ENHANCING ENVIRONMENTAL SUSTAINABILITY COMPETENCIES THROUGH DIGITAL PEDAGOGY: A PATHWAY FOR 21ST-CENTURY EDUCATION

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Abstract

Sustainability competence plays an important role in solving environmental problems such as environmental degradation, climate change, global warming and other sustainability issues. Sustainability competence can be improved through digital pedagogy characterised by the thoughtful use of digital technologies embedded in student-centred pedagogical approaches. This paper synthesised the recent research (2018–2026) on the impact of digital pedagogy on sustainability knowledge, skills, attitudes, and behaviours. From a thematic analysis of the studies, four main themes were identified: digital technologies and learning outcomes for sustainability competence; digital pedagogy models and competency models; barriers to integration; and recommendations. This paper posited that digital tools are effective in fostering sustainability competence when combined with a solid pedagogy, the relevant curriculum, and teacher education programmes. Four recommendations were provided for teachers, curriculum developers and policymakers.

Keywords: Environmental sustainability, competencies, digital pedagogy, digital tools, sustainability knowledge, skills, attitudes, behaviours.

Introduction

Education plays a crucial role in cultivating the skills needed to tackle contemporary environmental sustainability issues. Environmental sustainability competencies include cognitive knowledge, technical abilities, ethical values, and behavioural habits that enable learners to help protect ecological integrity and social fairness, and to ensure economic prosperity. Such competencies empower individuals to analyse complex ecological systems, make ethical decisions, and implement collaborative, long-term solutions focused on a sustainable future (Redman & Wiek, 2021; Wiek et al., 2011).

International frameworks, particularly the United Nations Sustainable Development Goals (UN SDGs), emphasise the need to develop such skills. SDG 4 and SDG 13 (along with others) indicate that education for sustainable development (ESD) is essential to develop the knowledge, skills and values required for sustainable futures. Contemporary frameworks identify systems thinking, anticipating thinking, norm-based (value) thinking, strategic thinking, interpersonal competence and intrapersonal reflection as foundational aspects (Redman & Wiek, 2021). The same period has also seen significant advances in digital transformation that have reshaped education, with faster implementation of tech-enhanced learning environments due to the COVID-19 pandemic.

Digital pedagogy not only refers to the use of technologies but is characterised by a synergistic approach in which digital resources and pedagogy work hand in hand to provide deeper learning, Critical reflection, collaboration, and reflective practice (Cols-Bravo et al., 2021). Digital pedagogy provides opportunities to enhance sustainability competencies; for example, virtual reality (VR) and augmented reality (AR) have the ability to provide students with experiential learning of processes which would otherwise be challenging to perceive or replicate (like environmental processes, ecosystems, resources), and adaptive systems based on data visualisation, gamification or artificial intelligence (AI) are useful tools for fostering systems thinking and action-oriented learning and reflecting practice. Furthermore, digital tools can support global collaboration, citizen science, access to Open Educational Resources (OER), and global dialogue on sustainability issues (Huang et al., 2024; Zhang et al., 2025).

Preliminary studies support this linkage. Cols-Bravo et al. (2021) report that Digital teaching competences have positive links with principles for sustainability learning; Sposab and Rieckmann (2024) state that digital tools have the potential to be used to foster action-oriented competences in secondary education; Huang et al. (2024) introduced a framework that suggests the integration of learner-centred design, digital competences, and human-AI co-design. Additionally, other studies reported that virtual learning modules could enhance nature connectedness and knowledge on biodiversity (Douglas, 2024) and that after COVID-19, technology expanded virtual fieldwork and access to real-time environmental data (Zhang et al., 2025).

Despite this convergence, the literature that specifically connects digital pedagogy to advancing sustainability competencies is limited and fragmented. Most of the literature focuses on how technology is adopted and on the specific use of tools, rather than on how pedagogy could be adapted. Other key challenges include equitable access, digital environmental footprint, and teacher training. There are very few works that review, synthesise, and theorise the connections between ESD and digital learning at various educational levels. This study aims to bridge this gap by systematically reviewing recent literature on this topic (2018-2026) and organising it according to 5 thematic areas: (a)Theoretical linkages between digital pedagogy and sustainability competence frameworks, (b)Empirical impacts of digital pedagogy on learners' knowledge, skills, values, and behaviours, (c)Innovative pedagogical models and case studies, (d)Challenges in the implementation and management of digital pedagogy in sustainability learning and the digital sustainability context, and (e)Future perspectives and role of new technologies, such as AI, and immersive technologies. By synthesising what is currently known, the review aims to identify viable pathways that connect digital pedagogy to the development of learners' ability to respond to current environmental problems.

Conceptual Foundations

Environmental Sustainability Competencies

Environmental sustainability competencies are by definition multidimensional. They are combinations of integrated knowledge, skills, values, and behavioural dispositions that allow learners to understand complex socio-ecological systems and contribute to the realisation of sustainable transformations (Redman & Wiek, 2021; Wiek et al., 2011). Unlike disciplinary knowledge, these skills foster holistic reasoning, normative judgement, and action to address a range of compelling problems, such as climate change, biodiversity loss, and resource disparities (Redman & Wiek, 2021; Wiek et al., 2011). Systems thinking, understanding the interlinked natures of ecological, social, and economic elements of sustainability, is integral, as are critical thinking and decision-making.

Systems thinking facilitates an understanding of the interconnections and feedback loops, and an ability to identify leverage points, whereas critical thinking and decision-making help students analyse data, interrogate their own assumptions, and consider the feasibility and implications of possible solutions (Sposab & Rieckmann, 2024). Ethical reasoning and value-thinking is a third area to which learners attend, considering not only the consequences of environmental decisions but also their justice and equity, intergenerationality, and interspeciesity.

Lastly, an action orientation (or action competence) in which learners apply knowledge and learning to action is key, recognising students' agency, strategic skills, and efficacy within both local and global contexts (Rambaree, 2020; Sposab & Rieckmann, 2024). These areas of focus are consistent with well-established approaches in the field; Wiek et al. (2011) synthesised key competency areas as: systems thinking, anticipation (future thinking), normative (values) thinking, strategic thinking, interpersonal interaction, and intrapersonal reflection. Rambaree (2020) highlights a parallel "living systems" framing, considering sustainability competencies as a complex interplay of adaptive capacities built on values, knowledge, and active agency.

Recent reviews, such as those by Sposab and Rieckmann (2024), further underline systems thinking, critical thinking, and action competence as essential areas within secondary ESD. Thus, Education for Sustainable Development (ESD) requires the careful, integrated development of all of these competencies both within the curriculum and outside of it; ESD should not be seen as a discrete subject, but as an approach which helps students learn and develop the capacity for holistic thinking and effective action within existing learning situations (Rambaree, 2020). In designing and evaluating digital pedagogy, these multidimensional competencies will guide the creation of impactful technology-enhanced interventions.

Digital approaches have the potential to strengthen systems thinking through simulations and data visualisation, enhance critical thinking through the analysis of globally diverse data and authentic problem scenarios, promote ethical reasoning and values-thinking through debates and global communication platforms, and further develop action competence through citizen science projects and real-world simulations. Therefore, understanding sustainability competencies as multidimensional is fundamental to the effective design of digital pedagogy for sustainability.

Digital Pedagogy Frameworks

Digital pedagogy frameworks provide structured guidance for integrating technology into teaching practices. In sustainability education, three frameworks are particularly relevant: TPACK, SAMR, and blended learning models. These frameworks ensure that technology use is pedagogically meaningful and aligned with learning objectives.

TPACK: Technological, Pedagogical, and Content Knowledge

Proposed by Mishra and Koehler (2006), the Technological Pedagogical Content Knowledge (TPACK) framework highlights the fluid intersections between content knowledge (CK), pedagogical knowledge (PK) and technology knowledge (TK) that are crucial for the successful integration of technology in the classroom. In sustainability education, CK is the understanding of environmental sciences and sustainability issues; PK relates to pedagogical approaches that support engagement, critical thinking, and reflection; and TK is the expertise in using digital tools and platforms. The interplay of these three knowledge domains is key to designing meaningful digital experiences to improve students' ability to think critically and analytically, solve problems, and develop applied sustainability skills, with variations of TPACK (i.e. S-TPACK) that aim to guide the integration of technology to meet sustainability values (Chai et al., 2021; Abu-Daabes et al., 2023).

SAMR: Substitution, Augmentation, Modification, Redefinition

According to Puentedura's (2006) framework of Substitution, Augmentation, Modification, and Redefinition (SAMR), the levels of potential transformation are very helpful in judging the extent to which a digital intervention transforms learning in education. At the lower levels, substitution means using technology as a direct substitution with no functional change, for example, students submitting homework electronically, or augmentation involves added function, like an online interactive quiz for a lesson about sustainability. At higher levels, modification involves significantly modifying a task, for example, analysing locally collected environmental data in collaboration through a digital platform, and redefinition allows totally new tasks unimaginable before, for example, interactive maps of sustainability in the local area or virtual environmental simulations that reflect climate change effects. In sustainability education, the SAMR model is useful for evaluating a digital intervention to ensure that, rather than just digitising existing teaching, technology is used in a transformative manner to effectively nurture sustainability competencies (Prastiyono & Isaias, 2025).

Blended Learning Models

Blended learning combines the advantages of traditional face-to-face sessions with well-designed digital learning environments, fostering active learner participation and rich interaction with content. The pedagogical strategies in environmental education might include: online learning modules preceding class on an environmental problem, followed by problem-based learning in class; virtual tours of natural ecosystems, followed by an on-campus debate; online simulations of water and energy resource management systems, followed by structured reflective practices in class. Properly implemented, learning and environmental sustainability-related skills can be reinforced through blended learning, using frameworks such as TPACK and SAMR, among others, as well as pedagogical approaches such as systems thinking, collaboration, reflection, and action skills (Garrison & Vaughan, 2018; Cols-Bravo et al., 2021).

Integrating Frameworks for Sustainability Competencies

By applying TPACK, SAMR, and blended learning together, educators can design comprehensive digital learning experiences that:

1. Align technology use with pedagogy and sustainability content.
2. Promote engagement at increasing levels of cognitive and transformative complexity.
3. Foster reflection, collaboration, and action-oriented competencies.

For example, a blended lesson on climate change could use TPACK-informed simulations (SAMR Redefinition), paired with collaborative classroom projects analysing local carbon footprints, cultivating both knowledge and applied sustainability skills.

Theme 1: Digital Tools and Sustainability Learning Outcomes

Between 2018 and 2026, empirical and review studies indicate that immersive digital technologies, including VR, AR, mobile games, and interactive simulations, can indeed have a substantial effect on improving learners' understanding of environmental subjects, knowledge of sustainability and attitude toward environmental issues. In a systematic review of digital tools for sustainability and environmental education, VR and AR were highlighted as among the most utilised tools for learning about the environment and showed a strong association with learners' attitudes toward sustainability and cognitive engagement with environmental content (Hajj Hassan et al. 2024).

Specifically, the use of mobile augmented reality games, for instance, has been empirically shown to develop environmental sustainability competencies, which include knowledge about environmental protection, cultural awareness regarding sustainability practices, and knowledge of the environment in a particular context, particularly when developed within the contexts of real-world settings and reflection (Marques et al., 2025). Using mobile AR, students could establish situation-based connections between abstract concepts of sustainability and physical environmental challenges by framing learning within real-world smart city environments. Other experimental and qualitative research indicated that VR and AR technologies promoted environmental consciousness, collaborative problem-solving and immersion with the environment, all of which have contributed to pro-environmental attitudes and behavioural intentions (Chen, 2025; Faiz, 2025; Sahabuddin & Makkasau).

Studies conducted more recently moved beyond single-technology use to the design of 360 VR simulation environments that may provide a spatial experience of ecosystems and environmental changes that is not accessible through traditional pedagogy, fostering empathy and motivations for sustainable behaviour (Guerriero et al. 2026; Nouri & Bouzaabia 2025). One study of VR serious games (in 2026) indicated that these serious games have provided effective experiential learning in systems thinking for environmental issues, although their effects on policy support have not yet been substantially explored (UNESCO, 2023).

However, it is important to notice that the effectiveness of technological affordances for sustainability learning outcomes is not inherently guaranteed. Systematic review studies indicate that many interventionist attempts achieved higher levels of learning, with cognitive and affective gains, when designed with a pedagogically coherent framework, including reflection, inquiry, and the context-based application of content (Marques et al., 2025; Hajj Hassan et al., 2024). Without proper curriculum integration, the use of technology will remain superficial and will not be translated into learners' environmental thoughts and behaviour.

These findings align with other learning models, including TPACK, SAMR, and blended learning approaches, which require meaningful technology integration with both pedagogy and content. With a TPACK-based design, for instance, VR simulation should be used in combination with guiding critical inquiry and discussions on sustainability topics, rather than in a standalone manner. And the SAMR model implies that teachers should shift from a substitution task to a transformative task to foster learners' application of environmental knowledge. In blended learning models, VR simulation can be combined with face-to-face reflective activities and group work so that learners can better connect the virtual experience and real-world environmental practice. Overall, it is concluded that the impact of digital technology use on learner sustainability competence requires a pedagogically sound curriculum design.

Theme 2: Pedagogical Frameworks and Competency Models

Frameworks such as TPACK, SAMR, and blended learning guide educators, both theoretically and practically, in designing digital education for sustainability. TPACK (Technological Pedagogical Content Knowledge) calls for simultaneously attending to content knowledge, pedagogical approaches and technology so that digital interventions are purposeful and not an afterthought in the learning process (Chai, Koh & Tsai, 2021; Abu Daabes et al., 2023). In terms of sustainability learning, lesson design following TPACK could mean utilising digital simulations or VR to teach ecological systems thinking while using interactive and collaborative tasks and reflection.

The SAMR model offers an additional approach to technology integration, classifying uses of technology from substitution to redefinition (Puentedura, 2006). Studies suggest that technology-enabled activities for sustainability are most powerful when moving from substitution (e.g., students digitally submit an essay) to higher-level transformation, such as collaboratively producing a digital project on resource management, creating interactive environmental data dashboards, or using a game-based approach to modify climate models and investigate the impacts of various factors (Filho et al., 2023; UNESCO, 2023). These transformational applications encourage higher-order skills and a deeper understanding of complex environmental systems, thereby fostering a broad understanding of sustainability literacy.

Blended learning frameworks extend TPACK and SAMR by defining models for combining online, digital, and face-to-face educational experiences. Combining online digital pre-class modules with virtual field trips, collaborative problem-solving exercises, face-to-face discussion sessions, and group projects can develop conceptual knowledge and practical skills for sustainability education (Garrison & Vaughan, 2018; Cols-Bravo et al., 2021; Nwafor et al., 2026). These combined approaches help in developing learners' experiential and reflective understanding and apply these concepts to sustainability.

In addition to these framework-based approaches to integrating technology, models for holistic competency development, such as the EDGES-AI Compass, focus on the intersection of ethical, digital, and green literacies for curriculum design in sustainability education (Anthuvan et al., 2025). By focusing on ethical considerations within the digital sustainability education experience, educators can nurture learners' knowledge, skills, attitudes and behaviours that align with the Sustainable Development Goals. For example, through an AI-based simulation, learners could investigate energy consumption patterns and discuss the ethical considerations and policy implications to develop complex sustainability competencies.

Furthermore, emerging research on digital humanities applications suggests that interactive storytelling, AI platforms, and game-based learning can be used to develop environmental literacy and promote behaviour change (Ibrahim, 2024; Kayr & Akyol, 2025; Ekpoto et al., 2026b).

Learners report higher engagement, deeper reflection and increased desire to exhibit pro-environmental behaviours when learning using highly interactive narratives and games for sustainability (Addo et al., 2025; Ekpoto et al., 2026a; Nkanu et al., 2025). VR-based environmental storytelling can enable students to visualise the consequences of environmental destruction (e.g., deforestation or water depletion), fostering empathy, systems thinking, and ethical reasoning for sustainability (Nkanu et al., 2024). Taken together, these models provide a strong foundation for educators to thoughtfully design digitally integrated, experiential, and transformative education for sustainability.

Theme 3: Challenges and Barriers

Despite potential benefits, challenges include:

1. Insufficient educator preparation in both technology use and sustainability pedagogy (McGarr, 2023).
2. Limited meaningful integration of sustainability content with digital tools (Prastiyono & Isaias, 2025).
3. Equity and infrastructure constraints restrict access to digital learning.
4. Environmental impacts of digital technologies themselves (Spangenberger & Söbke, 2025).

Addressing these barriers is critical to achieving transformative learning outcomes.

Conclusion

TPACK, SAMR, and blended learning frameworks, among others, offer rigorous and guided approaches to building 21st-century sustainability education capacities. Properly implemented, these frameworks move technology from substitution to redefinition, guiding teachers in creating immersive, interactive and action-oriented environments that challenge learners to develop deeper understandings of systems, moral judgment, critical thought, and concrete problem-solving approaches. When teachers effectively integrate technology into content and pedagogy, they create powerful learning experiences that enable students to contend with the Anthropocene's complexity. At the nexus of widespread digital advancement and environmental crisis, this intentional integration of digital pedagogy and sustainability education offers us a roadmap to a better, more hopeful future. It can be our hope and guide for educating learners who can become earth keepers, who value critical thought and understand their roles as change agents for sustainability.

Recommendations

Based on the study, the following recommendations were made:

1. Embed sustainability explicitly in digital curricula.
2. Provide professional development in TPACK-informed digital pedagogy.
3. Use SAMR to evaluate and enhance digital task complexity.

4. Adopt blended learning strategies to foster engagement and collaboration.
5. Evaluate the environmental impacts of digital tools and ensure equity of access.

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