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Advancing Education for Sustainable Development in STEM: A Systematic Review of Innovative Pedagogies, Digital Integration, Cognitive-Emotional Engagement, and Community-Policy Strategies

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ABSTRACT - The integration of Education for Sustainable Development (ESD) into Science, Technology, Engineering, and Mathematics (STEM) education (ESD-STEM) is essential to prepare students for global challenges. This systematic literature review (SLR), guided by the PRISMA framework, analysed 29 studies published between 2020 and 2024. Four key themes emerged: (1) innovative pedagogies, including problem-based learning, flipped classroom, and transdisciplinary approaches, which enhance critical thinking and problem-solving; (2) integration of digital tools such as AI, robotics, and Open Educational Resources, which support engagement and real-world application; (3) cognitive, emotional, and cross-disciplinary elements that foster intellectual readiness and emotional investment in sustainability; and (4) community and policy engagement that links theory to practice and institutional support. Despite these advances, challenges such as rigid curricula, insufficient resources, and limited teacher training remain. The study concludes that creative pedagogies, curriculum redesign, professional development, and resource allocation are pivotal to advancing 21st-century ESD-STEM.

INTRODUCTION

The 21st century represents a significant departure from the 20th century in terms of the skills and competencies required for employment, active citizenship, and self-realization. The rapid expansion of advanced Information and Communication Technologies (ICTs) has profoundly transformed the educational landscape, necessitating a paradigm shift in how students are prepared to address environmental, social, and economic challenges (OECD, 2018; Velasco et al., 2022; WEF, 2023). In this context, Education for Sustainable Development (ESD) has emerged as a key framework for addressing environmental degradation and socioscientific issues while aligning with the Sustainable Development Goals (SDGs) (UNESCO, 2019; Wolff et al., 2017). ESD equips learners with the knowledge, skills, and values necessary to foster sustainable futures.

The integration of ESD into Science, Technology, Engineering, and Mathematics (STEM) education, commonly referred to as ESD-STEM, has gained significant attention as a powerful approach to addressing global sustainability challenges. STEM education, with its emphasis on problem-solving, innovation, and real-world applications, empowers learners to tackle urgent issues such as climate change, resource scarcity, and social inequality (Margot & Kettler, 2019). By embedding the SDGs into STEM curricula, ESD-STEM enables students to develop technologies and solutions that advance sustainability and social well-being.

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Despite its potential, the successful implementation of ESD-STEM requires a comprehensive understanding of effective pedagogical strategies, curriculum development, teacher training, and supportive learning environments (Kioupi & Voulvoulis, 2019; Laurie et al., 2016). Recent research highlights the transformative role of innovative pedagogical approaches, such as inquiry-based learning, Project-Based Learning (PBL) (Mangione & Cannella, 2021), and digitally enhanced learning (Teräs et al., 2020), in fostering student engagement and deepening understanding of sustainability concepts. Engagement with these approaches promotes essential skills, including critical thinking, creativity, collaboration, and digital literacy, which are vital for addressing complex sustainability challenges in the 21st century (Abdurrahman et al., 2023).

Moreover, emerging technologies and digital tools, such as Artificial Intelligence (AI), educational applications, and interactive platforms, can enhance ESD-STEM by providing engaging and personalized learning experiences. For example, AI-based systems are capable of evaluating student performance and adapting educational resources to individual learning needs. Empirical evidence indicates that AI-driven tools can effectively support differentiated instruction for diverse learners (Abdurrahman et al., 2023). In addition, simulations using virtual reality (VR) and augmented reality (AR) offer immersive learning experiences that bridge theory and practice, thereby enhancing student engagement and relevance in sustainability education (Teräs et al., 2020; Mangione & Cannella, 2021).

However, integrating ESD into STEM education is not without challenges. Emotional, cognitive, and cross-disciplinary factors play a significant role in shaping the effectiveness of ESD-STEM. Emotional engagement and motivation help sustain learners' interest in sustainability topics, while cognitive skills such as systems thinking and problem-solving are essential for addressing complex, interdisciplinary challenges (AlAli et al., 2023). In addition, community and policy engagement are critical for creating enabling environments that support ESD-STEM initiatives aligned with both local needs and global sustainability goals.

Although research on ESD-STEM continues to expand, comprehensive syntheses of the factors influencing its effectiveness remain limited. This gap constrains understanding of how ESD-STEM can be optimized for diverse 21st-century learners. To address this limitation, the present study conducts a Systematic Literature Review (SLR) on the integration of ESD into STEM education. An SLR, as defined by Higgins et al. (2011), ensures transparency, rigor, and reproducibility in synthesizing existing evidence. By mapping themes, trends, and gaps, this study offers insights for educators, policymakers, and scholars on advancing ESD-STEM. The guiding questions for this research are:

1. What are the innovative pedagogical approaches used in ESD-STEM, and what are their impacts on student engagement and learning outcomes?
2. What roles do emerging technologies play in enhancing teaching, learning, and sustainability competencies in ESD-STEM?
3. What roles do emotional engagement, cognitive development, and cross-disciplinary approaches play in shaping the effectiveness of 21st-century ESD-STEM?
4. What community and policy engagement strategies effectively support the integration and scalability of ESD-STEM?

THEORETICAL BACKGROUNDS OF INNOVATIONS AND SDG FOR STEM IN THE TWENTY-FIRST-CENTURY SKILLS

ESD-STEM necessitates a robust theoretical foundation to guide pedagogical strategies and align with 21st-century learning goals. Accordingly, the P21 Framework for 21st Century Learning (P21, 2019a, 2019b) serves as the primary theoretical lens for this study due to its strong alignment with sustainability competencies and STEM education objectives.

The P21 Framework, developed by the Partnership for 21st Century Learning (P21), provides a structured approach to preparing students for contemporary workforce demands (P21, 2019a). It categorizes 21st-century competencies into three key domains: (1) Learning and Innovation Skills (critical thinking, creativity, collaboration), (2) Information, Media, and Technology Skills (digital literacy and ICT proficiency), and (3) Life and Career Skills (adaptability, leadership, and social responsibility).

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These competencies are directly aligned with the goals of ESD-STEM, which seeks to equip students with the capabilities required to address sustainability challenges through interdisciplinary problem-solving (Kay & Greenhill, 2011; Voogt & Roblin, 2012).

The Learning and Innovation Skills domain of the P21 Framework emphasizes critical thinking, creativity, communication, and collaboration, all of which are foundational to sustainability education (Kay & Greenhill, 2011). In particular, this domain aligns with pedagogical approaches such as Problem-Based Learning (PBL) and transdisciplinary education, which promote higher-order thinking and collaborative problem-solving in sustainability contexts (Margot & Kettler, 2019; Hernández-Barco et al., 2021). Within ESD-STEM, cross-disciplinary integration further strengthens these competencies, for example through the application of engineering solutions in climate change mitigation, physics in renewable energy systems, and data science in environmental monitoring, thereby enhancing the interdisciplinary cognitive dimension of learning (Kioupi & Voulvoulis, 2019).

The Information, Media, and Technology Skills domain of the P21 Framework highlight the role of ICT literacy, digital tools, and emerging technologies in supporting interactive and technology-enhanced sustainability education (Henze et al., 2022; Teräs et al., 2020). For instance, Henze et al. (2022) demonstrated that the use of robotics and artificial intelligence in STEM education enhances creativity and technical competence, enabling students to design solutions for sustainability challenges such as renewable energy systems. This aligns with P21's emphasis on technology as a driver of innovation. In ESD-STEM contexts, digital competencies drawn from computer science and data analytics further enable learners to evaluate environmental risks, design smart cities, and model climate change scenarios (Voogt & Roblin, 2012).

The Life and Career Skills component of the P21 Framework underscores adaptability, leadership, and social responsibility, which are critical for nurturing sustainability-oriented citizenship (OECD, 2005). The affective dimension of ESD-STEM is closely reflected in this domain. Laurie et al. (2016) emphasize that partnerships with local communities and non-governmental organizations enable students to apply STEM knowledge in authentic contexts through sustainability projects, thereby fostering leadership and civic engagement. Similarly, service-learning initiatives in renewable energy education (Nguyen, 2023) reinforce P21's focus on life and career skills while supporting the broader aims of ESD-STEM.

LITERATURE REVIEW

ESD is gaining global recognition as a key element of quality education and is closely aligned with the Sustainable Development Goals (SDGs). By promoting ESD, individuals develop essential knowledge, skills, attitudes, and values that empower them to contribute meaningfully to the development of sustainable societies (UNESCO, 2021). It emphasizes the development of competencies such as critical analysis, problem-solving, collaboration, and ethical reasoning, which are essential for addressing complex global challenges (Kioupi & Voulvoulis, 2019; Teh & Koh, 2019).

For instance, academic institutions are increasingly adopting programs that leverage quantitative and interdisciplinary approaches to address environmental degradation, underscoring the social dimensions of sustainability that extend beyond traditional STEM boundaries (AlAli et al., 2023; Turner et al., 2022). Such integration not only enhances student competencies but also prepares future generations to address complex challenges, including climate change and resource depletion, through innovative and ethically grounded solutions.

ESD is particularly relevant within STEM education, as it provides an interdisciplinary platform for exploring scientific, technological, engineering, and mathematical solutions to sustainability challenges. ESD-STEM enhances learners' capacity for practical problem-solving, ethical decision-making, and sustainable innovation (Teh & Koh, 2019). Its alignment with the SDGs is evident: SDG 4 promotes sustainability literacy through digital resources; SDG 7 advances renewable energy education; SDG 9 supports green industry and innovation; SDG 11 emphasizes sustainable cities and communities; and SDG 13 addresses climate action. Embedding these goals within STEM curricula bridges technical expertise with socially responsible decision-making (Bobko et al., 2024).

A fundamental aspect of ESD-STEM integration is the adoption of innovative pedagogical approaches. Traditional instructional methods have focused primarily on technical problem-solving; however, recent

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research highlights student-centred models such as Problem-Based Learning (PBL), Service Learning (SL), and Open-Ended Design (OED) (Tharakan, 2022). These approaches foreground sustainability-oriented solutions while fostering ethical responsibility and interdisciplinary thinking. Empirical evidence indicates that PBL effectively cultivates sustainability competencies in engineering education (Namasivayam et al., 2023; Terrón-López et al., 2020).

For example, Podgórska and Zdonek (2022) reported that energy-saving technologies developed through PBL in Poland supported SDGs while facilitating green business models. Similarly, experiential projects, such as logistics planning for refugee camps, have been shown to enhance students' awareness of social responsibility in engineering practice (Terrón-López et al., 2020). Nevertheless, balancing sustainability content with existing STEM curricula remains challenging, often necessitating incremental reforms and cross-disciplinary collaboration (Hopkinson et al., 2010).

The incorporation of emerging digital technologies has further transformed ESD-STEM education, particularly in response to the COVID-19 pandemic (Himang et al., 2023; Lo et al., 2022). Digital tools, including artificial intelligence (AI), virtual reality (VR), and Open Educational Resources (OERs), enable personalized learning experiences, interactive simulations, and global collaboration (Bobko et al., 2024).

However, technology alone does not ensure meaningful learning outcomes; pedagogical design remains a determining factor (Savelyeva & Park, 2022). For instance, the Edu-Metaverse ecosystem supports immersive virtual environments that enhance sustainability learning by enabling students to engage in simulated environmental problem-solving activities (Altan et al., 2019; Sergeyev et al., 2019). Despite these advances, the digital divide continues to pose a significant challenge, as unequal access to technological infrastructure limits the scalability of technology-driven ESD-STEM initiatives, particularly in developing regions.

Beyond pedagogy and technological tools, ESD-STEM has notable implications for learners' cognitive and emotional development. Cognitive benefits include enhanced creativity, systems thinking, and self-directed learning through Challenge-Based Learning (CBL) and interdisciplinary collaboration (Namasivayam et al., 2023; Nwankwo & Njoku, 2020). Equally important, sustainability education extends beyond cognitive outcomes to include affective dimensions, such as ethical responsibility, empathy, and global citizenship (Pérez-Rodríguez et al., 2022).

Real-world sustainability projects have been shown to foster motivation, resilience, and emotional engagement. Studies indicate that humanitarian PBL initiatives strengthen students' ethical awareness and emotional investment, reinforcing the importance of integrating affective outcomes alongside cognitive learning objectives (Savelyeva & Park, 2022). Terrón-López et al. (2020) further demonstrated that PBL projects situated in humanitarian contexts translated theoretical knowledge into empathetic and socially responsible practice. Accordingly, STEM curricula should incorporate both cognitive and affective dimensions to cultivate socially responsible graduates.

Community and policy support are critical for the effective implementation of ESD-STEM. Local communities play an important role in sustainability education, as students often apply their learning to address region-specific environmental challenges (Kioupi & Voulvoulis, 2019). For example, partnerships between universities, local industries, and non-governmental organizations enable students to engage in authentic sustainability projects, thereby bridging theoretical knowledge and practical application (Hopkinson et al., 2010).

At the policy level, governments and educational institutions must establish coherent guidelines, sustainable funding mechanisms, and professional development programmes to support educators in implementing ESD-STEM effectively (Nwankwo & Njoku, 2020; Podgórska & Zdonek, 2022). Comparative studies suggest that countries with well-established sustainability-oriented curricula, such as Finland and Germany, demonstrate greater success in embedding ESD principles within STEM education (Teh & Koh, 2019). Ongoing global collaboration and policy alignment remain essential for scaling effective practices and ensuring equitable access to ESD-STEM worldwide.

Overall, the literature indicates that ESD-STEM strengthens technical, ethical, emotional, and cognitive competencies, preparing learners to address contemporary sustainability challenges. Innovative pedagogies, digital technologies, and supportive policy frameworks emerge as key enablers, although

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persistent barriers related to curriculum reform, resource allocation, and global standardization continue to require attention.

RESEARCH METHODOLOGY

This review focused on studies published within the last five years (2020–2024) to capture recent developments in ESD-STEM and to ensure that the findings remain relevant for current and future research. The majority of full-text publications were accessed through academic subscriptions; however, a limited number of articles were unavailable. To mitigate this limitation, additional searches—restricted to final publications that met the inclusion criteria—were conducted on alternative databases such as ERIC. Despite these efforts, a small number of studies remained inaccessible and were therefore excluded from the review.

The systematic literature review (SLR) commenced with the formulation of a research question guided by the Population, Interest, and Context (PICo) mnemonic (Lockwood et al., 2015). In accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Page et al., 2021), four sequential stages were implemented: question formulation, systematic searching, quality appraisal, and data extraction and analysis. Figure 1 shows the PRISMA flow diagram of the study selection process.

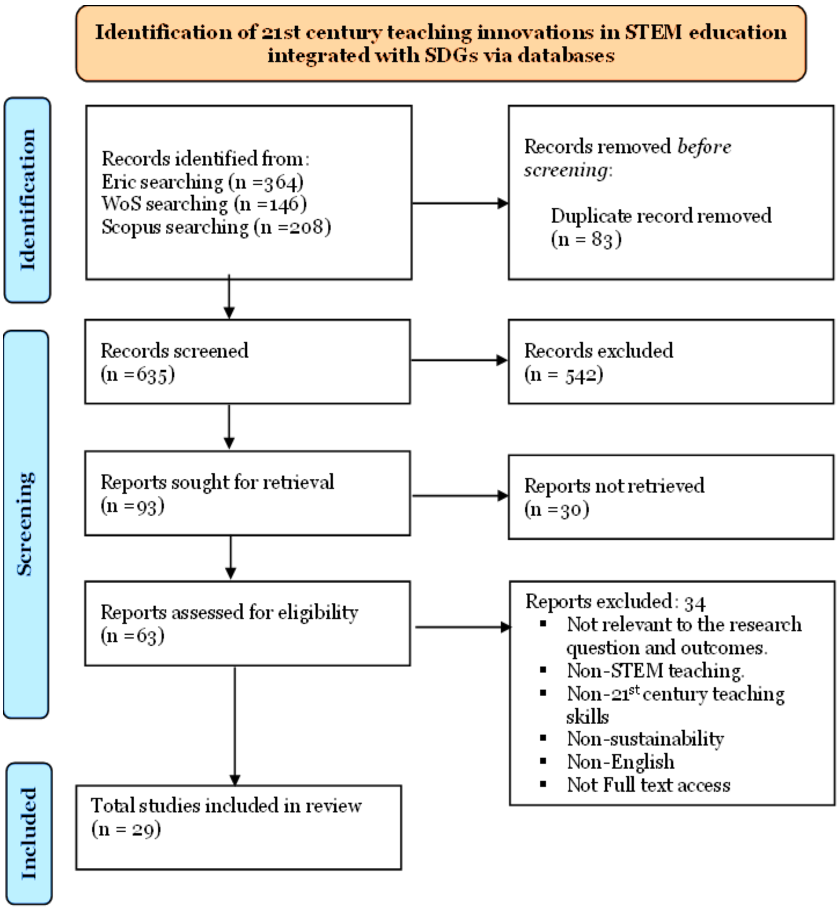

Figure 1. PRISMA Flow Diagram of the Study Selection Process

Note. This PRISMA Flow Chart is adapted from "The PRISMA 2020 Statement: An Updated Guideline for Reporting Systematic Reviews," by M. J. Page, J. E. McKenzie, P. M. Bossuyt, I. Boutron, T. Hoffmann, C. D. Mulrow, L. Shamseer, J. Tetzlaff, E. A. Akl, S. Brennan, R. Chou, J. Glanville, J. Grimshaw, A. Hróbjartsson, M. M. Lalu, T. Li, E. Loder, E. Mayo-Wilson, S. McDonald, ... D. Moher, 2021, Systematic Reviews, 10(1), 20-36. https://doi.org/10.1186/s13643-021-01626-4. Copyright 2021 by The Authors.

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This study employed a structured and rigorous SLR procedure to identify a comprehensive body of relevant literature. Initially, core keywords were identified, followed by the refinement of additional search terms through consultation of dictionaries, thesauri, encyclopaedias, and prior empirical studies. Boolean operators were subsequently applied to construct the final search string for Web of Science (WoS), Scopus (SCOPUS), and ERIC as follows:

> ("STEM education" OR "science education" OR "technology education" OR "engineering education" OR "mathematics education" OR "STEM teaching" OR "science teaching" OR "technology teaching" OR "engineering teaching" OR "mathematics teaching") AND ("21st century" OR "modern teaching" OR "digital education" OR "innovative teaching" OR "technology in education" OR "active learning" OR "inquiry-based learning" OR "project-based learning" OR "blended learning" OR "online learning") AND ("teacher" OR "educator" OR "instructor") AND ("Sustainable Development Goals" OR "SDGs" OR "sustainability education" OR "education for sustainable development" OR "SDG 4" OR "quality education" OR "global citizenship education").

These databases were selected due to their robustness and credibility in supporting systematic review searches, with WoS and SCOPUS widely recognised as leading sources of high-quality publication metadata and citation impact indicators. The search was conducted in June 2024 and initially yielded 718 publications.

During the first screening stage, 83 publications were excluded based on duplicate records and clearly irrelevant titles. In the second screening stage, the remaining 635 articles were assessed using predefined inclusion and exclusion criteria. The primary inclusion criteria focused on peer-reviewed scholarly works, including empirical research articles, review papers, and meta-analyses. Only English-language publications published between 2020 and 2024 were considered. As a result, 542 publications were excluded. A subsequent availability check further eliminated 93 studies due to the lack of full-text access, leaving 63 articles for eligibility assessment.

The eligibility stage involved a detailed examination of article titles, abstracts, and thematic relevance. Thirty-four studies were excluded due to limited relevance, insufficient alignment with the research objectives, or the absence of empirical evidence. Ultimately, 29 articles met all inclusion criteria and were retained for the final synthesis and analysis.

Quality Appraisal

To ensure that the articles meet the established quality standards; we employed a rubric that assessed six core components of every study in compliance with the guidelines for quality reporting (Abouzahra et al., 2020). By assessing six criteria: clarity of purpose (QA1), stated interest/utility (QA2), defined methodology (QA3), clear conceptualization (QA4), comparison/evaluation with similar works (QA5), and stated limitations (QA6). Each was scored Yes = 1, Partly = 0.5, No = 0; studies scoring below 3 were excluded. All three authors independently assessed articles, resolving disagreements through discussion. Two professionals further reviewed the remaining papers, classifying them as high, medium, or low quality (Mohamed Shaffril et al., 2020). Only high and medium-quality works were retained: 15 high and 14 intermediate, total of 29 included articles.

Data Extraction and Thematic Analysis

An inductive thematic analysis was conducted using the six-phase framework proposed by Braun and Clarke (2006) to systematically analyse the 29 selected studies and identify recurring patterns in ESD-STEM research. This approach enabled a transparent and rigorous process of data familiarisation, coding, theme development, and interpretation. Data extraction followed a structured and iterative procedure to ensure consistency and thematic coherence across studies.

The first phase involved immersion in the data through repeated and careful reading of all 29 publications, accompanied by detailed note-taking on key dimensions of ESD-STEM practices. Reflective memos were maintained throughout this stage to support reflexivity and analytic transparency. Coding was carried out independently by the first author and a research assistant, allowing for cross-validation of interpretations. For instance, Nguyen (2023) reported the integration of

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sustainability into science and mathematics syllabi, interdisciplinary course design, and targeted teacher training initiatives, all of which were coded as strategies for advancing ESD-STEM implementation.

During the second phase, inductive coding generated 329 meaningful data segments, including codes such as “innovative pedagogical strategies,” “technology integration,” “community engagement,” and “cross-disciplinary learning.” These codes were subsequently organised into a preliminary coding framework. In the third phase, related codes were clustered into broader conceptual patterns, resulting in the identification of four overarching themes: (1) Innovative Approaches for ESD-STEM (e.g., problem-based learning and flipped classrooms), (2) Integration of Technology and Digital Tools (e.g., robotics, artificial intelligence, and OERs), (3) Emotional, Cognitive, and Cross-Disciplinary Aspects (e.g., engagement, higher-order thinking skills, and interdisciplinarity), and (4) Community and Policy Engagement (e.g., partnerships with communities and policy-level support). Together, these themes provided a coherent framework for understanding ESD-STEM practices across diverse educational contexts (Nowell et al., 2017).

A rigorous review process was then undertaken to refine and validate the emergent themes in line with Braun and Clarke’s (2019) recommendations. This process involved merging overlapping codes (87 codes) to improve conceptual clarity, revising ambiguous codes (15 codes) to strengthen alignment with the dataset, and ensuring internal consistency through multiple iterative review cycles.

Throughout this phase, the research team engaged in reflexive discussions to address potential discrepancies in thematic categorisation and interpretation (Terry et al., 2017). Once finalised, the themes were clearly defined and named to reflect their conceptual essence, elaborated in relation to the research questions, ensuring alignment with the broader ESD-STEM literature (Nowell et al., 2017).

In the final phase, the results were compiled and reliability was assessed. Inter-coder agreement was calculated for 40% of the dataset (12 out of 29 articles) using Cohen’s Kappa coefficient. The resulting values ranged from 0.85 to 1.00, with an average of 0.92, indicating a high level of coding reliability. Any remaining discrepancies were resolved collaboratively through re-examination of the data and refinement of the coding framework, thereby enhancing the trustworthiness and credibility of the findings.

Table 1 presents the identified themes alongside the corresponding authors of 21st-century ESD-STEM studies, enabling systematic categorisation and interpretation of the literature. This structured presentation ensures that the review highlights substantive contributions to the advancement of ESD-STEM research and provides a clear foundation for subsequent synthesis and discussion.

Theme	Key Focus	Representative Studies
Innovative pedagogical approaches	Problem-based learning, active learning, flipped classroom, transdisciplinary instruction	Avsec & Jerman (2020); Duarte et al. (2020); Fishlock et al. (2023); González et al. (2023); Hernández-Barco et al. (2021); Hicks (2022); Hilger & Keil (2022); Howell (2021); Jeong & González-Gómez (2020); Karjanto & Acelajado (2022); Kubisch et al. (2021); Lozano et al. (2022); Pérez-Rodríguez et al. (2022); Ramos-Gavilán et al. (2024); Ricaurte & Viloria (2020); Rico et al. (2021); Singh-Pillaay (2020); Zizka et al. (2021)
Integration of technology and digital tools	Artificial intelligence, robotics, simulations, Open Educational Resources (OERs)	Duarte et al. (2020); Henze et al. (2022); Lo et al. (2022); Karjanto & Acelajado (2022); Pérez-Rodríguez et al. (2022)

continued

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Emotional, cognitive, and cross-disciplinary aspects	Engagement, critical thinking, systems thinking, interdisciplinary learning	Avsec & Jerman (2020); Chan & Nagatomo (2022); Costa et al. (2023); Hernández-Barco et al. (2021); Khandakar et al. (2020); Rico et al. (2021); Kulshreshtha et al. (2022); Míguez-Álvarez et al. (2022); Rampasso et al. (2020)
Community and policy engagement	Industry collaboration, service learning, policy support, institutional frameworks	Ariza & Olatunde-Aiyedun (2023); Haim & Aschauer (2024); Hicks (2022); Howell (2021); Nguyen (2023)

RESULTS

This section provides a systematic synthesis of the reviewed literature, highlighting key trends and dominant themes related to ESD-STEM in the 21st century. By examining the interrelationships among these themes, the SLR offers a comprehensive understanding of how contemporary pedagogical approaches and educational technologies can equip educators and education systems with the critical skills and knowledge required to address complex 21st-century sustainability challenges.

The SLR identified four overarching themes: (1) innovative approaches such as active learning, project-based learning (PBL), and collaboration; (2) the use of emerging technologies and digital tools in ESD-STEM teaching; (3) emotional, cognitive, and interdisciplinary aspects of ESD integration; and (4) community and policy involvement in advancing STEM teaching and ESD in the 21st century.

The Innovative Approaches for ESD-STEM in the 21st Century

The effectiveness of ESD-STEM relies on the integration of innovative teaching strategies that actively engage learners, cultivate an environment that values inquiry and critical analysis, and foster sustainability competencies. Such approaches extend beyond knowledge acquisition to enhance learners' ability to apply sustainability concepts in authentic, real-world contexts. One example is the combination of Fuzzy-DEcision-MAking Trial and Evaluation Laboratory (F-DEMATEL) and Multi-Criteria Decision Analysis (MCDA), as explored by Jeong and González-Gómez (2020), which was employed to evaluate sustainability criteria in e-learning environments and provided structured decision-making frameworks aligned with the SDGs. Similarly, Ramos-Gavilán et al. (2024) combined objective assessments and classroom debates to evaluate student learning outcomes. This dual strategy strengthened instructional effectiveness by simultaneously measuring knowledge retention and promoting critical thinking, communication skills, and engagement with sustainability issues. Collectively, these integrative approaches have been shown to enhance STEM learning outcomes and student engagement with the 2030 Agenda (Hernández-barco et al., 2021; Lozano et al., 2022; Zizka et al., 2021).

The integration of interdisciplinary Teaching–Learning Sequences (TLS), as proposed by Rico et al. (2021), further improves the effectiveness of ESD-STEM by bridging theoretical understanding and practical application. Through interdisciplinary project-based curricula, students develop a more holistic understanding of sustainability challenges and their real-world implications. This approach equips both future educators and learners with essential skills for applying STEM knowledge in sustainable development contexts, enabling more proactive engagement with SDG-related goals.

González et al. (2023) examined the application of Backward Design (BD) in the redesign of engineering courses to prioritise intended learning outcomes. The BD approach was found to foster creativity, self-efficacy, and proactive sustainability-oriented attitudes, aligning academic objectives with real-world challenges and preparing preservice teachers as active sustainability practitioners (Avsec & Jerman, 2020).

Transdisciplinary approaches play a pivotal role in enhancing ESD-STEM effectiveness by connecting academic learning with real-world community engagement. Hilger and Keil (2022) demonstrated that

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transdisciplinary-oriented courses, in which preservice teachers collaborate with civil society partners, foster change agency for sustainable development. Such approaches enhance learning effectiveness by enabling students to apply knowledge in complex, authentic scenarios while simultaneously developing responsible citizenship competencies.

Similarly, Zizka et al. (2021) reported that hands-on sustainability projects promote experiential learning and deepen students' understanding of real-world sustainability challenges. These approaches also support the development of critical and creative thinking, which are essential for addressing complex sustainability issues in STEM disciplines. Empirical findings indicate that students who completed transdisciplinary courses evaluated the learning process positively and demonstrated increased reflection on their roles within broader socio-environmental systems (Hilger & Keil, 2022; Kubisch et al., 2021; Pérez-Rodríguez et al., 2022).

Kubisch et al. (2021) further emphasised the role of transdisciplinary education in advancing sustainable development and enhancing community well-being. By engaging learners in real-world problem-solving with external partners, this approach strengthens critical reasoning, collaborative practices, and strategic problem-solving skills, thereby preparing students to address sustainability challenges at both local and global levels (Hernández-Barco et al., 2021; Lozano et al., 2022; Zizka et al., 2021).

Problem-Based Learning (PBL) is one of the most extensively documented pedagogical strategies within ESD-STEM. PBL enhances instructional effectiveness by promoting critical thinking, teamwork, and the transfer of knowledge to real-world contexts. Fishlock et al. (2023) found that PBL projects significantly improved student engagement, sustainability mindsets, and technical competencies, with learners demonstrating a strong willingness to apply sustainable design practices (Hicks, 2022; Howell, 2021).

Ricaurte and Viloria (2020) showed that multi-year PBL initiatives strengthened teamwork and logical reasoning, particularly among engineering students, while Duarte et al. (2020) reported improvements in critical thinking, equity awareness, and environmental consciousness through multicultural PBL teams. Singh-Pillay (2020) further highlighted that PBL enhanced preservice teachers' sense of responsibility, leadership, and collaboration in sustainability initiatives. Similarly, Hernández-Barco et al. (2021) found that PBL positively influenced emotional engagement and teachers' conceptual understanding of sustainability. Taken together, these studies underscore the central role of PBL in fostering problem-solving, collaboration, and sustainability competencies.

Moreover, the integration of PBL with place-based education has been shown to amplify ESD outcomes, particularly in shaping preservice teachers' sustainability attitudes when combined with complementary instructional strategies (Avsec & Jerman, 2020; González et al., 2023; Jeong & González-Gómez, 2020). Lozano et al. (2022) further compared PBL and cooperative learning approaches in ESD-STEM contexts and found that, while both were effective, cooperative learning was particularly beneficial in strengthening shared responsibility and collaborative engagement.

Active learning methodologies also play a significant role in advancing ESD-STEM. Pérez-Rodríguez et al. (2022) validated the effectiveness of active learning as a core implementation strategy within ESD-STEM courses, supported by complementary instructional tools. The authors proposed a framework for applying active learning approaches, demonstrating their capacity to develop professionally oriented competencies relevant to ESD-STEM implementation. Their findings further indicate that active learning effectively enhances students' sustainability competencies by supporting the resolution of complex, industry-related problems.

Finally, the Flipped Classroom (FC) model represents one of the most innovative instructional approaches for enhancing ESD-STEM effectiveness. Howell (2021) demonstrated that FC, when combined with reflective and active learning strategies, significantly increased student engagement and self-directed learning in interdisciplinary ESD-STEM courses. Similarly, Karjanto and Acelajado (2022) found that the application of FC in mathematics-based ESD courses improved students' retention and conceptual understanding of sustainability-related content.

By integrating reflective and interactive elements, the FC model enhances accessibility, engagement, and instructional effectiveness in sustainability education.

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Overall, the effectiveness of ESD-STEM is strengthened through innovative approaches that promote critical thinking, active learning, and the application of knowledge in real-world contexts. Pedagogical strategies such as problem-based learning, transdisciplinary education, active learning, and the flipped classroom model collectively enhance learners' capacity to address sustainability challenges. By bridging theory and practice, these approaches equip students with sustainability competencies essential for 21st-century careers and align ESD-STEM with the broader objectives of the 2030 Agenda and the SDGs, thereby ensuring meaningful and impactful educational outcomes.

The Integration of Technology and Digital Tools in 21st Century ESD-STEM

In the 21st century, contemporary knowledge acquisition extends beyond foundational content mastery to include proficiency in information and communication technologies (ICT) and digital tools. The integration of emerging technologies in ESD-STEM has strengthened sustainability-oriented education by enhancing learner engagement, enabling authentic problem-solving, and supporting the development of advanced competencies. Digital tools such as robotics, artificial intelligence (AI), open educational resources (OERs), and computer-aided design (CAD) platforms are increasingly embedded in STEM curricula to advance sustainability-related knowledge and skills.

Henze et al. (2022) introduced the 4C instructional package, an educational intervention incorporating robotics, coding, AI, and STEAM-based learning to strengthen students' creativity, cooperation, communication, and critical thinking. Although STEAM includes the arts, its technological components align closely with STEM, particularly through an emphasis on computational thinking and digital problem-solving, which are integral to ESD-STEM. The study demonstrated that digital tools enhance the visualisation and simulation of sustainability-related challenges, enabling learners to design creative solutions to real-world environmental and technological problems. These findings indicate that technology integration promotes sustained engagement with sustainability-related topicsamong both teachers and students (Henze et al., 2022; Karjanto & Acelajado, 2022; Lo et al., 2022).

Karjanto and Acelajado (2022) further demonstrated how AI-driven assessments and virtual collaboration tools improve cognitive learning outcomes and student engagement in higher education STEM courses. These technologies support real-time feedback, adaptive learning pathways, and interactive problem-solving environments, allowing students to engage meaningfully with sustainability-focused STEM applications, such as climate data modelling and renewable energy simulations. This technology-mediated approach directly supports ESD-STEM by enabling the application of STEM principles to sustainable development challenges (Duarte et al., 2020).

Lo et al. (2022) illustrated how OERs mitigated educational disruptions during the COVID-19 pandemic by providing free and adaptable digital learning materials for online STEM courses. For example, virtual laboratories and sustainability-focused OERs enabled students to conduct experiments remotely, ensuring continuity in ESD-STEM learning. Their findings suggest that digital resources support interactive learning, reduce barriers to access, and facilitate knowledge dissemination, thereby reinforcing the role of ESD-STEM in promoting equitable education. This aligns closely with SDG 4 (Quality Education) and highlights the potential of digital tools to democratise access to sustainability education (Karjanto & Acelajado, 2022).

Jeong and González-Gómez (2020) identified key criteria for effective sustainability science e-learning systems, including real-time collaboration features and adaptive feedback mechanisms, which enhance learner engagement with SDG-related content. Similarly, Pérez-Rodríguez et al. (2022) proposed the integration of CAD technologies in industrial engineering education to strengthen sustainability-driven design and manufacturing processes. These digital tools ranging from simulation platforms to blockchain-enabled learning environments support scalability, engagement, skill development, and accessibility, thereby reinforcing the long-term impact of ESD-STEM on sustainability education.

Overall, emerging technologies and digital tools play a critical role in advancing ESD-STEM by increasing interactivity, facilitating real-world application, and promoting personalised, data-driven learning experiences. The integration of AI, OERs, and simulation-based technologies ensures that learners transition from passive recipients of information to active problem-solvers capable of addressing global sustainability challenges. By embedding digital innovations such as AI-driven analytics, metaverse-based simulations, and cloud-based OER platforms, ESD-STEM equips learners

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with sustainability literacy, technological proficiency, and critical thinking skills essential for addressing 21st-century environmental and societal challenges.

The Emotional, Cognitive, and Cross-Disciplinary Aspects in 21st Century ESD-STEM

The effectiveness of ESD-STEM is strongly influenced by emotional, cognitive, and cross-disciplinary dimensions, which collectively equip students with the skills, dispositions, and mindsets required to address sustainability challenges. Emotional engagement refers to learners' affective responses, including motivation, interest, and personal connections to learning experiences. When students are emotionally engaged, they tend to participate more actively, experience reduced anxiety when confronting complex issues, and demonstrate stronger long-term commitment to sustainable practices (Avsec & Jerman, 2020).

Research indicates that pedagogical approaches fostering emotional engagement lead to enhanced cognitive outcomes and the internalisation of sustainability values. For instance, Avsec and Jerman (2020) found that a problem-based learning (PBL) model significantly increased preservice teachers' emotional engagement, thereby improving both their sustainability knowledge and attitudes. Similarly, Hernández-Barco et al. (2021) and Kulshreshtha et al. (2022) demonstrated that culturally responsive and transdisciplinary instructional practices enhance affective engagement, making STEM education more inclusive and meaningful.

Cognitive development in ESD-STEM centres on the cultivation of higher-order thinking skills, including critical thinking, problem-solving, and informed decision-making, which are essential for addressing complex sustainability issues (Chan & Nagatomo, 2022). Learning environments that promote active cognitive engagement move learners beyond rote memorisation and enable deeper conceptual understanding and practical application (Khandakar et al., 2020). Empirical evidence suggests that well-structured instructional designs are particularly effective in supporting these cognitive processes.

Kulshreshtha et al. (2022), for example, introduced a multi-course project-based learning (MPL) framework, highlighting critical thinking and collaborative decision-making as core elements of effective sustainability education. Similarly, Chan and Nagatomo (2022) proposed the STEM4S framework, which integrates design-based tasks into sustainability education. Implemented at National Taiwan Normal University, this framework demonstrated that structured ESD-STEM programmes can significantly enhance students' capacity to engage critically with global challenges, such as climate change.

Cross-disciplinary learning refers to the integration of multiple academic disciplines to foster a holistic understanding of complex, real-world problems (Rico et al., 2021). Sustainability challenges are inherently multifaceted and require learners to synthesise knowledge from STEM fields alongside insights from the social sciences, humanities, and policy studies (Costa et al., 2023). Studies consistently show that interdisciplinary approaches strengthen both cognitive and affective learning outcomes within ESD-STEM contexts.

Rico et al. (2021) found that integrating mathematics and science through structured teaching–learning sequences enhanced preservice teachers' self-efficacy and conceptual understanding of sustainability. Similarly, Rampasso et al. (2020) reported that interdisciplinary problem-solving experiences improved critical thinking and prepared future professionals to manage sustainability challenges across diverse domains.

Costa et al. (2023) further argued that cross-disciplinary education is essential for bridging theoretical knowledge and practical application in sustainability contexts. Míguez-Álvarez et al. (2022) additionally demonstrated that interdisciplinary digital resources improve knowledge retention, collaboration, and creative problem-solving, thereby fostering adaptability and systems thinking in a globalised educational landscape. By integrating cognitive and emotional dimensions, cross-disciplinary approaches ensure that learners are both intellectually equipped and personally invested in sustainability-related issues.

Overall, emotional engagement, cognitive development, and cross-disciplinary learning constitute foundational pillars of effective ESD-STEM implementation. Emotional engagement sustains motivation and personal relevance, cognitive development strengthens analytical and problem-solving capacities, and cross-disciplinary strategies promote collaboration and holistic thinking. Together, these

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dimensions enhance learning outcomes and amplify the transformative potential of ESD-STEM, underscoring the need for integrated and innovative pedagogical strategies to prepare learners for 21st-century sustainability challenges.

The Community and Policy Engagement in 21st Century ESD-STEM

Community and policy engagement play a pivotal role in strengthening Education for Sustainable Development in STEM (ESD-STEM) by promoting real-world application, interdisciplinary collaboration, and sustained institutional support for sustainability education. Community engagement refers to collaborative partnerships among schools, local communities, industries, and non-governmental organizations (NGOs) that facilitate place-based and experiential learning opportunities (Hicks, 2022).

Policy engagement, in contrast, encompasses governmental policies, curriculum reforms, professional development initiatives, and institutional strategies that support the systematic integration of sustainability within STEM education (Nguyen, 2023). The coordination of community and policy engagement ensures that ESD-STEM remains relevant, scalable, and aligned with global sustainable development goals.

Through community engagement initiatives in ESD-STEM, students gain authentic learning experiences that enable them to address sustainability challenges in real-life contexts. Approaches such as service learning, industry collaboration, and project-based learning (PBL) enhance students' problem-solving abilities, environmental awareness, and civic responsibility (Howell, 2021). Hicks (2022) demonstrated the effectiveness of community-based learning models that integrate service-learning projects with PBL in industrial ecology and sustainability education. A longitudinal analysis of student reflections revealed that direct engagement with community sustainability initiatives strengthened conceptual understanding and the practical application of ESD-STEM principles. Similarly, Haim and Aschauer (2024) introduced the Innovative FOCUS initiative, which immersed students in real-world STEM sustainability projects in collaboration with trained teachers. This approach fostered creativity, community ownership, and local problem-solving capacity, highlighting the transformative potential of community-based ESD-STEM initiatives.

Nguyen (2023) further emphasised that embedding circular economy principles within secondary STEM education requires sustained community participation. Engagement with initiatives related to waste management, renewable energy, and sustainable agriculture enables students to translate theoretical concepts into actionable strategies, thereby fostering environmental consciousness and responsible consumption behaviours.

Additional evidence of effective community engagement is observed in industry–academia collaborations, where students work alongside professionals to develop sustainability-oriented innovations. Ariza and Olatunde-Aiyedun (2023) documented such collaborations through renewable energy projects in which students designed and constructed electric vehicles. These experiences enhanced technical competence, teamwork, and sustainability literacy, although challenges related to project complexity and communication underscored the need for structured stakeholder coordination.

Policy engagement is equally critical for institutionalising sustainability education within STEM curricula. Regulatory frameworks, curriculum reforms, funding mechanisms, and professional development programs enable the systematic and consistent adoption of sustainability principles across educational contexts (Nguyen, 2023). In the absence of strong policy support, sustainability initiatives may remain fragmented and unevenly implemented. Studies indicate that policy frameworks integrating circular economy concepts into STEM syllabi, interdisciplinary course structures, and teacher training programs significantly enhance adoption and coherence. Moreover, research highlights the central role of teachers' beliefs and practices in the successful integration of sustainability principles, reinforcing the need for sustained policy and professional development support (Ariza & Olatunde-Aiyedun, 2023; Haim & Aschauer, 2024; Nguyen, 2023).

Overall, community engagement enriches ESD-STEM by connecting STEM knowledge with authentic sustainability challenges, thereby fostering environmental awareness, problem-solving skills, and civic responsibility. Industry partnerships and service-learning initiatives extend learning beyond the classroom through hands-on experience, while policy engagement institutionalises sustainability through curricular reform, teacher capacity building, and supportive governance structures. Together,

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community- and policy-level strategies operate synergistically, ensuring the effectiveness, sustainability, and long-term impact of ESD-STEM in advancing global sustainable development objectives.

DISCUSSION

ESD-STEM represents a transformative educational approach for addressing complex sustainability challenges in the 21st century. Grounded in the P21 Framework for 21st Century Learning (P21, 2019a, 2019b), this review demonstrates a strong alignment between sustainability competencies and STEM learning objectives, particularly in fostering critical thinking, creativity, collaboration, and digital literacy. The findings of this systematic literature review indicate that ESD-STEM is not only a pedagogical innovation but also a strategic imperative for advancing the Sustainable Development Goals (SDGs). Nevertheless, persistent structural barriers including curriculum rigidity, limited resources, and insufficient teacher preparedness have continued to constrain effective implementation across educational contexts (UNESCO, 2021; OECD, 2020).

The P21 framework provides a robust conceptual foundation for ESD-STEM by articulating three interrelated competency domains: Learning and Innovation Skills, Information, Media and Technology Skills, and Life and Career Skills (Kay & Greenhill, 2011; Voogt & Roblin, 2012). These domains closely correspond with the aims of ESD-STEM, which seeks to prepare learners to address sustainability challenges through interdisciplinary problem-solving, such as engineering solutions for climate change mitigation and data-driven environmental monitoring. Evidence from education systems in countries such as Finland and Japan suggests that strong integration of sustainability within STEM curricula contributes to measurable progress towards SDGs, reinforcing the relevance of P21 as a guiding framework for ESD-STEM implementation (OECD, 2020).

Synthesising the reviewed literature, this study identifies four interrelated themes that underpin the effectiveness of ESD-STEM in the 21st century: innovative pedagogical approaches, integration of technology and digital tools, emotional and cognitive development, and community and policy engagement. These themes do not operate independently; rather, they interact dynamically to strengthen learners’ sustainability competencies.

Figure 2 presents an integrative conceptual model of Education for Sustainable Development–STEM (ESD-STEM) comprising four interrelated dimensions that collectively support the development of 21st-century sustainability competencies. Positioned at the centre, ESD-STEM represents a holistic pedagogical approach that integrates sustainability principles within STEM education to address complex real-world challenges. The first dimension, Innovative Approaches for ESD-STEM, emphasises learner-centred and inquiry-based pedagogies that promote creativity, critical thinking, and collaboration. The second dimension, Integration of Technology and Digital Tools, highlights the role of digital literacy and emerging technologies in enhancing innovation, interactive learning, and solution design for sustainability issues. The third dimension, Emotional, Cognitive, and Cross-Disciplinary Aspects, reflects the integration of affective engagement, higher-order thinking, and interdisciplinary STEM knowledge to foster systems thinking and informed decision-making. The fourth dimension, Community and Policy Engagement, underscores the importance of partnerships with communities and policy stakeholders in translating STEM knowledge into socially responsible sustainability actions. Together, these dimensions form a coherent framework aligned with the P21 competencies, enabling ESD-STEM to function as an integrative pathway for developing SDG-oriented 21st-century skills.

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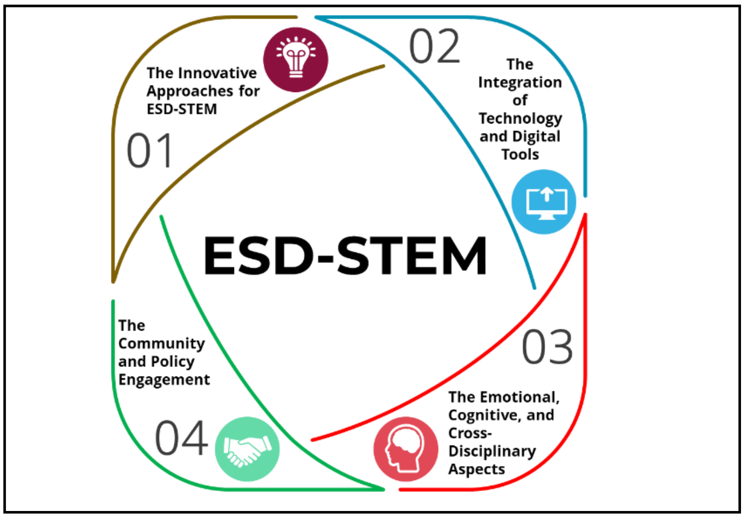

Figure 2. Integrative Conceptual Model of Education for Sustainable Development–STEM (ESD-STEM)

Innovative pedagogical approaches such as problem-based learning (PBL), active learning, flipped classrooms, and transdisciplinary instruction emerge as the primary instructional drivers of ESD-STEM. These strategies consistently enhance critical thinking, problem-solving, and collaborative skills, enabling learners to engage meaningfully with real-world sustainability challenges (Howell, 2021; Karjanto & Acelajado, 2022; Kubisch et al., 2021). However, implementation remains uneven, particularly in contexts characterised by large class sizes, limited digital infrastructure, and insufficient pedagogical support. UNESCO (2021) reported that schools in rural and low-resource settings often face infrastructural constraints that restrict adoption, as illustrated by ESD-STEM pilot programmes in India where urban schools benefited from digital laboratories while rural schools struggled due to inadequate support (Zizka et al., 2021).

Effective implementation of innovative ESD-STEM pedagogies depends heavily on the availability of well-prepared educators capable of facilitating active, interdisciplinary, and technology-enhanced learning environments. Yet many teachers lack sufficient access to professional development opportunities related to sustainability integration. UNESCO (2021) reported that only approximately 30% of teachers in low-income countries have participated in ESD-related professional development programmes, underscoring the urgent need for sustained capacity-building initiatives. Without targeted training, teachers may struggle to translate ESD principles into effective STEM classroom practices.

Assessment practices also require reconsideration to align with ESD-STEM objectives. Traditional examination-oriented assessments frequently fail to capture competencies such as collaboration, systems thinking, and problem-solving (Hernández-Barco et al., 2021). Alternative assessment strategies including classroom debates, portfolio-based assessment, and multi-criteria evaluation tools have demonstrated stronger alignment with sustainability competencies. Ramos-Gavilán et al. (2024) showed that combining debates with objective assessments fosters deeper conceptual understanding, while Jeong and González-Gómez (2020) applied F-DEMATEL and MCDA techniques to evaluate sustainability criteria in e-learning systems. Comparative evidence from Finland and the United States further suggests that portfolio-based approaches are more effective than conventional examinations in evaluating problem-solving and sustainability-related competencies (Altan et al., 2019).

Emerging technologies including artificial intelligence (AI), virtual reality (VR), and Open Educational Resources (OERs) have significantly reshaped ESD-STEM by enabling immersive, flexible, and personalised learning experiences (Henze et al., 2022; Lo et al., 2022). These technologies support real-time feedback, systems modelling, and global collaboration, thereby strengthening Information, Media and Technology Skills within the P21 framework. However, the digital divide remains a critical challenge, particularly in underserved communities where access to advanced infrastructure is limited (Savelyeva & Park, 2022).

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Teacher readiness to leverage digital tools effectively also remains uneven, reinforcing the need for targeted technological and pedagogical professional development (Duarte et al., 2020; Lo et al., 2022).

Beyond pedagogy and technology, emotional engagement and cognitive development play a central role in the effectiveness of ESD-STEM. Emotional connections to sustainability issues have been shown to enhance motivation, knowledge retention, and long-term engagement with sustainability initiatives (Avsec & Jerman, 2020; Hernández-Barco et al., 2021; Kulshreshtha et al., 2022). Emotional engagement also facilitates deeper participation in community-based sustainability projects and supports ethical commitment to sustainable practices (Chan & Nagatomo, 2022). However, balancing cognitive demands with emotional engagement remains challenging in intensive, project-based learning environments that require sustained effort and collaboration.

Community and policy engagement further ground ESD-STEM in authentic contexts. Partnerships with industries, non-governmental organisations, and local communities enable learners to apply STEM knowledge directly to sustainability challenges, strengthening environmental awareness and civic responsibility (Hicks, 2022; Nguyen, 2023). At the policy level, curriculum alignment, funding mechanisms, and professional development structures are essential for scaling and sustaining ESD-STEM initiatives. Nevertheless, misalignment between academic priorities and real-world needs, competing political agendas, and administrative delays may limit impact (AlAli et al., 2023; Hopkinson et al., 2010). Long-term institutional commitment is therefore critical to sustaining community-based ESD-STEM initiatives (Ariza & Olatunde-Aiyedun, 2023; Haim & Aschauer, 2024).

Overall, ESD-STEM presents both significant opportunities and persistent challenges. While innovative pedagogies, digital tools, emotional engagement, and cross-disciplinary learning enhance sustainability competencies, issues related to scalability, digital inequality, and policy coherence must be addressed to optimise implementation. The integrative ESD-STEM–P21 model proposed in this study provides a theoretically grounded and practice-oriented synthesis that supports a multi-stakeholder approach involving educators, policymakers, technology developers, and community partners. By addressing these challenges, ESD-STEM can function as a powerful mechanism for equipping future generations with the skills, knowledge, and ethical values required to advance global sustainability efforts. Programmes such as UNESCO's Green Skills for Teachers initiative offer promising models for linking professional development with real-world sustainability projects and may be adapted across diverse educational contexts (UNESCO, 2021).

CONCLUSIONS

This systematic literature review (SLR) provides a comprehensive synthesis of ESD-STEM, underscoring its critical role in addressing contemporary sustainability challenges. The findings identify four central themes that explain the effectiveness of ESD-STEM: (1) innovative pedagogical approaches in 21st-century ESD-STEM, such as problem-based learning (PBL) and transdisciplinary education, which enhance critical thinking and problem-solving skills; (2) the integration of technology and digital tools in 21st-century ESD-STEM, including artificial intelligence (AI), robotics, and Open Educational Resources (OERs), which promote learner engagement and real-world application; (3) the emotional, cognitive, and cross-disciplinary dimensions of ESD-STEM, which ensure learners are both intellectually prepared and emotionally invested in sustainability issues; and (4) community and policy engagement in 21st-century ESD-STEM, which links theoretical knowledge with authentic sustainability projects and institutional support mechanisms.

These findings carry important implications for multiple stakeholders. Effective integration of sustainability into STEM education requires coordinated, system-level transformation to ensure long-term impact and coherence. For educators, the findings highlight the importance of adopting innovative instructional strategies and leveraging digital tools to enhance student engagement and learning outcomes. Policymakers are urged to prioritise curriculum reform, allocate sufficient resources for teacher professional development, and establish supportive policy frameworks to enable the widespread and consistent adoption of ESD-STEM practices.

Researchers are encouraged to examine scalable, context-sensitive ESD-STEM models, particularly in resource-constrained settings, and to develop robust assessment frameworks capable of capturing sustainability-related competencies. Teacher education institutions play a critical role in preparing future

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educators with the pedagogical knowledge and practical skills required to implement sustainability-focused STEM curricula. Teacher preparation programmes should incorporate ESD-STEM instructional strategies, digital integration, and interdisciplinary collaboration. Mentorship initiatives and professional learning communities (PLCs) should also be strengthened to support novice teachers in navigating the complexities of sustainability education. Moreover, the effective implementation of ESD-STEM depends on active collaboration among government agencies, non-governmental organisations, and the private sector, particularly through public–private partnerships that address digital inequality and improve access to technological resources in marginalised regions.

This study contributes to the growing body of ESD-STEM scholarship by highlighting the interdisciplinary nature of sustainability education and its strong alignment with 21st-century skills. However, empirical evidence remains limited regarding how ESD-STEM fosters systems thinking and ethical reasoning among learners. Future research should investigate the long-term impacts of sustainability education on students' career trajectories and engagement in sustainable innovation. In addition, there is a pressing need for standardised sustainability assessment instruments that can be applied across diverse educational contexts to measure learning outcomes more effectively (Hernández-Barco et al., 2021).

While integrating ESD-STEM into educational systems offers significant potential for addressing global sustainability challenges, its effectiveness depends on sustained collaboration among educators, policymakers, researchers, and institutional stakeholders. This review underscores the importance of curriculum flexibility, investment in teacher capacity building, interdisciplinary pedagogical design, and strong stakeholder engagement. Future studies should focus on developing scalable and cost-effective approaches to support the expansion of ESD-STEM initiatives across diverse educational contexts. By addressing these challenges, ESD-STEM can function as a transformative educational approach that builds technical knowledge, practical competencies, and ethical values among future generations.

Despite its contributions, this study has several limitations. The reliance on selected databases (Scopus, Web of Science, and ERIC), together with the exclusion of non-English publications, may have resulted in the omission of relevant studies. Future systematic reviews should consider broader database coverage and multilingual sources to enhance the comprehensiveness and representativeness of findings.

Looking forward, future research should examine the sustained influence of ESD-STEM on students' career choices and participation in sustainability-driven initiatives. Further investigation into low-cost technological solutions and community-led approaches is also needed to address the digital divide and expand sustainability education in underserved regions. Addressing these gaps will enable the field to continue evolving and maximising its educational and societal impact.

In conclusion, ESD-STEM represents a transformative pathway for equipping future generations with the critical knowledge, practical skills, and ethical orientations required to address global sustainability challenges. Through pedagogical innovation, cross-sector collaboration, and supportive policy frameworks, ESD-STEM has the potential to catalyse meaningful educational change and contribute substantively to the achievement of the Sustainable Development Goals.

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DECLARATION ON THE USE OF GENERATIVE AI

In the preparation of this manuscript, the author used ChatGPT for language editing and clarity enhancement purposes. The use of generative artificial intelligence was limited to editorial support; all ideas, arguments, data, interpretations, and analyses remain the sole intellectual work of the author. The author has reviewed, verified, and exercised full control over the entire content and assumes complete academic responsibility for this publication.

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