

Pedagogical Practices and Reflections on AI-Enhanced Innovation in Sustainability Education: Guiding AI Integration Through the IDEA Framework



Dharel P. Acut and Manuel B. Garcia

Abstract Artificial intelligence is increasingly influencing sustainability education by providing dynamic tools that foster systems thinking, data literacy, ethical reasoning, and creative problem solving. Yet despite growing experimentation with AI in teaching and learning, there remains a notable gap in practice-based frameworks that guide educators in integrating AI into ESD in ethically grounded and pedagogically purposeful ways. Addressing this need, this chapter explores how AI can be thoughtfully integrated into Education for Sustainable Development (ESD) through innovative pedagogical approaches. Drawing on teaching cases and reflective analysis, it introduces the IDEA (Innovation, Design, Evaluation, and Anchoring) framework as a structured yet flexible guide for integrating AI into practice. The framework is illustrated through practice-informed vignettes, including the use of generative AI for futures thinking, machine learning for environmental data analysis, AI-powered feedback in ethics debates, and co-designed projects with pre-service teachers. These examples highlight both the affordances and tensions of using AI in higher education and teacher preparation programs. The IDEA framework encourages educators to critically examine how AI tools align with sustainability goals, support meaningful learning outcomes, and surface issues of ethics, equity, and digital competence. Situating AI not as a disruptive novelty but as a pedagogical mediator, the chapter contributes to the discourse on ESD and the responsible integration of emerging technologies. Drawing on interdisciplinary scholarship, it reflects on implications for curriculum design, faculty development, and education policy, offering actionable recommendations for creating ethical, inclusive, and future-facing learning environments.

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W. Leal Filho et al. (eds.), *Artificial Intelligence in Sustainability Teaching and Research*, World Sustainability Series, https://doi.org/10.1007/978-3-032-34574-5_3

Keywords AI-enhanced innovation • Sustainability education • Education for sustainable development • Pedagogical practices • Reflective inquiry

1 Introduction

Amid rising seas, warming skies, and shifting social landscapes, artificial intelligence (AI) has emerged as a transformative force across sectors. It introduces new capacities for interpreting complexity and navigating rapidly changing global conditions (Toderas 2025). Its expanding influence is reshaping how knowledge is created, accessed, and applied in contemporary society. Within education, AI provides powerful tools that can enhance pedagogy, personalize learning pathways, and deepen engagement with real-world challenges such as those posed by sustainability transitions (Leal Filho et al. 2025; Strielkowski et al. 2024). As climate change, biodiversity loss, social inequities, and other manifestations of unsustainable development intensify, the need for education systems to cultivate adaptive, future-oriented, and critically aware learners has become increasingly urgent (Asian Development Bank 2024). The complexity and interconnected nature of sustainability issues require pedagogical approaches that help learners work with uncertainty, analyze large datasets, and consider multiple future scenarios. AI-supported methods offer capacities that can contribute to these aims in practical and meaningful ways. Integrating AI into sustainability education holds considerable potential to support this work by strengthening data-driven inquiry, systems-level thinking, and ethically grounded decision-making processes (Torres-Rivera et al. 2025). These possibilities create a foundation for examining how AI can contribute to sustainability learning in higher education and how educators can engage with these tools in responsible and reflective ways.

Framing these pedagogical possibilities within the broader agenda of Education for Sustainable Development (ESD) positions AI as a tool that can support transformative learning. ESD promotes a holistic, interdisciplinary, and action-oriented approach that prepares learners not only to understand sustainability issues but also to respond to them in informed and responsible ways. The United Nations Educational, Scientific and Cultural Organization (UNESCO) Roadmap for ESD (2020) highlights the need for pedagogical innovation that encourages learners to examine dominant systems, imagine alternative futures, and participate meaningfully in sustainability transitions. This vision requires a shift away from transmissive forms of instruction and toward participatory, reflexive, and experiential approaches that strengthen learner agency and dialogue (Acut et al. 2025a). AI technologies can contribute to these goals when they are used with intentionality. They provide tools that can enhance collaboration, model complex systems, and support interdisciplinary exploration (Tian and Zheng 2025). These capacities align closely with the aims of sustainability learning, which seeks to build competencies that prepare learners to engage with uncertainty and change.

Integrating AI into educational environments introduces a range of risks that require careful consideration. Adaptive systems, intelligent tutoring platforms, and natural language models can expand opportunities for personalized learning and offer access to real-time feedback (Sharma et al. 2025). These opportunities must be balanced with a critical awareness of ethical and epistemological concerns that continue to surface in the field (Garcia et al. 2025). Algorithmic bias, inadequate data privacy protections, techno-solutionist tendencies, and the potential erosion of human judgment represent key critiques that educators and institutions need to address (Alvarez et al. 2024). For AI to serve the goals of sustainability education, its integration needs to maintain equilibrium between innovation and caution (Chigbu and Makapela 2025). This balance ensures that educational technologies support values of justice, equity, and human dignity rather than compromise them. A critical and reflective approach is essential for navigating these tensions.

Responding to this complex landscape, the present chapter explores innovative pedagogical practices in sustainability education that utilize AI tools and technologies in higher education settings. It draws from the experiences of educators engaged in designing and delivering courses where AI supports lesson development, classroom engagement, assessment strategies, and student inquiry. The aim is to provide examples that are locally situated yet globally relevant. These teaching cases offer insights into how AI integration can enrich transformative sustainability learning while also foregrounding the ethical, practical, and pedagogical considerations that accompany its use. Through a practice-informed lens, the chapter engages with both the tensions and affordances of AI-enhanced pedagogy and contributes to ongoing dialogue about responsible innovation in education.

To support this reflection, the chapter introduces the IDEA (Innovation, Design, Evaluation, and Anchoring) framework as a structured approach that guides educators in analyzing and improving their use of AI in sustainability teaching. The framework consists of four interconnected dimensions. *Innovation* highlights emerging pedagogical strategies and practices that become possible through AI use. *Design* focuses on how instructional planning, contextual alignment, and tool selection shape the implementation of AI within learning environments. *Evaluation* centers on critical reflection related to impact, challenges, and unintended consequences. *Anchoring* situates teaching practice within broader research, theoretical perspectives, and the core values of sustainability education. Together, these dimensions form a scaffold for documenting and interpreting practice in ways that are both reflective and generative. They support educators, researchers, and policymakers in examining the pedagogical opportunities and limitations associated with AI as they work to advance sustainability competencies. The remainder of the chapter outlines the methodological approach used to collect and synthesize the reflective teaching cases, presents a series of practice-based vignettes analyzed through the IDEA framework, and concludes with insights, limitations, and implications for integrating AI into ESD.

2 Methodology

This chapter is guided by a practitioner-informed reflective inquiry approach, grounded in our lived pedagogical experiences as higher education educators engaged in sustainability teaching (Schön 1992; Zeichner and Liston 2013). Reflective inquiry, as used here, positions our instructional practices as both the subject and source of analysis, enabling a deeper understanding of how AI-enhanced innovations unfold in real classroom contexts (Cochran-Smith and Lytle 2009). Through systematic reflection on our planning decisions, classroom interactions, and student outcomes, we aim to surface pedagogical insights that are context-sensitive and critically informed (Brookfield 2017). This approach acknowledges the iterative, situated, and value-laden nature of educational innovation, particularly when integrating emerging technologies like AI into curriculum and instruction in support of transformative sustainability education.

To guide this inquiry, we draw on three interrelated conceptual frameworks that inform both the design and interpretation of AI integration in our teaching practice. The Technological Pedagogical Content Knowledge (TPACK) model (Mishra and Koehler 2006) offers a lens to examine how disciplinary knowledge, pedagogical strategies, and digital tools intersect to shape instructional decision-making. The SAMR (Substitution, Augmentation, Modification, Redefinition) model (Puentedura 2014) provides a continuum for evaluating the depth of technology integration, ranging from surface-level enhancement to the transformation of learning experiences in ways previously unattainable. Complementing these, Kolb's Experiential Learning Theory (1984) frames our ongoing professional learning as a cyclical process of concrete experience, reflective observation, abstract conceptualization, and active experimentation. Together, these frameworks support a dynamic, practice-sensitive understanding of educational change, enabling us to critically examine how AI mediates both teaching and learning within sustainability-focused contexts.

2.1 *Study Context and Participants*

The reflections and data presented in this chapter were drawn from three education-related courses offered at a public university in Central Visayas, Philippines, during the academic years 2024 and 2025. These courses spanned undergraduate science teacher education, graduate-level technical and vocational education, and development education, which collectively provided complementary contexts for exploring how AI can be meaningfully integrated into sustainability-focused learning across disciplines.

Each course incorporated AI-enhanced activities aligned with its specific outcomes. In science education, students used ChatGPT and AI-assisted visualization tools to generate climate models and interpret sustainability scenarios. In the technical and vocational program, generative AI and automation simulators supported

discussions on Industry 4.0 and sustainable workforce development. Meanwhile, in the development education course, learners engaged in AI-mediated storytelling and ethical decision-making on global sustainability challenges.

Three educators participated in this reflective inquiry, including the first author. The other two educators, specializing in development education and technology management, consented to the inclusion of their anonymized reflections and instructional materials but opted not to take part in authorship. This arrangement ensures transparency and alignment with COPE authorship and ethical standards.

At the time of the study, the university did not yet have formal institutional guidelines on AI use in teaching and learning. This absence created both flexibility and uncertainty, allowing instructors to experiment with innovative pedagogical applications while engaging in ethical self-regulation. The inquiry thus served as an informal testbed for examining the pedagogical, ethical, and institutional implications of AI in higher education.

All three educators shared a commitment to transformative pedagogy grounded in the principles of ESD, using AI not merely as a tool but as a catalyst for ethical reflection, systems thinking, and creative problem-solving. The study adhered to institutional and national ethical standards, with voluntary participation and informed consent obtained from all educators. Reflective records and instructional materials were anonymized to ensure confidentiality. Compliance with Republic Act No. 10173, or the Philippine Data Privacy Act of 2012, was maintained throughout to ensure responsible data handling.

2.2 *Data Collection and Synthesis*

Data for this chapter were generated through multiple sources that captured both planned and emergent aspects of AI integration in teaching. We documented reflective teaching journals, prepared weekly during and immediately after class sessions, which detailed instructional decisions, student interactions, and observed challenges. We also compiled classroom vignettes describing notable moments of AI use, such as student engagement with generative tools for project work. In addition, learning artifacts, in particular student outputs, lesson materials, and assessment rubrics, were collected to provide evidence of how AI applications shaped both teaching practice and learner outcomes. Course syllabi and instructional resources further contextualized the pedagogical approaches under review.

The synthesis of these materials followed an iterative process informed by the IDEA Framework (Fig. 1). Episodes of AI integration were coded and organized into four dimensions:

- **Innovation:** identifying what was introduced or altered in practice, such as novel uses of generative AI or redesigned student tasks.
- **Design:** documenting the curricular and classroom contexts where innovations occurred, including the rationale for tool selection and pedagogical alignment.

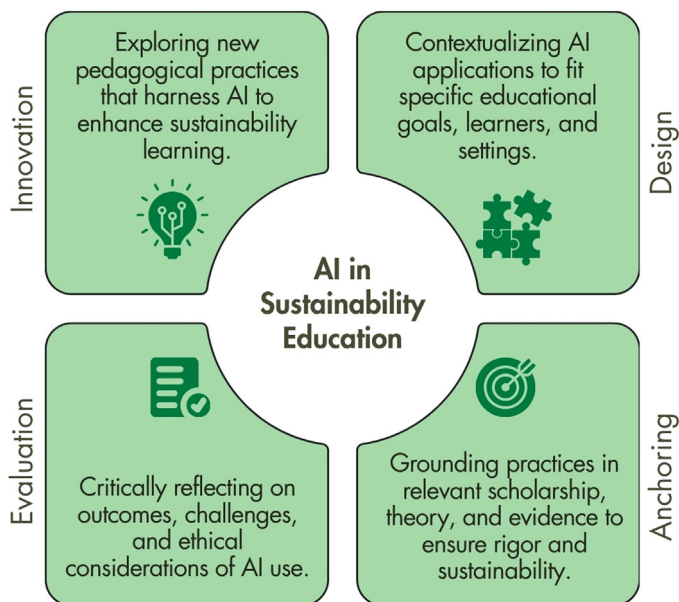


Fig. 1 The IDEA framework for analyzing teaching cases on AI in sustainability education. *Source* Author

- **Evaluation:** capturing critical reflections on outcomes, highlighting both opportunities and challenges in teaching and learning.
- **Anchoring:** linking the practices and reflections to relevant research and theoretical constructs, ensuring that insights were both experiential and scholarly.

To enhance the robustness of the analysis, we engaged in collaborative sense-making, reviewing journals, vignettes, and artifacts across the three courses to identify recurring themes and divergences. Pattern coding (Saldaña 2016) was applied to surface broader insights, such as the affordances of AI for fostering creativity, the risks of over-reliance on automated systems, and the pedagogical shifts required for meaningful integration. The synthesis thus represents a blend of personal reflection, participant experience, and conceptual grounding, providing a practice-informed contribution to the discourse on AI in sustainability education.

2.3 Trustworthiness and Rigor

Given the reflective and practice-based nature of this inquiry, we employed several qualitative research strategies to ensure trustworthiness and rigor, guided by the Standards for Reporting Qualitative Research (SRQR) (O'Brien et al. 2014) and recent

guidelines for conducting qualitative research (Lim 2024). Reflexivity was maintained throughout the process, as we explicitly examined our dual roles as educators and researchers, recognizing how our positionalities and commitments to sustainability education shaped the interpretations we drew from classroom experiences. We documented reflexive memos alongside our journals to surface assumptions, biases, and value orientations, thereby aligning with methodological standards that emphasize transparency, researcher characteristics, and contextual sensitivity.

To strengthen credibility, we drew on triangulation across multiple data sources, including journals, classroom vignettes, student outputs, and instructional materials, which allowed us to compare and corroborate insights from different perspectives. This multi-source approach reduced the risk of overreliance on a single type of evidence.

Collaborative review further enhanced the dependability of findings. The three educators involved in the courses revisited one another's reflections and artifacts, which enabled a cross-checking of interpretations and opened space for dialogue about points of convergence and divergence. While students were not formal co-researchers, informal member-checking was achieved by revisiting interpretations against student feedback and observed classroom responses, ensuring that the insights resonated with actual learner experiences.

Finally, thick description of the instructional context—public higher education in Central Visayas, Philippines, within science teacher education, technical education, and development education programs—supports transferability by enabling readers to assess the applicability of our findings to other teaching and learning environments. Collectively, these practices provide a foundation for rigor while honoring the situated, experiential, and value-laden character of reflective inquiry.

3 Reflective Vignettes: AI-Enhanced Practices in ESD Contexts

The following vignettes illustrate concrete examples of how AI tools were integrated into sustainability-focused teaching and learning across undergraduate and graduate courses. Each vignette highlights a distinct pedagogical innovation, the design and implementation of AI-enhanced activities, and the corresponding outcomes observed in learners. These cases are organized according to the IDEA framework and aligned with the key domains of AI application in ESD, including systems thinking, data literacy, ethical reasoning, and creative problem solving, as shown in Fig. 2. Together, the vignettes provide practice-informed insights into the affordances, challenges, and ethical considerations of AI integration, serving as illustrative touchpoints for educators seeking to implement AI responsibly in sustainability education contexts.

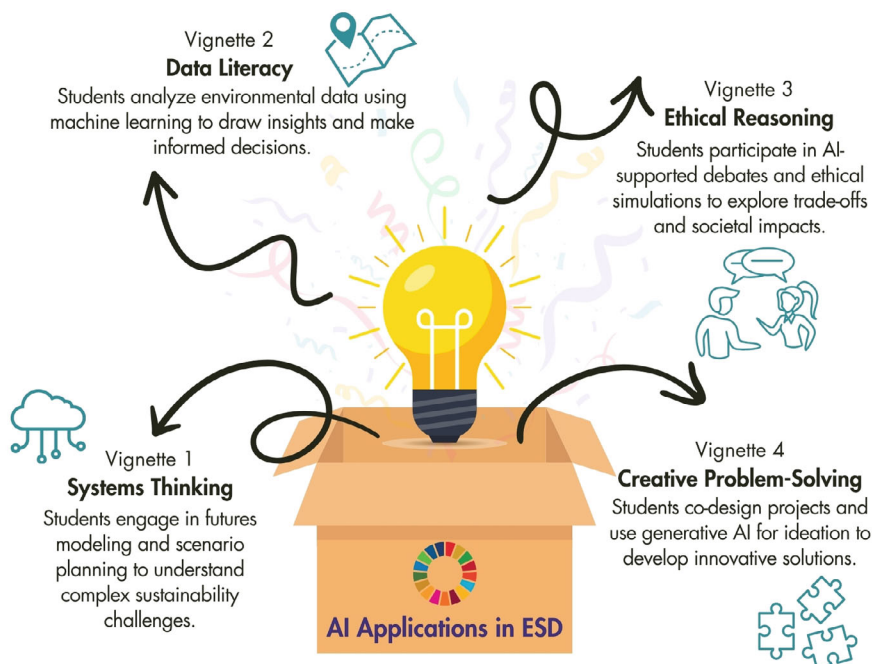


Fig. 2 AI applications in ESD with key domains and sample use cases. *Source* Author

Vignette 1: Generative AI for Climate Futures Thinking

Innovation. In an undergraduate module on environmental justice, we experimented with the use of generative AI to support climate futures thinking. The innovation centered on AI-assisted storytelling, where students used ChatGPT to co-develop narrative prompts and Google Gemini to generate visualizations of possible climate futures. Gemini’s multimodal capabilities allowed learners to move beyond text-based scenarios by producing illustrative images and infographics that reflected their climate narratives. These outputs provided students with creative pathways to imagine and communicate complex environmental transformations.

Design. The activity was structured around climate scenario exploration. Students began by analyzing scientific datasets and policy reports on climate impacts across biomes, then crafted speculative narratives that explored both sustainable and unsustainable futures. Using ChatGPT, they generated storylines, which were then paired with Gemini-produced images of future landscapes, cities, or ecosystems under varying conditions. The combination of textual and visual artifacts encouraged multimodal engagement and stimulated discussion about the plausibility, ethics, and consequences of each scenario.

Evaluation. The integration of generative AI fostered greater creativity and expanded the imaginative range of student projects. Learners reported that visual outputs from

Gemini helped them think more concretely about abstract climate data, while narratives from ChatGPT provided structure and depth. However, critical issues emerged: some Gemini images tended to exaggerate dystopian themes or simplify complex systems, prompting reflection on AI's limitations. The exercise reinforced the importance of human judgment in interpreting AI outputs and situating them within ethical and scientific frames.

Anchoring. This vignette draws on principles of futures thinking (Miller 2018), where learners anticipate and evaluate multiple possibilities for environmental change. It also resonates with speculative design (Dunne and Raby 2013), in which creative provocations are used to question assumptions and inspire alternative imaginaries. Finally, the activity promotes AI literacy (Leal Filho et al. 2023), encouraging students to critically engage with generative AI outputs while developing agency in shaping sustainable futures.

Vignette 2: Machine Learning for Environmental Data Exploration

Innovation. In an undergraduate sustainability education module, we adapted Microsoft's (2025) Hacking STEM lesson plan, "Analyze astronauts' photos of Earth to predict climate change", to introduce students to machine learning as a tool for environmental inquiry. The innovation lay in combining authentic satellite and astronaut imagery with computational techniques to detect seasonal changes in biomes and explore long-term climate impacts. Bridging hands-on classroom learning with AI-enabled analysis allowed students to engage with real-world data in ways that made abstract concepts of climate systems and machine learning more tangible.

Design. The lesson was structured as a progressive inquiry cycle. Students began with an introduction to Earth's seven major biomes and their seasonal characteristics, using temperature and precipitation data. They then examined attributes of their local biome before exploring how computers represent color through the hexadecimal system. Next, students worked with astronaut and satellite photographs to model seasonal color changes within biomes. This activity transitioned into using machine learning modules to detect seasonal patterns in the images and compare the interpretive processes of humans versus AI systems. The sequence concluded with students projecting how biomes might change under climate stressors and articulating actions (social, political, environmental, or economic) that individuals and communities could take to protect the planet.

Evaluation. This activity enhanced students' data interpretation skills and their ability to connect computational reasoning with sustainability challenges. Learners valued the opportunity to compare human and machine perspectives, recognizing both the potential and limitations of AI in environmental monitoring. At the same time, the lesson revealed the need for scaffolding, as students often required support in understanding technical aspects of hexadecimal color codes and ML outputs. Without adequate guidance, some learners struggled to critically interpret AI-generated classifications, underscoring the importance of framing these tools as complements to, rather than replacements for, human judgment.

Anchoring. The vignette reflects principles of inquiry-based learning (Pedaste et al. 2015), encouraging students to investigate real-world phenomena through cycles of questioning, exploration, and reflection. It also aligns with the integration of data science in education (Weintrop et al. 2016), providing learners with computational experiences that extend disciplinary knowledge in environmental science. Embedding AI and ML within a structured pedagogical design demonstrated how digital innovation can cultivate not only technical literacy but also sustainability-oriented civic engagement.

Vignette 3: AI-Powered Feedback in Sustainability Ethics

Innovation. In a graduate course on sustainability leadership, we introduced the use of ChatGPT as a feedback partner in structured debates and policy writing exercises centered on the Sustainable Development Goals (SDGs). The innovation involved positioning generative AI as a “critical interlocutor” that could provide real-time counterarguments, highlight overlooked dimensions, or suggest refinements to students’ reasoning. Students engaged with AI both during debate preparation and in the drafting of short policy briefs, using the feedback to strengthen their arguments and critically examine trade-offs in sustainability decision-making.

Design. The activity was implemented over two sessions. In the first, students were divided into debate teams representing different SDG priorities (e.g., economic growth vs. climate action, industrial development vs. biodiversity preservation). Prior to the debates, teams used ChatGPT to generate potential counterarguments and identify weaknesses in their own positions. During the debate, AI outputs were consulted in real time as provocations for rebuttals or evidence-building. In the second session, students drafted short policy briefs on their assigned SDG trade-offs, again employing ChatGPT to receive suggestions for structure, clarity, and rhetorical persuasiveness. AI-generated feedback was treated as a draft scaffold, with students required to critically review, edit, and annotate AI contributions.

Evaluation. The use of ChatGPT enriched argumentation by exposing students to perspectives they might not have initially considered, fostering more nuanced engagement with sustainability dilemmas. Learners reported that AI feedback encouraged them to anticipate counterarguments and clarify their ethical reasoning. However, the activity also surfaced concerns. AI-generated arguments occasionally revealed bias or oversimplification, and some students worried about overreliance on AI for rhetorical support. This underscored the importance of positioning AI as a dialogic tool rather than an authoritative source, with human critical judgment remaining central.

Anchoring. This vignette draws from traditions of argumentation in science education (Jiménez-Aleixandre and Erduran 2007), which emphasize the development of critical reasoning, evidence evaluation, and dialogue in grappling with socio-scientific issues. It also engages with scholarship on ethical AI use (Floridi and Cowls 2019), particularly the imperative to frame AI as augmenting rather than displacing

human deliberation. Situating AI within structured debate and policy writing demonstrated its potential to cultivate both argumentative competence and ethical reflexivity in sustainability education.

Vignette 4: Collaborative Sustainability Project Design with AI

Innovation. In a graduate course on technical and vocational education focused on civil construction, ChatGPT was introduced as a collaborative partner in the design of sustainability-focused construction projects. The innovation centered on using AI to scaffold creativity in project ideation, planning, and documentation. This support helped students generate proposals that addressed sustainability concerns such as green building practices, waste reduction, and energy efficiency in construction.

Design. The activity was structured in three stages. First, student groups identified pressing sustainability challenges in construction, such as materials sourcing, carbon footprint, or water management in building design. Next, they engaged with ChatGPT to brainstorm possible project solutions, refine their objectives, and outline implementation steps. AI support was used to suggest sustainable construction methods, stakeholder involvement strategies, and measurable environmental impacts. Finally, students integrated AI contributions with professional standards and local regulations to draft comprehensive project proposals. Instructors facilitated discussions where learners critically evaluated AI outputs, comparing them with technical best practices and feasibility within the Philippine context.

Evaluation. Students reported that AI helped expand their thinking about sustainable construction, particularly by introducing practices and technologies they had not previously considered. The tool was especially valuable in structuring proposals and exploring alternative approaches. However, concerns about overreliance were noted, with some groups initially adopting AI recommendations without sufficient technical scrutiny. This underscored the importance of positioning AI as a creative aid rather than a substitute for technical expertise and critical judgment.

Anchoring. This vignette builds on the principles of project-based learning in technical and vocational education, where learners tackle authentic, applied challenges (Thomas 2000; Guo et al. 2020). It resonates with research on creativity support in professional practice, highlighting how AI can extend idea generation in highly technical fields (Shneiderman 2007; Lubart 2017). Finally, it draws from the literature on human–AI collaboration in engineering education, emphasizing the need for critical engagement with AI-generated content to ensure both technical accuracy and ethical responsibility in sustainability-oriented construction projects (Elmousalami et al. 2025).

4 Discussion

Across the four vignettes, innovation surfaced as a central characteristic of AI integration, with digital tools enabling forms of teaching and learning that extended beyond traditional pedagogical constraints. Whether through generative storytelling, machine learning–driven data exploration, AI-supported ethical debates, or collaborative design of sustainability-oriented construction projects, AI functioned as a catalyst that opened pathways for experimentation, multimodal engagement, and new forms of inquiry. These innovations suggest that the pedagogical value of AI lies not in technological novelty but in its capacity to reorganize how learners interact with content, collaborate with peers, and construct meaning around complex sustainability challenges. This aligns with recent scholarship, such as Henriksen et al. (2024), who highlight AI's potential to personalize learning and foster creative problem solving while cautioning against approaches that lack interdisciplinary grounding or real-world applicability. Likewise, Leal Filho et al. (2025) emphasize how the thoughtful deployment of AI in education can enrich learning experiences, strengthen exploratory thinking, and support the development of sustainable solutions through more adaptive instructional designs. Taken together, these perspectives and our classroom observations illustrate that AI-driven innovation becomes pedagogically meaningful when it amplifies human creativity, deepens engagement with sustainability concepts, and enables learners to explore ideas and practices that would be difficult to realize through conventional methods.

AI as a Partner in Creativity Enhancement

Creativity emerged as a recurring theme across the vignettes, with AI expanding the imaginative range of learners by supporting speculative futures thinking, offering alternative design pathways, and providing multiple perspectives in ethical decision-making. In these contexts, AI acted as a collaborator that helped students reframe problems and consider ideas they might not have otherwise explored, aligning with research suggesting that AI can enhance creative problem-solving when learners maintain agency and guide the direction of exploration. Urmeneta and Romero (2025) emphasize that AI's value in creative tasks depends on its role as a co-participant that broadens rather than constrains human ideation, while Zhang et al. (2025) argue that emerging technologies are reshaping creativity itself by fostering a dynamic interplay between human and machine inputs. This process is described by Garcia (2024) as artificial creativity, where algorithmic contributions augment human imagination. This reconceptualization has practical implications for sustaining innovation in educational settings, particularly when creativity intersects with sustainability challenges that require flexible thinking and interdisciplinary synthesis. As Mangubat et al. (2025a) note, the expansion of creative possibilities through AI must be supported by equitable policy frameworks and safeguards that ensure intellectual contributions (whether human-generated, machine-assisted, or hybrid) remain ethically and professionally recognized. Across the vignettes, AI enabled learners

to generate diverse options, iterate complex ideas, and approach sustainability problems with greater originality than traditional methods alone often permit, illustrating the transformative potential of human–AI creative partnerships in ESD.

AI as a Cognitive Amplifier for Complexity

Another common thread across the vignettes is the capacity of AI to support learners in engaging with complexity, particularly in domains such as climate change, sustainability ethics, and civil construction where systemic interdependencies and uncertainty shape both understanding and decision-making. In our cases, AI helped students visualize multifaceted climate patterns, frame ethical trade-offs in SDG debates, and explore interlinked design considerations in technical projects, illustrating how digital tools can act as cognitive amplifiers that help synthesize diverse information sources and reveal patterns that may be difficult to discern through manual analysis alone. However, this amplifying role must be approached with caution. As Jose et al. (2025) warn, the convenience of AI-generated synthesis can inadvertently suppress higher-order thinking skills by encouraging students to rely on automated responses rather than developing their own judgment, analytical reasoning, or reflective critique. Scholes (2025) similarly emphasizes that while AI can strengthen adaptability and responsiveness in learning, such benefits depend on sustained human oversight to ensure that students interpret outputs with nuance rather than deferring to them as authoritative. The risk of inaccuracy further complicates this dynamic. As Acut et al. (2025b) demonstrate, generative AI can produce speculative, misleading, or fabricated information that compromises academic rigor when used uncritically, particularly in domains where decisions have ethical and ecological consequences. Together, these insights reveal that AI's role as a cognitive amplifier is contingent on pedagogical design that foregrounds critical engagement, scaffolds interpretive judgment, and cultivates learners' ability to interrogate automated outputs, ensuring that AI enhances rather than erodes the intellectual rigor essential to ESD.

Persistent Challenges in AI Integration

Despite the promising outcomes illustrated across the vignettes, persistent challenges complicate the meaningful integration of AI in sustainability education. Digital literacy gaps emerged as a significant barrier, with some students struggling to interpret AI-generated content or lacking the foundational knowledge necessary to critically evaluate automated outputs, which in turn heightened the risk of uncritical adoption. Ethical dilemmas also surfaced, especially in activities that relied on generative AI for debates, policy analysis, or project design, where issues of algorithmic bias, authenticity, and overreliance became evident and exposed the need for deliberate pedagogical framing. These challenges were compounded by structural inequities, since not all learners or institutions had access to stable internet connectivity, advanced AI platforms, or appropriate technical support. As Mangubat et al. (2025b) emphasize, strengthening technological self-efficacy is essential in teacher education because confidence with digital tools shapes both instructional choices and learner engagement, yet such capacity is unevenly distributed. Similarly,

Hammerschmidt et al. (2025) argue that the “AI divide” operates across interdependent sociotechnical layers where systemic inequalities can cascade. These structural constraints are further echoed in the findings of Gantalao et al. (2025), who highlight how infrastructure limitations, uneven access to hardware and software, and persistent algorithmic biases complicate attempts at equitable AI integration. Taken together, these challenges reveal that without intentional strategies that address literacy, ethics, and structural inequity, efforts to embed AI in sustainability education risk deepening disparities rather than fostering the just learning environments envisioned in ESD.

Implications for Teacher Training and Professional Development

The findings from the vignettes underscore important implications for teacher training and professional development, particularly as educators navigate the pedagogical, ethical, and epistemic shifts introduced by AI in sustainability learning. Preparing teachers to use AI meaningfully requires training that moves beyond functional tool familiarity and cultivates reflective, critical, and sustainability-oriented perspectives that help educators frame AI as a support for inquiry rather than an automated shortcut. This includes developing AI literacy tailored to developmental contexts, strengthening educators’ capacity to interrogate bias and algorithmic limitations, and fostering the dispositions necessary to guide students toward ethical and critical engagement with generative and data-driven technologies (Funa and Gabay 2024). Continuous professional development must also emphasize the evolving nature of AI systems, helping teachers adapt to rapid technological change through collaborative learning communities, iterative experimentation, and shared pedagogical reflection. As Acut et al. (2026) highlight, sustained reskilling and upskilling efforts require cross-sector collaboration among educational institutions, industries, and government agencies to cultivate a future-ready teaching workforce equipped to integrate AI responsibly. Embedding these competencies within teacher preparation programs can ensure that educators are well positioned to support learners in navigating complex sustainability challenges in ways that maintain human judgment, ethical awareness, and pedagogical integrity.

Institutional and Policy Imperatives for Responsible AI Integration

At the institutional and policy levels, the strategic integration of AI in sustainability education requires alignment with broader digital transformation agendas so that adoption moves beyond surface-level technological add-ons and instead supports coherent pedagogical and developmental goals. Institutions must invest in infrastructure, technical support, and curriculum redesign to ensure that AI meaningfully enhances learning processes and does not reinforce existing inequities in access or participation. Policy frameworks likewise need to balance innovation with safeguards for ethical use, data privacy, transparency, and inclusivity by establishing mechanisms that monitor AI deployment, support accountable decision-making, and ensure that learning environments remain responsive to diverse student needs (Funa and Gabay 2024; Xiao et al. 2025). National and international models such

as Germany's Industry 4.0 initiative demonstrate the importance of scalable workforce development strategies, yet also reveal the structural constraints (e.g., limited budgets, uneven access to digital tools, and gaps in technical expertise) that institutions must address to create equitable and context-sensitive AI ecosystems (Acut et al. 2026). Coordinated efforts across educational institutions, government agencies, and industry partners will be essential to sustain ethical AI integration that genuinely advances the goals of sustainability, equity, and social justice, ensuring that technology serves as an enabler of transformative learning rather than a driver of further educational stratification.

Positioning AI as a Pedagogical Mediator in ESD

This practitioner inquiry contributes to the broader discourse on ESD by illustrating how AI can function as a pedagogical mediator that supports transformative learning aligned with sustainability principles. When AI is embedded in futures thinking activities, inquiry-based approaches, ethical argumentation, and project-based tasks, it extends pedagogical practices that resonate with UNESCO's ESD framework, which emphasizes critical reflection, anticipatory competence, and collaborative problem-solving (UNESCO 2020). The vignettes show how AI can help learners visualize complex scenarios, interrogate socio-environmental trade-offs, and iterate solutions in ways that deepen engagement with SDGs. These findings align with prior studies highlighting the importance of student-centered integration of sustainability themes, the role of institutional leadership in fostering ESD adoption, and the value of interdisciplinary approaches in sustaining curricular reform (Acut et al. 2025a; Leal Filho et al. 2019, 2020). Foregrounding the interplay between human agency and AI-mediated support illustrate how technology can enable educators to design learning environments that are context-sensitive, reflective, and action-oriented. In this sense, AI reinforces the notion that responsible innovation depends on educators' ability to situate technological tools within ethical, ecological, and societal commitments at the heart of sustainable development.

Future Directions for AI-Human Collaboration in Sustainability Education

Looking ahead, the integration of AI into sustainability education invites a deeper shift in how educators balance human judgment with machine intelligence. It also opens pathways for practices that are more inclusive and responsive to global challenges. Future work can explore how AI supports long-term scenario building in ways that cultivate foresight rather than simple prediction and how learners can co-create sustainability solutions with AI through iterative design environments that mirror real-world complexity. More research is also needed on AI tools that adapt to local ecological and cultural contexts so that sustainability learning remains grounded and relevant across diverse communities. Teacher education will benefit from models that integrate AI literacy with ethical reasoning and systems thinking so educators can guide students in using AI for critical reflection rather than automated shortcuts. Institutions can experiment with collaborative labs where students, industry partners, and community groups work with AI to address urgent sustainability problems, which can build civic capacity and strengthen interdisciplinary problem-solving. As these

directions evolve, the field must pay close attention to issues of equity, transparency, and accountability to ensure that AI amplifies human agency rather than narrowing it. Approaching AI as a partner in inquiry and innovation can help shape learners who are equipped to navigate uncertainty, act with ethical purpose, and imagine futures that honor both human and ecological well-being.

5 Conclusion

This chapter has demonstrated how the IDEA Framework offers a structured yet flexible approach for reflecting on the integration of AI into sustainability teaching. Through four vignettes, we explored diverse pedagogical practices that illustrate both the promise and the challenges of bringing AI into higher education contexts. Across cases, AI tools supported innovation, enhanced creativity, and helped learners grapple with the complexity of sustainability issues, while also raising critical questions of access, ethics, and responsible use. The reflections underscore the importance of fostering reflective, ethical, and creative engagements with AI in teaching and learning. Rather than treating AI as a neutral instrument, educators must guide students in critically examining how algorithms shape knowledge, whose perspectives are amplified, and what risks arise from automation and bias. In this way, AI becomes not only a pedagogical tool but also an object of inquiry, enabling students to understand its implications for sustainability, equity, and justice.

While the vignettes offer rich, practice-informed insights, several limitations should be acknowledged. The cases presented were drawn from a limited number of contexts and disciplines, which may not represent the full spectrum of AI integration efforts in ESD. Because the study focused on qualitative synthesis, it privileges depth of reflection over breadth of coverage, and thus cannot claim statistical generalizability. Moreover, the interpretations relied on researcher and practitioner perspectives, which may introduce subjective bias despite efforts toward triangulation and reflexivity. The framework itself, while useful as a conceptual scaffold, remains open to refinement through empirical validation and cross-cultural application. Future work could benefit from longitudinal, mixed-method, and comparative studies that test the IDEA framework's transferability across diverse educational systems and sustainability domains.

Moving forward, the integration of AI in ESD requires interdisciplinary collaboration that brings together educators, technologists, policymakers, and students. Faculty upskilling will be crucial, as many educators need both technical literacy and pedagogical strategies to meaningfully embed AI in their courses. Equally important are research–practice partnerships that can document, test, and refine emerging approaches, ensuring that innovations are not only creative but also scalable, equitable, and context-sensitive. Hence, we envision AI as a co-pilot in shaping education for sustainable futures. When thoughtfully and responsibly integrated, AI can expand the capacity of educators to design transformative learning environments that

cultivate critical thinking, creativity, and ethical responsibility, which are competencies at the heart of ESD. The challenge and opportunity ahead lie in harnessing AI not as a replacement for human judgment, but as a collaborator in the urgent task of preparing learners to address the intertwined social, environmental, and technological challenges of the twenty-first century.

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