sustainability

Review

Challenges and Opportunities for Leveraging Generative AI for Sustainability Education: A Critical Review

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Abstract

The integration of generative artificial intelligence (Gen-AI) into sustainability education is justified by its potential to introduce sustainability perspectives through transformative learning. By encouraging individuals to critically reflect and challenge their prior beliefs and assumptions, Gen-AI can deepen their understanding of sustainability concepts and inspire long-term commitment to sustainable practices. While the broader educational potential of Gen-AI has been widely explored, previous research tends to overlook its specific benefits and implications within the context of sustainability education. This paper addresses this gap by exploring both the opportunities and challenges of employing Gen-AI in the context of sustainability education through a critical review of diverse outputs. A thematic analysis of the outputs reveals a complex interplay between the opportunities and challenges. While Gen-AI offers access to information, personalised learning, fosters creativity, and decision-making support, the associated challenges, such as unequal access, overreliance on use, unreliable outputs, and environmental cost, may undermine the opportunities and the broader efforts to foster sustainability. The originality of this paper lies in providing critical insights for institutions, educators, and policymakers seeking to harness generative AI to advance sustainability education, an area pivotal to the pursuit of a just and sustainable future.

Keywords: generative AI; sustainability education; transformative learning; opportunities; challenges

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1. Introduction

Artificial intelligence (AI) is changing the education sector, with a growing number of AI-driven applications now being utilized in educational settings [1]. Following recent developments, generative AI (Gen-AI) can produce meaningful text related content, images, audios, and videos based on the data it was trained on [2]. The emergence of Gen-AI brings us new experiences and opportunities for creativity, including but not limited to employing various resources for analysis needs and even automation processes [3,4]. Within the field of education, Gen-AI is expected to transform the future by enhancing learning experiences within various educational tasks, resulting in much research conducted to explore its potential and benefits for the institution, teachers, and students [5]. This paper critically examines the role of Gen-AI specifically in sustainability education contexts, as it can be asserted that while Gen-AI offers significant potential to enhance teaching and learning, its integration should be considered carefully to tackle challenges that may arise. The paper begins by reviewing how Gen-AI is currently used by students and educators in general, followed by the analysis of its role in the context of sustainability education, drawing on relevant outputs. Conclusively, the paper discusses the findings regarding the interconnected opportunities and challenges that can inform the effective integration of Gen-AI in sustainability education.

2. Gen-AI for Education

The integration of Gen-AI into education is transforming how both students and educators engage with teaching and learning at various levels [6]. This section explores how Gen-AI is being utilized within an educational context to support students and educators in teaching and learning, along with broader institutional challenges. Here, we highlight its benefits as well as the ethical and pedagogical challenges it introduces.

In the educational domain, students have been using Gen-AI mainly for information search and text generation along with improving academic productivity and quality through explaining concepts and summarizing educational materials [7]. Gen-AI can assist with grammar, structure, and citations, which helps improve the efficiency and quality of academic writing standards [8]. While students recognize the use of Gen-AI to enhance learning effectiveness through idea brainstorming and academic writing, concerns arise from their excessive dependence on this technology [9]. Students' overreliance on AI may paradoxically hinder rather than enhance learning because Gen-AI-generated content may lack contextual relevance, making it challenging to attain authentic learning [10]. Furthermore, students find themselves in a comfort zone where Gen-AI overuse can lead them to learn and make decisions based solely on generated answers, thereby restricting their personal development in critical thinking [9]. These concerns emerge with wider implications, acknowledging that Gen-AI responses contribute to assessment integrity issues, particularly the risk of plagiarism from AI-generated content that remains unchecked [11]. Naturally, this raises questions about whether students are presenting their own understanding in assessment, as it is difficult to distinguish content generated originally by students from that generated by AI [12]. Hence, the intention to support learning might be blocked in the process, highlighting the importance of integrating Gen-AI into educational settings thoughtfully and ethically [13].

While students primarily use Gen-AI to support their learning and writing, educators utilize Gen-AI to automate repetitive and time-consuming tasks, from creating teaching plans, preparing learning materials to assisting in assessment [14]. This utilisation of Gen-AI to reduce educational workloads provides teachers more time to focus on improving their teaching, ultimately enhancing the learning experience for both teachers and students [15]. Additionally, Gen-AI promotes teaching by cultivating personalized learning with customized high-quality content based on students' preferences, which also allows for the development of specific questions and assessments based on students' needs [11]. Ultimately, the difficulty with setting learning tasks can be dynamically modified in response to students' performance, offering opportunities for critical engagement [16].

However, both students and educators must be cautious when adding resources, that is, materials or students' assessment sheets into Gen-AI to generate content. Since Gen-AI uses large amounts of data to be able to automate tasks, it often requires collecting personal and confidential information of students and institutions, bringing up important ethical and privacy issues [17,18]. This indicates that the use of Gen-AI in education emphasizes the importance of considering institutional accountability [19], which covers broader challenges at the institutional level. The use of user-prompted data to create content has also caused another problem with the correctness of information and the possibility of biased information. This is due to Gen-AI limitations in producing information based on their training data, indicating challenges to producing good quality and reliable content with such systems [11]. Consequently, ensuring the quality and reliability of generated content for integration into educational materials can be challenging. Moreover, institutions also face challenges due to the lack of clear guidance on Gen-AI, since both students and educators are already leveraging Gen-AI in their academic activities despite the absence of institutional regulation [20]. Taken together, these issues demonstrate that employing Gen-AI in education goes beyond learning and teaching practices and requires coordinated accountability at the institutional level.

Building on these broader institutional implications, Gen-AI's potential within sustainability education deserves particular attention. Sustainability education's aim extends beyond knowledge sharing to building values and motivating action for sustainability worldwide [21]. The following section explores how Gen-AI can contribute to this broader aim.

3. Gen-AI for Sustainability Education

With all the potentials mentioned before, Gen-AI presents a transformative opportunity to enhance sustainability education. One of the sustainability criteria defined by Ruggerio [22] is the need to consider both intergenerational and intragenerational equity, meaning we meet present needs without harming future resources. Hence, sustainability education could be seen as part of an evolving learning ecosystem where knowledge is shared, and future learners can continue to benefit from it. Within this context, Gen-AI could serve innovative teaching and foster a mindset of continuous learning and flexibility [23]. Due to the broad definition of sustainability education, the potential of Gen-AI can promote sustainability in several ways. In terms of resources, Gen-AI has the capacity to lead to efficient use of resources (such as reducing paper waste, optimizing energy consumption in school, and decreasing carbon emissions with the presence of virtual learning that limits the amount of travel), contributing further to sustainability in higher education from an environmental standpoint [24]. When Gen-AI is harnessed for personalized learning by analyzing learning patterns and preferences [25], it transforms students' learning experience from a teacher-centered to a student-centered approach that is suitable for individual needs. Eventually, this transformation ensures inclusive and fair quality education for all individuals as it is accessible for students in different situations [26,27]. However, we should acknowledge that access to Gen-AI will not be forever free to everyone. Updated Gen-AI versions are only available with a subscription and limit access for those who cannot afford the premium version, resulting in further concerns about equity and accessibility by opposing the democratization of knowledge [28]. This limitation in access also limits the wider potential of Gen-AI's use in fostering sustainability education.

Furthermore, and despite its capability to generate sustainability information, Gen-AI depends on the quality and quantity of users' prompts; while it typically produces concise and straightforward responses, more specific prompts are needed for detailed information [28]. This poses an issue with energy consumption as Gen-AI works across several accelerators and servers that use a lot of energy to operate and generate responses, leading to a larger amount of energy, which contrasts with the concept of sustainability [29]. The rise of global environmental issues has led to the development of sustainability in the education sector [14]. Sustainability education with Gen-AI promotes environmental awareness by providing students with the knowledge to understand and address ecological concerns. Gen-AI can introduce real sustainability challenges into the curriculum by engaging students in simulations and interactive learning experiences that reflect real-world issues about climate change, biodiversity, and resource degradation [24]. Moreover, Gen-AI can help students make ethical decisions while dealing with environmental issues by assisting them to feel more positive about protecting nature [30]. Addressing global ecological challenges within sustainability education is essential, as reducing the environmental impact of education can ensure that future generations have access to high-quality learning through various applications of Gen-AI [25].

Existing research has indeed highlighted Gen-AI's abilities to promote sustainability education by facilitating different academic endeavors, from personalized learning experiences to addressing environmental challenges. Even though Gen-AI offers promising prospects, it should be acknowledged that there is significant uncertainty about Gen-AI implementation in higher education [31]. Previous research tends to overlook the context of sustainability education to underlying challenges and opportunities. This paucity presents an opportunity for this research to address a critical question, that is: What are the opportunities and challenges for employing Gen-AI in sustainability education contexts?

While sustainability education transcends the mere concept of longevity; it emphasizes transformative approaches that reshape both the world and the educational experience needed to promote new ways of living (United Nations Educational, Scientific and Cultural Organization [32]. Therefore, we turn to transformative learning theory as our conceptual foundation to provide analysis on how Gen-AI can transform students' understanding of sustainability issues. By doing so, we hope to provide meaningful insights for institutions, policymakers, and educators, guiding them to understand Gen-AI's role in cultivating transformative learning experiences that promote sustainability awareness and action within the educational context.

4. Conceptual Framework: Transformative Learning

Transformative learning describes how individuals revise their frames of reference, specifically, their habits of mind and points of view to better interpret and understand their experiences, thereby forming more justified beliefs and opinions to guide their actions [33]. This concept has gained prominence in education, as it promotes sustainable development by challenging and reshaping people's assumptions about their socio-environmental contexts [34]. For example, transformative learning can shift individuals' perspectives on environmental issues, sparking greater interest and commitment to advancing community sustainability [35]. It also positions interactions and discussions on sustainability as valuable learning spaces [36]. Ultimately, such perspective shifts can strengthen sustainability education, particularly for students whose initial assumptions or beliefs conflict with sustainability principles. However, students often lack the skills to identify their own or others' underlying assumptions and prior experiences [37]. As a result, transformative learning may fall short in supporting sustainability education, given that critically revising the meaning of one's experiences lies at its core [38]. Therefore, students require targeted guidance to fully uncover and interrogate their assumptions in sustainability education.

A main question about transformative learning for sustainability in institutions is how learners experience the process and manage the complex issues related to sustainability while fulfilling the responsibility to sustainability education at the same time [36,39]. Alhadeff-Jones [40] argues that transformation is more likely to result in personal adjustments rather than actual efforts to social action and change, revealing tensions in achieving the goals for sustainability that is transformative. Hence, students and teachers must be open and ready to take part in a transformative learning process that starts by asking if their beliefs and knowledge help bring about sustainability changes or need to be changed [39,41]. However, Tully [42] argues that human imagination, creativity, and innovation have not provided enough answers to sustainability issues due to the limitations of thought that have kept their knowledge separated. Hence, designing specific learning activities in the classroom, such as group discussions, writing reports, and selfevaluations, can facilitate transformative learning by enhancing students' understanding of sustainability concepts through negotiation and critical reflection [42,43].

As we are shifting into an era characterized by a technologically advanced industry, educational institutions have utilized existing technological tools to remain relevant and effective while adapting to the concept of sustainability. In the context of transformative learning for sustainability education, Gen-AI can serve as a tool to generate context-based and human-like feedback that supports students' reflections [44]. Naturally, the interaction between students with Gen-AI responses reflects transformative learning, as this concept is grounded in human communication [45]. When students engage in discussions, Gen-AI can assist in exhibiting new sustainable topics as students inquire about sustainable issues and prompt reflective questions to develop their knowledge. The habits of mind—a series of thinking, feeling, and acting [37]—can shift into a new perspective through self-critical reflection as students receive generated responses. Through guided reflection supported by Gen-AI, students can re-examine their assumptions and develop new ways of thinking and acting toward sustainability. Taylor and Cranton [38] argue that it is empathy that enables learners to reflect by engaging with the emotional dimension of their assumptions. This raises questions about how effectively Gen-AI can promote sustainability through reflection, as such systems may have limited capacity to engage with complex aspects of human development [46].

Knowing how Gen-AI could facilitate transformative learning by introducing novel viewpoints on sustainability gives us a valid justification to integrate Gen-AI in sustainability education. Yet, we must still address the challenges that arise from harnessing Gen-AI to maintain the commitment to managing environmental and social impacts, which is associated with sustainability education. Furthermore, this theoretical lens provides the foundation for this review, specifically informing how the analysis identifies evidence of perspective change through critical reflection that suggests the potential of Gen-AI to facilitate transformative learning.

5. Methodology

Based on the purpose of this study, we employ a qualitative approach. The nature of this approach allows for answering the "what," "how," and "why" questions in a specific context [47], making it well-suited to examine both the benefits of Gen-AI for sustainability and its limitations. From the previous section, it can be implied that sustainability within educational contexts is a complex issue, and this underscores the relevance of employing a qualitative approach to thoroughly explore the subject.

In matters of sustainability, systems are interconnected within a complex network of cause and effect, action and reaction, making it essential to understand the issues on a larger scale in order to contribute to the sustainability of entire systems [48,49]. We applied a critical review of secondary sources to capture insights into the connections between Gen-AI and sustainability education. As the subject of this paper is an emerging one, the choice of a critical review is justified, rather than a systematic or scoping one [50].

The literature search included peer-reviewed journal articles identified through databases, including Scopus, Web of Science, and Google Scholar, using a combination of keywords i.e., "Generative AI" OR "Generative Artificial Intelligence") AND ("sustainability Education" OR "sustainable education" OR "Education for sustainable development" OR "environmental education" OR "climate change education." Aligned with the public launch of Gen-AI, the articles included were published between 2022 and 2025, where the initial search yielded 53 studies as depicted by Figure 1. After removing duplicates, 35 studies remained for further screening. These studies were then reviewed for eligibility based on relevancy to the application of Gen-AI in sustainability education. Only studies that investigated the use or integration of generative AI in sustainability education related contexts were included. This encompassed primary, conceptual, and exploratory research. The scope of inclusion was broadened due to the limited amount of existing work on this topic. Furthermore, a range of studies employing diverse typologies and methodologies were included, as long as they aligned with the focus of the research, namely sustainability education and the use of generative AI. Studies that focused primarily on the technical development of Gen-AI models were excluded, as they fall outside the educational and practical scope of this review. In total, 20 studies that did not meet these criteria were excluded. Accordingly, we assessed the remaining 15 studies to full-text eligibility, with no further exclusions at this stage. We evaluated the relevance of each study by examining all sections labelled as 'results' or 'findings' and determining their suitability for inclusion in the analysis. The limited number of the articles retained is owed to the emerging nature of this topic, as they provide valuable insights into the development of the field. The articles were subsequently subjected to thematic analysis, categorizing findings into opportunities and challenges to provide a structured synthesis of the existing research.

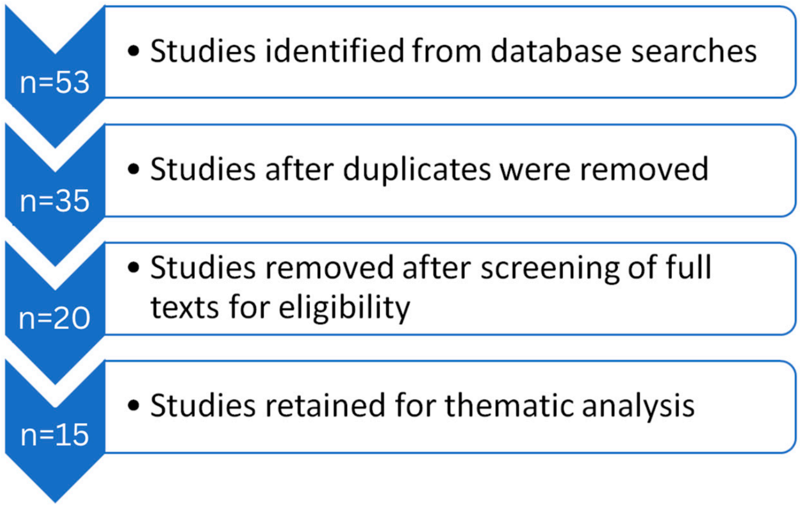

Figure 1. The literature search process.

6. Data Analysis

The thematic analysis allows us to identify, categorise, and report meaningful patterns within a qualitative data source [51], enabling us to link emergent themes and information of Gen-AI to the topic of sustainability and obtain a nuanced exploration of Gen-AI's role in fostering sustainability education. We implemented and adapted the six-step process of thematic analysis that includes: data familiarization; keyword identification; code selection; theme development; conceptualization through the interpretation of keywords, codes, and themes; and, finally, the development of a conceptual model, to obtain the patterns and understand the meaning of keywords from the data [52].

As we examined the retained articles, we observed common themes emerge that are relevant to our research objectives. We recognized the common terms and patterns to label them into several important keywords that act as a preliminary filter to ensure the following coding process remains aligned with the objectives of the study. In the coding step, we assigned codes i.e., short phrases, into segments of text and captured the core message of the data to simplify the complex data and transform it into a more structured form. To ensure consistency and better capture the underlying meaning, we reviewed assigned codes and assessed whether additional coding was necessary for patterns that emerged across initial codes. Next, we arranged the codes into meaningful groups of themes to find connections, helping to provide answers to the research question. We used these generated keywords, codes, and themes to obtain definitions from the concepts. Finally, we developed the conceptual model of Gen-AI implementation in sustainability education by constructing and interpreting a unique representation from the data with insights from the transformative learning concept.

7. Findings

This section presents the findings derived from the selected articles concerning various applications of Gen-AI in sustainability education. Our conceptualization of sustainability education touch on education for sustainable development, environmental education, and climate change education. Table 1 presents the list of the reviewed articles, and the subsequent analysis identifies recurring themes across these studies, offering a comprehensive understanding of the opportunities and challenges Gen-AI presents within the context of sustainability education. For the review, opportunities are understood as the positive outcomes or advantages mentioned in the literature that could be achieved by leveraging Gen-AI in sustainability education. Challenges denote the problems, limitations, or potential risks associated with its implementation.

The thematic analysis revealed several interconnected themes demonstrating the potential of Gen-AI in fostering sustainability education: access to information, personalized learning, fostering creativity for sustainability education, and data-driven decision-making to reduce workload and optimize resources. The reviewed studies suggest that Gen-AI offers readily available information and resources that naturally promote sustainability by transforming education through personalized learning experiences and practical engagement with sustainability matters. Since addressing sustainability challenges requires creative and adaptive educational approaches, Gen-AI has also been shown to foster creative learning environments that lead to innovative solutions for sustainability. Furthermore, Gen-AI plays a significant role in data-driven decision-making to support sustainability by managing and analyzing environmental data, thereby informing strategic decisions and actions towards sustainability issues.

While these themes emphasize the promise of Gen-AI in supporting sustainability education, they also underscore the risks associated with the overreliance on Gen-AI, which may undermine the long-term aims of sustainable development. As Gen-AI offers access to knowledge, we found out that there are disparities in accessing the tools due to digital literacy and infrastructure gaps, which create barriers while adopting Gen-AI tools for sustainability and education. Additionally, there are concerns about how AI-generated misinformation (referred to as “hallucinations”) and bias affect the reliability and accuracy of Gen-AI outputs. In the following subsections, we explore these themes further under the headings of “Opportunities” and “Challenges”.

Table 1. Table of Reviewed Articles.

Author(s)	Year of Publication	Title	Objective	Methodology	Overarching Contribution	Limitation of the Study
Boustani et al. [53]	2024	Leveraging ICT and Generative AI in Higher Education for Sustainable Development: The Case of a Lebanese Private University	Explore the role of Gen-AI in fostering sustainable development within higher education.	Descriptive survey	Examine how ICT and Gen-AI jointly influence higher education and sustainable development in a developing country, highlighting their interconnections and providing practical strategies for institutions in similar contexts to enhance sustainability.	As the study focuses on a specific environment (a Lebanese private university), its findings may have limited generalizability and should be interpreted with caution when applied to other contexts.
Li et al. [54]	2024	Generative AI for Sustainable Design: A Case Study in Design Education Practices	Explore the interactions between Gen-AI tools and novice designers in developing sustainability education practices.	Case study	Contributes to the growing literature on Gen-AI and sustainable design, delivering useful insights into future research and development of Gen-AI tools for design.	The study involved primarily novice, first and second-year design students; its findings on Gen-AI tool may not apply to experienced or professional designers.
Henriksen et al. [55]	2024	Creative Learning for Sustainability in a World of AI: Action, Mindset, Values	Explore the intersection of sustainability, creativity, and technology for education, particularly focusing on artificial intelligence.	Conceptual approach	Introduces a novel conceptual framework that integrates creative pedagogies with sustainability principles, providing guidance for the responsible use of Gen-AI to foster both environmental care and creative exploration.	The framework is intentionally theoretical and untested, aiming to inspire further research rather than provide empirical validation or specific tool guidance.
Iatrellis et al. [56]	2024	Leveraging Generative AI for Sustainable Academic Advising: Enhancing Educational Practices through AI-Driven Recommendations	Explore the integration of ChatGPT, a Gen-AI tool, into academic advising systems and assess its effectiveness in comparison to traditional human-generated advice.	Mixed-mode research design	Assessing the integration of Gen-AI into academic advising resulted in a new hybrid advising framework designed to enhance the effectiveness and sustainability of educational practices.	A comprehensive evaluation of the data needed to assess the system's impact on student decision-making and advising quality is crucial for validating the prototype's practical utility but very limited focus on the actual subject of sustainability.
Chang and Kidman [57]	2023	The rise of generative artificial intelligence (AI) language Models—challenges and opportunities for geographical and environmental education	Conduct an illustrative experiment on Gen-AI language models, such as ChatGPT, and explore the challenges and opportunities they present for geographical and environmental education.	Exploratory approach	Introduce and frame the discussion regarding Gen-AI, such as ChatGPT, specifically within the context of geographical and environmental education by demonstrating practical utility.	The assessment of Gen-AI relies on basic experiments in which the authors posed a limited set of geographical and environmental education questions to ChatGPT, highlighting the need for more critical frameworks and comprehensive evaluations.
Nezhyva et al. [23]	2025	AI tools for sustainable primary teacher education: literary-artistic content generation	Explore the possibilities of using Gen-AI to generate literary-artistic content in sustainable primary teacher education.	Mixed-methods research	Advance sustainable education practices in primary education to better prepare future teachers for navigating the digital age.	The limited time dedicated within this study was a constraint that prevented the full exploration of Gen-AI potential.
Lee et al. [58]	2023	Designs and practices using generative AI for sustainable student discourse and knowledge creation.	Explore the potential of Gen-AI, particularly GPT, in education design to foster sustainable student discourse and knowledge creation.	Exploratory approach	Demonstrate the feasibility and designing appropriate methods and practices for integrating Gen-AI to support and sustain student discourse and knowledge creation in educational settings.	The necessary restriction on the amount of discourse data that could be analyzed in a single session constrained the scope of Gen-AI's immediate analytical capabilities.

Jost et al. [59]	2025	Enhancing sustainability decisions: AR and AI in gamified public education for environmental decision-making.	Investigate the impact of integrating AR and Gen-AI into museum learning experiences to enhance sustainability decision-making.	Design Research	Provide valuable insights for creating accessible, engaging, and effective digital tools in public education that support environmental decision-making.	Although the experiential aspect of sustainability education was enhanced, there was no significant increase in visitors' overall awareness of sustainability decisions, raising important questions about how to effectively foster sustainability awareness.
Xiaoyu et al. [60]	2025	Evaluating the efficacy of ChatGPT in environmental education: findings from heuristic and usability assessments	Evaluating ChatGPT usability and efficacy to inform its effective integration in environmental education concerning sustainable development goals.	Usability testing approach	Enhances understanding of Gen-AI's impact on environmental education and highlights the critical role of human involvement.	Focused solely on ChatGPT, overlooking the potential contributions of other Gen-AI tools and limiting a comprehensive understanding of Gen-AI's impact on environmental education.
Paxinos and Robertson [61]	2024	Abuzaharen's Challenge: Building Sustainability Competencies through Science-Fiction Narratives and Game-based Learning	Incorporating Gen-AI into game-based learning to enhance student engagement and develop sustainability competencies in higher education.	Case study	Offer practice-based insights and guidance for sustainability educators, interactive learning designers, and innovators exploring Gen-AI narrative games for future developments.	The study did not explore the potential of Gen-AI in more realistic learning contexts, where Gen-AI could enable educators to adopt new roles and enhance the overall learning experience.
Ellahi [30]	2024	Leveraging Generative AI for Environmental Education: Effects on Students' Environmental Knowledge and Attitudes with Moderating Influence of Ecological Susceptibility	Look at how using Gen-AI, in environmental education affects university students' understanding of nature and their feelings toward protecting it.	Quantitative research	Provide empirical evidence for the efficacy of Gen-AI in environmental education through connections between the tool and learning outcomes.	The study' reliance on self-reported data may introduce bias and the restricted university students' sample potentially limiting the generalizability of the findings to other populations.
Liu and Château [62]	2025	Fostering hope and action on climate change among University Students: Impact of a Futures-Oriented Teaching Module with Generative AI integration	Examines the development and impact of a future-oriented teaching module integrated with Gen-AI to cultivate foresight and engagement with climate change action.	Mix-methods approach	Highlight on how using structured, future-focused teaching that incorporates Gen-AI helps students identify practical steps they can take toward sustainability.	The study explicitly identifies the ceiling effect as a limitation that obscured the observation of significant improvement in the specific variable of Knowledge of Action Possibilities (KAP)
Laranjeiro et al. [63]	2025	Generative AI in Climate Change Communication and Education	Ascertain whether Generative AI may facilitate understanding and reduce barriers to climate communication.	Exploratory approach	Demonstrate that ChatGPT can enhance communication and deliver climate change information to promote understanding and encourage climate-friendly practices.	The study intentionally designed and used a set of generic prompts that were simple questions with little context, which led to answers that were too brief or general for analysis.
Nguyen et al. [64]	2024	Misrepresentation or inclusion: promises of generative artificial intelligence in climate change education	Examine the promises and challenges of Gen-AI to depict climate issues from an intersectional perspective.	Data generation and content analysis	Advance research on emerging technologies by exploring intersectional and culturally sustaining perspectives, contributing valuable insights into which identities are represented or excluded in AI-generated content.	The study evaluated generated content with feedback from a small group or participants, specifically 10 individuals.
Al Naqbi et al. [65]	2025	Generative AI Integration: Key Drivers and Factors Enhancing Productivity of Engineering Faculty and Students for Sustainable Education	Investigate the integration of Gen-AI within the context of engineering education, emphasizing its role in advancing sustainable development.	Mix-method design	Enhance theoretical knowledge and offer practical guidance to fully leverage Gen-AI for promoting sustainable engineering education and development.	The study's findings may have limited generalizability due to being conducted at a single institution with a small, potentially non-representative sample, and focusing solely on engineering disciplines, excluding insights from other academic fields.

7.1. Opportunities

7.1.1. Access to Information on Sustainability

Gen-AI enhances sustainable development by facilitating educational access for all, thereby ensuring equitable opportunities for learning [53]. The authors argue that there is a positive perception of Gen-AI's role in enhancing sustainability education due to its potential to provide immediate and easy access to educational content and resources, even in remote areas. Xiaoyu et al. [60] add that the rapid access provided by Gen-AI saves a lot of time compared to traditional searches. Like Boustani et al. [53], Chang and Kidman [57] maintain that Gen-AI tool like ChatGPT has instant access to information enhances learning, with a further claim supported by the observation that Gen-AI possesses an extensive knowledge base. This could be achieved as Gen-AI exhibits the ability to elaborate on selected existing content in a precise and summarized format [58]. Jost et al. [59] support this view by suggesting that AI-summarized information related to sustainability promotes local actions for sustainable development. Adopting similar positions, Nezhyva et al. [23] argue that Gen-AI enables the creation of high-quality multimedia educational products that provide information to be integrated into a sustainable educational process. In the context of geographical and environmental education, this easy access means that students can quickly find specific information about geographical phenomena, environmental challenges, and related concepts [57]. Additionally, Gen-AI can present complex environmental and climate information in accessible and engaging formats, assisting students to explore and encourage visionary thinking in sustainability education [55]. This is because users can access both general and specific information on climate change, its causes, impacts, and possible personal actions [63].

7.1.2. Personalized Learning on Sustainability

Henriksen et al. [55] observe that Gen-AI generates tailored prompts and dialogue with students, aligning educational content with students' specific interests and learning requirements. Similarly, Chang and Kidman [57] point out that the interactive nature of ChatGPT actively includes students in engaging conversations as they seek information related to geographical and environmental education. They further explain that this interactivity contributes to a more personalized learning experience by allowing learners to receive Gen-AI immediate feedback and grasp materials at their own pace. Similarly, Paxinos and Robertson [61] contend that Gen-AI can serve as an assessor that provides students with feedback based on their learning outcomes. Essentially, personalized feedback is an essential factor in enhancing students' achievement [56]. Boustani et al. [53] support this point by emphasizing that Gen-AI responses can be customized to individual learning needs, making students more responsive and engaging more deeply with sustainability concerns. From another point of view, Nezhyva et al. [23] note that personalized learning could be achieved with Gen-AI's ability to create unique and personalized learning materials using specific keywords captured in a detailed content description. As a result, Gen-AI can assist in tailoring and contextualizing content for diverse students [59]. Adopting a similar position, Xiaoyu et al. [60] emphasize ChatGPT's effectiveness in providing precise information based on given prompts and facilitating personalized interactions that promote self-directed learning among students. When the content was tailored to students' interest and interaction, Gen-AI effectively engaged them and encouraged positive attitudes toward environmental responsibility by boosting their positive feeling toward the environment [30]. Collectively, these findings highlight the capability of Gen-AI to tailor and enhance learning experiences in sustainability education.

7.1.3. Fostering Creativity for Sustainability Education

Nezhyva et al. [23] claim that personalized learning through Gen-AI supports the development of students' creativity and critical thinking skills, since it aids in creatively showcasing materials that are pretty complex to understand. Moreover, Liu and Château [62] support this idea further by stating how Gen-AI can visually enhance students' creativity by generating complex images that help them communicate their ideas efficiently. This aligns with Henriksen et al. [55], who highlight the significant potential of Gen-AI to support creativity by creating interactive experiences and enabling problem-solving through ecosystem simulations that imitate real-life scenarios related to sustainability issues. The authors further explain that this kind of creative learning builds important skills that will remain with students for a long time, encouraging them to stay involved in sustainability efforts even after they finish their education. In another case, Li et al. [54] present that Gen-AI helps generate a wide range of ideas and concepts that are essential in sustainability education design. Designers value the creative potential of Gen-AI, which provides unprecedented materials and streamlines the design process by automatically generating multiple solutions. Adding to this view, Iatrellis et al. [56] claim that the AI-generated recommendations from ChatGPT were appreciated in sustainable academic advising for being relevant and clear. These insights suggest that, along with its creative potential, Gen-AI also contributes to decision-making through its capacity to provide recommendations that inform practical sustainability efforts.

7.1.4. Data-Driven Decision-Making to Reduce Workload and Optimize Resources

With its ability to generate creative and innovative solutions, Gen-AI can also refine all generated materials to support informed decision-making, leading to more efficient and effective sustainability outcomes [54]. The authors assert that this capability stems from Gen-AI proficiency in handling substantial amounts of information and its significant level of semantic comprehension. Al Naqbi et al. [65] further support this argument, noting that this capability helps bridge the gap between theory with practice, while also fostering sustainable design and responsible innovation. Related to that, Chang and Kidman [57] suggest that Gen-AI can help in managing textual tasks, organizing data, and suggesting ways to present findings related to environmental education, leading to more informed decision-making and a deeper comprehension of environmental issues. This Gen-AI function not only supports better decision-making in sustainability education but also helps reduce the time and administrative workload at the same time [54,56]. Lee et al. [58] add to this perspective, writing that Gen-AI assistance in executing educational tasks has provided teachers more time to focus on knowledge development. Gen-AI's potential to manage information also contributes to the optimization of resources through effective resource management, which eventually leads to favorable environmental outcomes [53].

7.2. Challenges

7.2.1. Overreliance on Gen-AI

Despite the benefits that Gen-AI offers in sustainability education, there is a risk of overreliance on its use in educational settings. Chang and Kidman [57] identify the danger of students depending too heavily on Gen-AI to generate materials, causing them to fail in developing critical thinking. Along the same lines, Henriksen et al. [55] argue that overreliance on Gen-AI without active human engagement and critical evaluation is likely to lead to suboptimal learning outcomes. As Gen-AI becomes widely used in educational settings, it reduces the quality of human interaction and undermines the need for students to develop essential skills [57]. Li et al. [54] support this view by stating that Gen-AI replaces skills like searching for academic literature or making detailed outlines. The writers elaborate that when we rely too much on Gen-AI, we might stop learning or practicing these skills. This issue raises important questions about the long-term implications of integrating Gen-AI into educational environments, as its overuse could even hinder students' ability to ask effective questions and get relevant, meaningful answers from the AI itself [53,57]. Likewise, Henriksen et al. [55] hold the view that isolated use of Gen-AI leads to a learning that is overly focused on theory and data that does not equip students with the practical, creative, and problem-solving skills they need to address real-world sustainability challenges.

7.2.2. Inequalities in Levels and Access

Another key challenge identified from the literature is the inequality in both access to and experience with Gen-AI tools. Boustani et al. [53] note that inequality persists as certain rural regions or institutions that have fewer resources and inadequate infrastructures struggle to integrate Gen-AI effectively into educational settings, resulting in a significant gap in digital access. The authors further argue that this limited access not only hinders educational equity but also obstructs broader sustainability efforts by restricting the capacity to adopt and use Gen-AI information for addressing sustainability issues. A broadly similar point has also been made by Chang and Kidman [57], who state that socioeconomic factors as the main factor influencing unequal access to Gen-AI. They imply that students who lack access to Gen-AI will experience different learning achievements compared to those who have ample access to these resources. With unequal learning outcomes, the issue of access is associated with digital literacy gaps, as there are various levels of familiarity and proficiency with technological tools that can create disparities in how effectively Gen-AI is integrated into learning environments [53]. Even when access is available, uneven skill levels result in inconsistent benefits. This is supported by Al Naqbi et al. [65], who found that participants with higher levels of Gen-AI familiarity generally demonstrated more effective integration. Ultimately, this reinforces existing sustainability educational inequalities rather than addressing them.

7.2.3. Unreliability of Gen-AI Outputs

There is a serious concern about reliability due to the risk of Gen-AI generating inaccurate and biased results [54] Lee et al. [58] observe that the cause of this issue is because of invalid references that were used by Gen-AI, leading to partially incorrect responses. For instance, these responses may imply or manipulate opinions that natural and human causes are equally significant, which is not accurate in the context of climate change education [63]. Such inaccurate responses also oversimplify the complex phenomena that exist within communities [64]. In the same vein, Henriksen et al. [55] note that Gen-AI relies on human historical data, which does not rule out the possibility of inaccurate and biased information from a specific situation, leading to Gen-AI producing answers based on wrong or biased information. In their study, Iatrellis et al. [56] witnessed different cases of partially correct and entirely incorrect responses while using ChatGPT for sustainable academic advising, where AI yielded recommendations with non-existent information. The authors from both studies describe this phenomenon as AI hallucination, where Gen-AI predicts that results in the fabrication of information, providing outputs that it believes to be true based on the trained data it has received. Another concern regarding Gen-AI outputs relates to how it responds to various prompts, where Iatrellis et al. [56] see that ChatGPT answers can vary notably depending on the different wording and structures of the input sentences, leading to even inconsistent results. This view is supported by Paxinos and Robertson [61], who write that the possibility of Gen-AI being unpredictable as it produces varied responses even with the same prompts.

7.2.4. Limited Advanced Information

Gen-AI responses are overly brief, highlighting the importance of supplementing it with additional resources [63]. Nguyen et al. [64] further argue that these responses usually only emphasize straightforward and mainstream narratives about climate change. The authors also point out that generated responses tend to rephrase given prompt without elaborating scientific explanations or concrete examples of environmental issues. Xiaoyu et al. [60] discovered in their study that ChatGPT has limited resource diversity and current information in environmental education. The authors claim that this limitation causes Gen-AI to fail when addressing advanced environmental topics. Li et al. [54] add to this issue by clarifying that Gen-AI does not have access to the most recent data available. This is because Gen-AI was trained using data available only up to a specific year or date, which certainly does not take into consideration the recent information in educational practices, technologies, or policies [56]. Therefore, when Gen-AI is asked for the latest information, it will clearly state that it is unable to provide information or insights regarding any developments that occurred after a specific date without any hesitation [57]. In the case of visually generated content, reliance on pre-existing data leads to the production of unrealistic and lack of detailed visuals that do not match students' intended scenes [62].

7.2.5. Practical Limitations and Environmental Costs

On the other hand, Iatrellis et al. [56] discovered in their study that ChatGPT recommendations received an average rating for their impact on sustainability education but are perceived poorly for their practical implementation. They clarify that the reason behind this perception is that although educational stakeholders valued the thoroughness of the AI-generated solution, it needed more context and resources for including extensive resource management, and to be effectively implemented. With greater resource requirements, Henriksen et al. [55] claim that the use of Gen-AI leads to higher energy consumption and carbon footprint related to the training of Gen-AI systems. Furthermore, the researchers conclude that the integration of Gen-AI raises significant environmental concerns, particularly as it may contribute to damage through environmental degradation.

8. Discussions

The findings have highlighted opportunities and challenges related to the use of Gen-AI in sustainability education. Drawing upon the themes identified, the opportunities of Gen-AI fostering sustainability education are closely connected and often complicated by the challenges associated with its implementation. To start with, Gen-AI's ability to provide access to information enriches sustainability education by fostering broader knowledge that includes sustainability and environmental matters [53,57]. This knowledge covers both general and specific information—including definition, causes and consequences—that can serve as a first understanding of sustainability issues [63]. The sustainability insights can be integrated into the sustainable education process, which can ultimately encourage actions that support sustainability [23,59]. With this base, transformative learning plays a role in enhancing students' understanding by challenging their prior knowledge and assumptions [33,45]. Nonetheless, the generated information was mostly presented as concise instructions without explanations, which may fail to motivate behavior change [63]. This suggests that, in practice, transformative learning may remain limited to personal awareness rather than driving meaningful social action that supports sustainability [40].

On the other hand, access to information initiates personalized learning, as Gen-AI responds to individual inquiries and adapts to students' specific interests and needs [57].

Aligning with Harish et al. [25], Gen-AI personalized learning enhances students' engagement and motivation, which leads to better academic performance. This is because Gen-AI can also act as an evaluator that gives students feedback according to their learning results [61]. Singer-Brodowski [36] suggests that the interactions and dialogues between students and Gen-AI regarding sustainability can be viewed as possible learning environments when perceived through the lens of transformative learning. Eventually, it promotes sustainability education since Gen-AI responses encourage students to engage more with sustainability issues. This also accords with Ellahi's [30] findings which showed Gen-AI encourages students to develop a stronger sense of responsibility toward conserving the environment. However, we discovered an inequitable access to Gen-AI that poses a significant challenge to sustainability education. Lim et al. [28] state a problem related to unequal access that counters the widespread knowledge in their work. Comparing this statement with the findings from the reviewed studies confirms that the difference in access limits the ability for specific communities to utilize Gen-AI information for learning, resulting in inconsistent learning achievements that contradict the concept of sustainability [53,57].

While Gen-AI transforms sustainability education through personalized learning, Boustani et al. [53] identify that a lack of creativity in learning will hinder sustainable development, as creativity is viewed as a positive aspect that can significantly contribute to advancing sustainability efforts. Along the same lines, Henriksen et al. [55] argue that creativity in teaching and learning naturally aligns with the goals of sustainability education, serving as an effective model that fosters a sustainability mindset and embeds sustainability values into real-world applications. As creativity in learning aligns with sustainability education, the support that Gen-AI provides is shown through its capacity to foster creativity by generating a diverse array of recommendations related to sustainability concepts [54,55]. This creative progress is possible because Gen-AI helps to creatively present sustainability information that is quite difficult to comprehend [23]. Moreover, Gen-AI generated images enhance creativity by producing more compelling visuals that can potentially motivate stronger drive toward action [62].

The emphasis on creativity aligns with transformative learning theory, which highlights the importance of encouraging learners to question their assumptions and reflect on whether these beliefs are contributing to sustainability or need to be adjusted [41]. Nevertheless, this transformative potential may be hampered when students overuse AI to generate outputs, which hinders their ability to develop essential skills for navigating complex sustainability challenges [57]. This finding is consistent with that of Chan and Hu [9], who claim that being overly reliant on Gen-AI restricts students' development by guiding them to make decisions based on the answers generated alone. As a direct outcome, this challenge reduces students' ability to formulate effective prompts to Gen-AI that elicit relevant responses, whereas the responses should be viewed as starting points for further exploration to address sustainability [53,55,57]. The inability to formulate prompts may indicate a broader challenge in transformative learning, where students are often unable to recognize prior assumptions and experiences [37]. Under these circumstances, transformative learning with Gen-AI may fail to promote sustainability education because students ultimately do not challenge their assumption and foster the critical reflection needed.

Gen-AI's ability to handle large amounts of data and support data-driven decision-making plays a crucial role in enhancing the effectiveness and efficiency of sustainability education and practice [54]. These findings are in line with Nikolopoulou's [24], which emphasizes utilizing data to optimize the use of resources in educational practice to reinforce environmental sustainability through reducing resources and energy use. On the other hand, this opportunity is made more complex by the presence of biased and inaccurate outputs discovered in the reviewed studies [54,56]. The problem arises from Gen-AI's invalid references and limitations in producing recent information related to sustainability and the environment [58,60] Hence, the information used to inform decisions may not be appropriate for current sustainability issues since Gen-AI does not account for the latest information. This issue may also be acknowledged by Ahmed et al. [11], who note that the limitations of Gen-AI that generate information based on its training data emphasize the difficulties in producing high-quality and reliable content. To solve such an issue of unreliability, Li et al. [54] suggest investing in sophisticated computation infrastructure. Eventually, extensive energy resources will also be needed to ensure an effective implementation of Gen-AI solutions, triggering environmental concerns and contradicting the sustainability efforts [55,56]. This challenge underscores the need to critically question sustainability knowledge provided by Gen-AI instead of just accepting them as true. A one-way uptake of sustainability knowledge emerges through discussion, and as community of practice forms, students' identities evolve and make room for transformative learning [66]. Therefore, we underscore that transformative learning plays a crucial role in effectively integrating Gen-AI into sustainability education, as it equips learners with the necessary perspective to engage with this technology meaningfully.

9. Conclusions

Gen-AI presents valuable opportunities to enhance sustainability education by providing easy and immediate access to various insightful information related to sustainability and the environment. Gen-AI's capability to present complex information in a concise and approachable format also helps to simplify the understanding of sophisticated sustainability problems. With its nature of generating answers based on user prompts, Gen-AI makes personalized learning possible as the valuable insights offered are tailored according to students' needs and interests in sustainability matters. Through the lens of transformative learning, Gen-AI enhances individuals' understanding of sustainability and environmental issues by encouraging them to reevaluate their initial beliefs and adopt more sustainable perspectives that guide them to sustainability efforts. Hence, these opportunities have advanced students' creativity and critical thinking skills, contributing to long-term student engagement and effective sustainability practices. Furthermore, Gen-AI's ability to process a vast amount of information and organize data to optimize resources and assist educational tasks promotes efficiency in sustainability education from both learning and environmental aspects.

Nevertheless, it can be acknowledged that introducing Gen-AI can lead to complications to these opportunities. As the opportunities encourage educators and students to use Gen-AI, its excessive use causes them to become dependent on Gen-AI. Overreliance on Gen-AI eliminates the potential that was initially provided to develop student skills, since it limits their exploration to learn and make decisions for sustainability. Students may begin to lose their ability to think critically, which is essential for formulating effective prompts that elicit quality responses from Gen-AI. Additionally, it is worth noting that Gen-AI itself might already produce unreliable responses, reducing the potential of Gen-AI to provide valuable sustainability information even further. It is also significant to mention that inequitable access to Gen-AI poses a challenge to sustainability education, as it leads to uneven learning opportunities and outcomes for certain communities, resulting in an educational gap that contradicts the principles of sustainability. Along with these challenges, Gen-AI poses environmental concerns due to its high energy demands to operate and offer its opportunities. These challenges that Gen-AI bring, in conjunction with one another, raise critical questions about the alignment of Gen-AI with sustainability values.

Given the complex interplay between opportunities and challenges of Gen-AI, future implementation must be approached with consideration, striving to harness Gen-AI's potential without compromising the core principles and commitments of sustainability education. To ensure this, coordinated efforts are needed by institutions, policymakers, and educators. Institutions should make efforts to integrate Gen-AI thoughtfully by providing access that ensures equitable learning across communities. Policymakers can support this further by developing ethical guidelines that promote responsible Gen-AI use such that will prevent harmful environmental impact. Meanwhile, educators should provide explicit explanations or discussions about the ethical and environmental implications of Gen-AI use and help students connect them to sustainability values. Moreover, educators should utilize Gen-AI as a complementary tool that enhances rather than diminishes students' critical thinking skills to avoid potential decline associated with its overuse. This can be done by designing learning activities that encourage students to question and reflect on Gen-AI outputs around advance sustainability information. These balance and mindful approaches can be used as suggestions that ensure Gen-AI promotes, rather than undermines the goal of sustainability education.

Although this review is limited by the small number of articles retained, which restricts its generalizability, future research could address these shortcomings through a more comprehensive systematic review guided by PRISMA guidelines or primary studies to verify the findings' validity.

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