPR/FERPA, use robust data governance frameworks, and enforce informed consent.

5. Discussion

Synthesis of findings, contextual interpretation through theory, honest appraisal of limitations, and careful management of causal claims.

5.1. Synthesis and Interpretation of Findings

The discussion must evaluate the results through the lens of your initial research questions and the **Sustainable Development Goals (SDGs)**, particularly **SDG 4 (Quality Education)** and **SDG 12 (Responsible Consumption)**.

- **Thematic Alignment:** Interpret identified opportunities—such as personalized learning, adaptive tutoring, and instructional automation—not just as technical successes but as catalysts for **transformative learning**.
- **Addressing the "Sustainability Paradox":** Discuss the tension between GenAI's role as a "dematerialized" tool and its significant **physical resource footprint** (energy, water, and e-waste).
- **The Global Perspective:** Contrast the surge in global scholarship with the persistent **digital divide**, noting that while research is becoming more "multipolar," Western institutions still maintain dominant citation influence.

5.2. Contextualization Through Educational Theory

Rather than just listing results, use your discussion to ground the data in established pedagogical frameworks:

- **Constructivism and Agency:** Discuss whether AI-generated content supports **active knowledge construction** or if it risks creating "metacognitive laziness" and dependency.
- **Cognitive Load and Offloading:** Use **Cognitive Load Theory** to explain how GenAI acts as a learning scaffold by reducing extraneous load, while cautioning against "cognitive offloading" where the AI performs the thinking for the student.
- **Framework Integration:** Compare your findings against proposed models like the **GAISE (Generative AI-Enabled Sustainable Education) framework** or the **Three-Layer Architecture (Efficiency, Pedagogy, Ideology)**.

5.3. Honest Acknowledgment of Limitations

A rigorous review must disclose factors that may restrict the validity of its conclusions:

- **Search and Language Bias:** Note if the review is restricted to **English-language publications**, which limits the cultural and geographical range of evidence.
- **Database Omissions:** Acknowledge that the omission of certain repositories (e.g., specialized computer engineering or local regional databases) may leave out innovative practices from the Global South.
- **Temporal Boundaries:** Since GenAI is rapidly evolving, specify that your findings represent a **"snapshot in time"** and that new models (e.g., GPT-5 or Claude updates) may have emerged after your review period.

5.4. Avoiding Overstated Causal Claims

The discussion must distinguish between **correlation, observation, and established causality**:

- **Self-Reported Data:** Many studies rely on surveys of student perceptions; the discussion should clarify that **perceived helpfulness** does not always equate to **measurable learning gains**.
- **Methodological Divide:** Be cautious in applying technical benchmarks (like carbon intensity per token) to classroom settings, as educational research often relies on **indirect proxies** rather than direct hardware measurements.
- **The Correctness-Control Fallacy:** Avoid claiming that AI-generated labor is strictly more "efficient" or "sustainable" than human labor without accounting for the **iterative prompting and human verification cycles** required for academic accuracy.

6. Recommendations for Future Research

The column should conclude by identifying specific "research gaps" identified during the review:

- **Longitudinal Studies:** Note the urgent need for studies tracking the **long-term cognitive impact** of GenAI beyond a single semester.
- **Sector-Specific Evidence:** Highlight the lack of empirical environmental data in **primary and secondary education** compared to higher education.
- **Ethics in Practice:** Call for research that converts abstract ethical principles (transparency, bias reduction) into **quantifiable classroom indicato**

7. Conclusion

The integration of Generative AI into higher education represents a **fundamental paradigm shift** rather than a mere technological update. This review has illuminated a complex landscape where the promise of **personalized, adaptive, and inclusive learning** is closely intertwined with a "sustainability paradox" that institutions must navigate with caution.The sources consistently indicate that GenAI uniquely supports **SDG 4 (Quality Education)** by acting as a "cognitive stimulator" and a "co-teacher". By shifting from product-focused to **process-oriented assessment**, GenAI encourages students to develop **transversal competencies** such as critical thinking, self-regulation, and creativity. However, the potential for **"metacognitive laziness"** and cognitive over-dependence highlights the need for pedagogical designs that require active human–AI collaboration rather than passive output generation.A critical finding of this review is the invisibility of AI's **physical resource footprint**. While GenAI is marketed as a dematerialized tool, its operation drives massive electricity consumption, high carbon emission, high water demand for cooling, and accelerated e-waste cycles. For education to be truly sustainable, institutions must move toward **"Green AI Literacy"** and prioritize the use of specialized, small language models (SLMs) over resource-intensive general-purpose systems.The successful adoption of GenAI depends on robust **institutional stewardship**. This review identifies **algorithmic bias, data privacy, and academic integrity** as the primary ethical barriers to sustainable integration. Furthermore, the concentration of AI research and infrastructure in the Global

North threatens to widen the **global digital divide**, necessitating a shift toward **multipolarity** where non-Western scholars and institutions are equitable participants in AI-driven transformation.To achieve long-term resilience, the sources suggest that educational systems must align five strategic pillars:

- **Critical and ethical appropriation** of technology.
- **Institutional management** of infrastructure that ensures equitable access.
- **Comprehensive faculty development** focused on AI literacy and evaluative judgement.
- **Curricular transformation** that integrates AI as a co-creator.
- **Pedagogical innovation** that prioritizes human empathy and critical thinking.

In summary, the role of Generative AI in sustainable education is not determined by the technology itself, but by the **intentionality of its implementation**. If universities embrace GenAI with a commitment to **ethical stewardship, environmental transparency, and pedagogical integrity**, they can create a resilient ecosystem that empowers all learners for an AI-enabled world. Future research must now prioritize **longitudinal studies** to evaluate the long-term cognitive and environmental impacts of these tools as they become permanent features of the academic landscape

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Conflict of Interest

"Declare no conflict of interest."

Data Availability Statement

No new data were generated or analyzed in this study. The findings are based exclusively on published literature retrieved from academic databases, and all referenced sources are cited within the article.

AI Usage Disclosure

Used **ChatGPT (OpenAI, GPT-5.5)** during the preparation of this manuscript to assist with language editing, grammar refinement, sentence restructuring, and improving the clarity and readability of the text. The AI tool also supported brainstorming and organizing the review content. All generated content was critically reviewed, verified, and revised by the authors, who take full responsibility for the accuracy, originality, and integrity of the final manuscript.

Author Contributions

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