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Integrating gamification and artificial intelligence in sustainability education: a conceptual framework toward the 2030 Agenda

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While gamification has shown strong potential to enhance motivation and engagement in educational contexts, its application to sustainability education aligned with the 2030 Agenda remains insufficiently explored from an integrative perspective. This conceptual analysis synthesizes theoretical and empirical literature on gamification, sustainability education, and artificial intelligence (AI), examining their theoretical foundations and documented applications. The findings indicate growing interest in applying gamification across sustainability dimensions, yielding positive effects on knowledge transfer and behavioral change. However, most studies still emphasize extrinsic motivation and lack longitudinal assessment. This article proposes an integrative conceptual model that positions education as the transformative core where gamification, AI, and sustainability converge, distinguishing between instrumental and transformative approaches. The framework contributes to a deeper understanding of how these domains can act synergistically to cultivate critical and engaged citizens capable of addressing the Sustainable Development Goals.

KEYWORDS
artificial intelligence, gamification, sustainability education, Sustainable Development Goals (S.D.G.s), transformative learning

1 Introduction

Education constitutes a fundamental pillar of sustainable development, particularly in the face of the challenges outlined in the United Nations 2030 Agenda (United Nations, 2015). Achieving the Sustainable Development Goals (SDGs) requires not only structural and policy reforms but also transformations in educational practices that foster the development of critical and committed citizens capable of addressing complex global issues. Within this framework, innovative pedagogical strategies have emerged, among which gamification has gained increasing relevance as a field of study and practice since the mid-2010s (Werbach, 2014; Seaborn and Fels, 2015).

Gamification—defined as the application of game design elements in non-game contexts—has demonstrated positive effects on motivation (Buckley and Doyle, 2016), active participation (Murillo-Zamorano et al., 2021), enjoyment in educational processes

(Villalustre Martínez and Del Moral Pérez, 2015), knowledge acquisition (Alajaji and Alshwiah, 2021), and behavioral modification (Schöbel et al., 2020). Its application in organizational contexts has also proven effective in promoting sustainable practices (Kirchner-Krath et al., 2024). However, most research has concentrated on specific game mechanics and extrinsic motivational factors (Mabalay, 2025), without critically examining its potential to generate transformative learning aligned with the SDGs or to cultivate deep ecological awareness and sustained civic engagement.

This gap becomes particularly evident when examining the intersection between gamification and sustainability in education. Although documented experiences exist in both educational and corporate settings, significant conceptual gaps persist regarding how to design, implement, and evaluate gamified interventions that effectively advance education for sustainable development. Key questions remain insufficiently explored: What type of learning does gamification promote—instrumental or transformative? What indicators allow for measuring its real impact? And how can these strategies be coherently integrated within the sustainability competencies framework?

At the same time, artificial intelligence (AI) has emerged as a transformative technology within teaching and learning processes (Wang et al., 2024). The convergence of gamification and AI creates opportunities to personalize educational experiences, adapt game dynamics to learning profiles, deliver real-time feedback, and scale interventions more efficiently. However, this integration also raises pressing ethical, methodological, and pedagogical concerns that demand critical examination: How can we ensure that AI does not reproduce biases or deepen digital divides? What are the environmental implications of AI systems' energy consumption? And how can AI enhance—rather than replace—critical thinking and human agency in sustainability education?

Given this scenario, conceptual synthesis is required to organize existing knowledge and propose an integrative framework. This article addresses that need through a conceptual review of the literature on gamification, sustainability education, and artificial intelligence, pursuing the following objectives:

1. To analyze the theoretical foundations that support the use of gamification in education, with particular emphasis on motivation and learning theories.
2. To identify and classify the main applications of gamification associated with the social, economic, and environmental dimensions of sustainability.
3. To examine the emerging role of artificial intelligence—including generative AI—as a catalyst for gamified experiences oriented toward the Sustainable Development Goals (SDGs).
4. To identify methodological gaps and propose criteria for the design and evaluation of gamified interventions in sustainability education.
5. To develop a conceptual model that integrates these elements and provides guidance for future research and pedagogical innovation.

This proposal is situated within the field of educational innovation and seeks to contribute to the debate on how technology-mediated pedagogical strategies can develop key competencies to address contemporary global challenges, particularly those defined by the 2030 Agenda.

2 Gamification: theoretical foundations and methodological approaches

Gamification involves the incorporation of game design elements into non-game contexts (Ibanez et al., 2014; Robson et al., 2015). It can be adapted to both physical (Arufe-Giráldez et al., 2022) and virtual environments (Barata et al., 2013) across multiple disciplines (Ayaz et al., 2023). This approach generates a trust-based learning environment (Kingsley and Grabner-Hagen, 2023) built upon three foundational principles: mechanics—the form and structure encompassing objectives, rules, levels, rewards, and scoring systems; dynamics—the interactions and behaviors emerging from participation; and aesthetics—the emotional responses ranging from frustration to a sense of accomplishment (Mullins and Sabherwal, 2018; Gómez-Carrasco et al., 2019; Khaleghi et al., 2021). This tripartite MDA framework (Mechanics–Dynamics–Aesthetics) offers an analytical lens for understanding how game components generate meaningful learning experiences (Hunicke et al., 2004).

Gamification extends across a wide range of domains (Hussain et al., 2023), with particular prominence in educational contexts (Murillo-Zamorano et al., 2023; Dehghanzadeh et al., 2024) and corporate environments (Murawski, 2021; Askarifar et al., 2023). However, its pedagogical potential fundamentally depends on the formative intention and the type of learning it promotes. A critical distinction arises between instrumental approaches, which focus on game mechanics and extrinsic motivation, and transformative approaches, which aim to develop critical competencies and intrinsic engagement. Mabalay (2025) warns that superficial implementations risk reducing interventions to mere point-collection systems. This review adopts a critical perspective on how gamification can be applied to sustainability education, analyzed in relation to SDG alignment, and reinforced through artificial intelligence.

Self-Determination Theory (SDT) provides a robust framework for understanding human motivation and psychological development (Ryan and Deci, 2017). It is grounded in regulatory processes that promote autonomous activities, enabling individuals to choose and regulate their actions (Deci and Ryan, 1987). SDT posits that self-determined motivation is sustained by three basic psychological needs: autonomy—control over one's decisions; competence—the ability to perform tasks successfully; and relatedness—the sense of belonging within meaningful contexts (Ryan and Deci, 2000b). In gamified environments, design elements can be strategically aligned with these needs: badges and leaderboards reinforce competence, while avatars and narratives foster social relatedness (Sailer et al., 2017). Motivation is maximized when all three dimensions are satisfied simultaneously (Deci and Ryan, 2000).

Both intrinsic motivation—linked to personal interest and enjoyment, and associated with wellbeing and performance—and extrinsic motivation—instrumental, driven by external incentives such as rewards or recognition—can enhance learning outcomes when appropriately integrated (Ryan and Deci, 2000a; Gagné and Deci, 2005). Gamification has been shown to influence goal achievement across diverse educational settings (Hamari et al., 2014; Sailer and Homner, 2020). In the context of sustainability education, ensuring that gamified interventions transcend extrinsic rewards to foster intrinsic commitment requires thoughtful design that balances immediate engagement with opportunities to develop autonomous motivation and ecological awareness.

A variety of methodologies incorporate gamification elements. Serious games, explicitly designed for educational purposes, represent a subset of gamification that applies game mechanics and game thinking (Kapp, 2012). These have proven effective in both academic and corporate contexts, including teacher training and cybersecurity education (De León and McGrath, 2015; Jaffray et al., 2021). Simulation-based approaches allow learners to engage with realistic scenarios in safe environments while receiving immediate feedback (Ahmed and Sutton, 2017; Brom et al., 2019). This is particularly relevant for sustainability education, as it enables the exploration of complex systems and long-term consequences without real-world risks. Interactive narratives promote decision-making and critical thinking through immersive experiences (Deterding et al., 2011), offering valuable opportunities to examine ethical dilemmas and sustainability trade-offs. The PBL model (Points, Badges, and Leaderboards), grounded in extrinsic motivation, has been widely implemented in Learning Management Systems (LMS) for both educational and corporate training (Werbach, 2014), although it has been critiqued for potentially undermining intrinsic motivation when not balanced with meaningful learning objectives. Additional approaches include gamified virtual boards inspired by Kanban methodologies (Werbach and Hunter, 2012), game-based learning environments facilitating skill development (Annetta et al., 2009; Nadolny et al., 2020), virtual and augmented reality for immersive spatial learning, and missions/challenges in mobile applications fostering intrinsic motivation (Hamari et al., 2014).

The methodological landscape reveals several critical tensions. Traditional methodologies, characterized by face-to-face dynamics and limited technological integration, often restrict scalability and hinder systematic monitoring. In contrast, emerging methodologies that incorporate simulations, digital platforms, and reward systems enable greater personalization and the use of learning analytics. However, methodological innovation is not always accompanied by corresponding evaluative rigor. Persistent gaps remain in empirical validation and real-world impact measurement—particularly concerning objective sustainability indicators such as carbon footprint reduction, energy savings, and waste diversion rates—rather than relying solely on perceptual or self-reported measures. Moreover, many gamified interventions continue to rely on conventional elements (points, badges, levels) without explicit alignment with the Sustainable Development Goals (SDGs), risking "pointsification"—a focus on superficial mechanics that undermines meaningful learning (Nicholson, 2015). Moving forward, gamification for sustainability education demands intentional design that explicitly connects game mechanics with sustainability competencies, ethical reflection, and measurable behavior change.

3 Gamification and sustainability: empirical applications and methodological gaps

Sustainability rests on three interdependent pillars—social, economic, and environmental (Barbier, 1987; Purvis et al., 2019)—which are integrated within the 17 Sustainable Development Goals (SDGs) established by the 2030 Agenda. Within this framework, gamification has been applied in diverse and heterogeneous ways to promote sustainable behaviors, with empirical evidence emerging from educational, corporate, and community contexts (see Table 1 for a systematic overview).

In the environmental domain, applications include mobile platforms designed to encourage recycling (Aguiar-Castillo et al., 2019), reduce CO_2 emissions (Cellina et al., 2019), and promote responsible household energy consumption (Wemyss et al., 2018; Chadoulos et al., 2020). These interventions are commonly evaluated using energy meters, digital analytics, and pre–post survey designs (Papaioannou et al., 2018; Mulcahy et al., 2020, 2021).

In educational settings, experiences such as environmental escape rooms have shown positive effects on motivation and self-efficacy (Yllana-Prieto et al., 2021), while other initiatives have focused on green chemistry (Mellor et al., 2018) and sustainable nutrition (Berger and Schrader, 2016). Gamified information systems support goal personalization, achievement visualization, and enhanced interactivity, typically assessed through Likert-type scales and models such as Kano (Du et al., 2020; Mahmud et al., 2020; Wang and Yao, 2020).

The combination of serious games, augmented reality (AR), and geolocation has proven effective in climate change education, employing quasi-experimental approaches to measure changes in knowledge and attitudes (Gandhi and Brager, 2016; Wang et al., 2021). These strategies are further complemented by smart technologies aimed at reducing energy consumption, thereby strengthening commitment and improving knowledge retention (AlSkaif et al., 2018; Whittaker et al., 2021).

In the corporate sector, gamification has been implemented to promote ecological habits, motivate employees, and raise awareness about carbon footprints. Positive outcomes have been reported in waste management, organizational commitment, and sustainable logistics (Ferreira et al., 2018; Maltseva et al., 2019; Souza et al., 2020; Hsu and Chen, 2021). Recent studies also highlight applications within supply chains, emphasizing reverse logistics, consumer engagement, and the environmental impact of e-commerce (Marcucci et al., 2018; Alves et al., 2023; Wernbacher et al., 2023; Behl et al., 2024b).

Logistics represents a critical component of corporate sustainability; however, gamification initiatives in this domain continue to face methodological constraints, as evidenced by empirical studies with limited validation (Warmelink et al., 2020). At the same time, positive effects of gamification on employee environmental awareness, workplace energy reduction, and the adoption of pro-environmental behaviors have been documented

TABLE 1 Gamification applications for sustainability education: methodological characteristics and outcomes.

Application context	Gamification approach	SDG dimension	Key findings	Methodological strengths	Limitations	References
Household energy conservation	Mobile app with challenges, feedback, and social comparison	Environmental (SDG 13)	Reduced energy consumption; enhanced awareness	Real-time data from energy meters; pre-post design	Short intervention period; limited generalizability	(Papaioannou et al., 2018)
University environmental course	Escape room with puzzles and challenges	Environmental (SDG 13)	Increased motivation and self-efficacy	Quasi-experimental design with control group	Self-reported outcomes; no behavioral follow-up	(Yllana-Prieto et al., 2021)
Recycling behavior	Gamified mobile platform with rewards and leaderboards	Environmental (SDG 12)	Improved recycling habits and environmental concern	Mixed methods; behavioral observations	Reliance on self-selection; external validity concerns	(Hsu and Chen, 2021)
Climate change education	AR game with geolocation	Environmental (SDG 13)	Enhanced knowledge and positive attitude shifts	Integration of immersive technology; pre-post assessments	Limited sample size; short-term measurement	(Wang et al., 2021)
Workplace sustainability	Gamified platform for eco-friendly behaviors	Environmental (SDG 12, 13)	Increased pro-environmental actions at work	Longitudinal design; objective behavior tracking	Context-specific; unclear scalability	(Oppong-Tawiah et al., 2020)
Green chemistry education	Serious game on safer chemical design	Environmental (SDG 12)	Improved understanding of green chemistry principles	Validated learning assessments; educational context	Limited to a specific discipline; no behavior transfer measured	(Mellor et al., 2018)
Corporate logistics sustainability	Simulation game for supply chain decisions	Economic and environmental (SDG 12)	Improved understanding of trade-offs; mixed behavioral results	Simulation allows risk-free experimentation	Transfer to real decisions unclear; limited validation	(Marcucci et al., 2018)
ICT energy consumption awareness	Scape room for "Digital Waste"	Environmental (SDG 12, 13)	Increased awareness regarding energy-saving practices in ICT usage	Educational context; pre-post assessments	Limited to a specific discipline; no behavior transfer measured	(Gil et al., 2024)

(Oppong-Tawiah et al., 2020). These practices are closely associated with value co-creation and business innovation, recognized as key pillars of sustainability in dynamic market environments (Colabi et al., 2022).

Table 1 presents an integrated analysis of documented gamification applications for sustainability education, systematically mapping the contexts of application, approaches employed, SDG dimensions addressed, key findings, methodological strengths, and identified limitations. The synthesis reveals clear patterns in how diverse strategies have been implemented across the environmental, social, and economic dimensions, while simultaneously highlighting persistent methodological gaps—particularly regarding longitudinal assessment and objective behavioral indicators.

The review of gamification experiences related to sustainability demonstrates considerable diversity in applications across educational, corporate, and community contexts. Although positive outcomes have been reported—such as increased environmental awareness, improved consumption habits, and strengthened social competencies—substantial methodological challenges remain. Many studies rely on exploratory designs lacking longitudinal impact metrics, which limits the evaluation of long-term sustainability outcomes. Moreover, there is a prevailing tendency to employ conventional gamification elements (points, badges, levels) without explicit integration of the SDGs, potentially constraining their transformative potential.

These findings underscore the need to advance toward more critical and contextualized gamification models capable of generating sustainable and measurable behavioral changes. Future research should prioritize:

1. Develop validated instruments to measure real-world sustainability impacts beyond self-reported attitudes.
2. Conduct longitudinal studies to track the persistence of behavioral change.
3. Ensure explicit alignment between game mechanics and SDG competency frameworks.
4. Undertake comparative research contrasting instrumental and transformative gamification approaches.
5. Explore cultural and contextual factors influencing the effectiveness of gamification.
6. Critically assess potential negative effects—such as competition undermining cooperation or extrinsic rewards diminishing intrinsic motivation.

4 Artificial intelligence as an emerging node in education for sustainability

The integration of artificial intelligence (AI) into gamified educational environments represents a paradigm shift in how sustainability competencies are developed, assessed, and scaled. While gamification provides the motivational and experiential architecture, AI technologies enable adaptive personalization, real-time feedback, predictive analytics, and intelligent content generation—capabilities that significantly amplify the transformative potential of sustainability education.

Contemporary AI systems allow for unprecedented levels of personalization through recommender systems (RS) that automate game elements based on user characteristics, geographic location, contextual variables, and learning activities (Rodrigues et al., 2022). These systems employ machine learning algorithms to model user preferences and predict optimal game mechanics, challenge levels, and reward structures. Adaptive learning pathways, powered by conditional decision trees, identify how specific interactions shape user experiences, enabling systems to adjust difficulty, provide scaffolded support, and present sustainability challenges aligned with learners' current competency levels. This personalization further extends to emotional state recognition and motivational profile mapping, allowing AI systems to detect frustration, disengagement, or flow states and respond in real time (Khakpour and Colomo-Palacios, 2021).

Emerging technologies expand gamified sustainability education beyond traditional digital interfaces. Smart devices equipped with embedded sensors, ubiquitous computing infrastructures, and social robots enable embodied learning experiences that blend physical and digital interactions (Xiao et al., 2022). Machine learning enhances these systems through advanced analytics that process behavioral data, biometric signals, and interaction patterns, allowing for dynamic, real-time adjustments that sustain motivation and engagement (Khakpour and Colomo-Palacios, 2021). In sustainability education, this translates into immediate, contextualized feedback on sustainable behaviors—such as energy consumption, recycling habits, or transportation choices—creating tighter feedback loops between action and consequence.

Generative AI—including large language models, image generation, and multimodal systems—introduces new possibilities for sustainability education. It can generate contextualized scenarios that reflect learners' geographic, cultural, and socioeconomic contexts; produce adaptive narratives with branching storylines that make the long-term consequences of sustainability choices visible; facilitate dialogues that guide learners through ethical dilemmas and systems thinking; and create personalized assessments aligned with SDG frameworks. However, such integration raises critical concerns regarding the accuracy of sustainability information, potential algorithmic biases, and the energy footprint of computational systems—a paradox when applied to environmental education.

The integration of blockchain with gamification and AI opens additional opportunities for verifiable sustainability claims and transparent reward systems. In supply chain education, blockchain enables learners to trace the provenance of eco-friendly products, verify carbon offset claims, and explore circular economy principles through interactive simulations (Liao, 2023).

The Internet of Things (IoT) further extends gamification into physical environments. Connected sensors in smart buildings and cities generate real-time data on energy consumption, waste generation, and resource utilization. When integrated with gamified applications, these technologies allow for immediate feedback on sustainable behaviors, competitive or collaborative challenges grounded in actual environmental impact, visualization of collective action effects, and long-term tracking of behavioral change. Ensuring seamless integration between physical and digital experiences is essential, as any disconnection may undermine engagement and perceived relevance (Rosenlund et al., 2025).

The convergence of IoT, AI, blockchain, augmented reality (AR), and virtual reality (VR) creates opportunities for systemic and collaborative approaches to sustainability education, integrated with public policies, corporate development strategies, and innovation initiatives (Guillen et al., 2023). Documented benefits include enhanced recycling behaviors, promotion of reuse practices, improved communication of circular economy principles, and organizational transformation toward sustainability. Within circular economy contexts, mobile applications and waste management systems exemplify how technological integration reshapes physical and digital experiences through sensors for material recognition, real-time feedback on recycling accuracy, computer vision for waste-sorting guidance, and IoT connectivity enabling system-wide optimization (Rosenlund et al., 2025).

While AI offers transformative potential, critical examination remains essential. Key considerations can be grouped into three domains: *Ethical dimensions:* algorithmic bias that may perpetuate inequalities, data privacy concerns—particularly for minors—and risks to autonomy arising from overreliance on AI-driven recommendations that diminish independent critical thinking. *Environmental paradox:* the energy demands of training and operating large AI models, electronic waste from IoT devices, and the measurable environmental costs of digital carbon footprints. *Pedagogical considerations:* risks of superficial engagement that prioritize metrics over deep learning, lack of transparency in AI decision-making that may undermine educational goals, and the need for teacher expertise to ensure critical evaluation rather than mere implementation.

Collectively, these technologies broaden the scope of gamification and redefine pedagogical possibilities by fostering more adaptive, immersive, and behavior-oriented learning environments. Yet realizing this potential requires intentional design that harmonizes technological capability with pedagogical purpose, ethical responsibility with innovation, and efficiency with equity. Integration should be guided by the principles of transparency, inclusivity, and critical reflection, ensuring that technology supports educational objectives rather than dictates them.

5 Convergence and integration: a conceptual framework for transformative education

The convergence of gamification, artificial intelligence, and sustainability education represents more than the sum of its parts—it constitutes an emerging paradigm of transformative learning capable of addressing the complex and systemic challenges articulated in the 2030 Agenda. This section introduces an integrative conceptual model that synthesizes theoretical foundations, empirical evidence, and technological possibilities, while critically examining the inherent tensions within this convergence.

The model establishes directional relationships between methodological approaches and learning outcomes. Traditional methodologies—characterized by serious games, simulations, and interactive narratives that emphasize face-to-face interaction and guided reflection—are hypothesized to create conditions conducive to transformative learning by prioritizing depth, critical dialogue, and socio-emotional engagement. Conversely, emerging digital methodologies—such as gamified virtual boards, VR/AR experiences, and automated missions—while offering scalability and personalization, may default toward instrumental learning when designed primarily to optimize metrics and behavioral compliance rather than critical consciousness. However, these pathways are not deterministic: intentional pedagogical design can leverage emerging technologies to foster transformative outcomes, just as traditional approaches may produce merely instrumental results if superficially applied. The model thus illustrates predominant tendencies rather than fixed trajectories, emphasizing the centrality of educational intentionality in mediating technological affordances toward transformative ends.

Figure 1 illustrates the proposed conceptual model, positioning education as the transformative core where gamification, AI, and sustainability interact synergistically. The model identifies three key intersections: (1) Gamification–AI: enabling adaptive learning platforms, (2) Gamification–Sustainability: promoting behavior change through game-based experiences, (3) AI–Sustainability: facilitating resource optimization and continuous monitoring. Education functions as the mediating force linking traditional and emerging methodologies, bridging corporate and academic contexts, and balancing instrumental and transformative learning approaches.

5.1 Key intersections and methodological distinctions

5.1.1 Gamification and AI: adaptive learning environments

This intersection enables dynamic learning platforms that respond to learners' profiles, emotional states, and performance patterns. Machine learning algorithms analyze interaction data to optimize challenge difficulty, reward timing, and feedback precision, thereby creating personalized sustainability learning experiences that adapt in real time.

5.1.2 Gamification and sustainability: evidence-based behavior change

Game-based experiences serve as effective mechanisms for translating knowledge into action. Empirical evidence demonstrates that gamified interventions facilitate the transition from awareness to sustainable behavior through point systems, real-time feedback, and social comparison dynamics (Han et al., 2023; Behl et al., 2024a). Environmental escape rooms and climate simulations further promote critical thinking by immersing learners in realistic scenarios that present immediate and tangible consequences (Bacca et al., 2014; Radianti et al., 2020).

5.1.3 AI and sustainability: data-driven optimization

This intersection leverages the computational power of AI for resource optimization, impact assessment, and predictive modeling. AI systems process datasets collected from IoT sensors to detect inefficiencies, forecast environmental impacts, and recommend targeted interventions, thereby enabling authentic learning experiences grounded in real-world data.

The model differentiates among approaches that vary in their pedagogical intent:

5.1.4 Traditional vs. emerging methodologies

Traditional approaches provide rich social interaction but are limited by scalability constraints. Emerging digital methodologies enable extensive data collection and personalized learning experiences, yet risk fostering technological determinism. The most effective implementations adopt hybrid models that preserve social–emotional dimensions while leveraging technological affordances to enhance learning outcomes.

5.1.5 Educational vs. corporate contexts

Educational settings prioritize the development of competencies and critical thinking (Brazão and Tinoca, 2025), whereas corporate contexts often emphasize immediate behavioral compliance. A growing convergence is emerging as corporations recognize the value of deeper learning, while educational institutions increasingly integrate authentic professional contexts into their practices.

5.1.6 Instrumental vs. transformative learning

Instrumental learning centers on skill acquisition and behavioral compliance driven by extrinsic incentives. In contrast, transformative learning fosters critical consciousness, systems thinking, and an intrinsic commitment to structural change. Effective implementations are intentionally designed to promote transformation, employing instrumental elements as initial entry points that progressively evolve toward deeper and more sustained engagement.

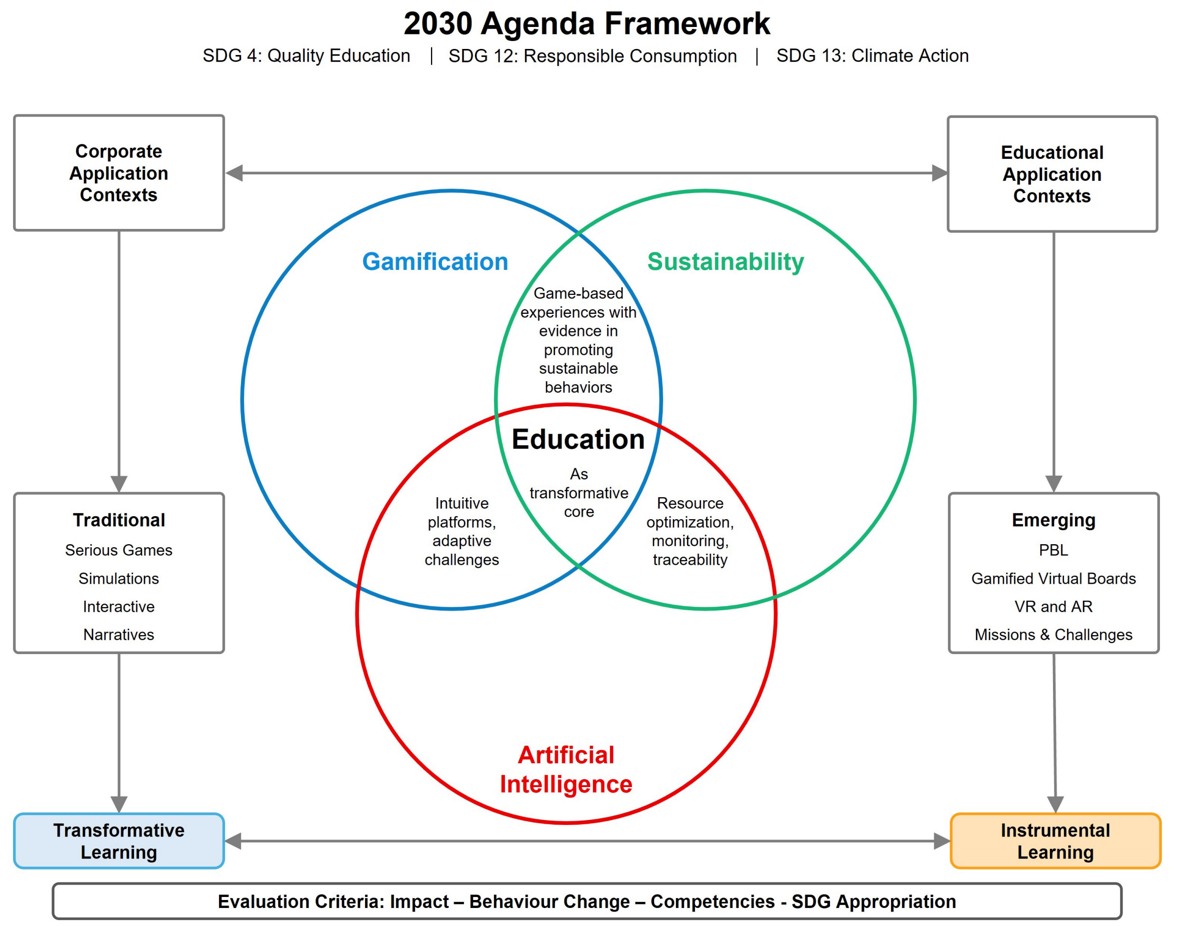

FIGURE 1
Conceptual model articulating gamification, sustainability, artificial intelligence, and education, with methodological mediators, application contexts, and evaluation criteria oriented toward the SDGs. Directional flows illustrate predominant (though not deterministic) relationships between traditional methodologies and transformative learning outcomes, and between emerging digital methodologies and instrumental learning outcomes, mediated by pedagogical intentionality.

5.2 Evaluation framework

The model proposes a set of multidimensional evaluation criteria:

Impact indicators: behavioral (objective sustainability metrics), cognitive (systems thinking capacity), affective (ecological identity formation), and social (collective efficacy and community engagement).

Critical consciousness: the ability to identify systemic barriers, recognize equity dimensions, question techno-solutionist narratives, and analyze power dynamics within sustainability transitions.

SDG appropriation: the personal relevance of SDG principles, their integration across life domains, individual agency in contributing to specific targets, and the persistence of long-term commitment.

This framework aligns with the principles of Education for Sustainable Development (UNESCO, 2020), emphasizing competency development rather than mere information transmission. The primary SDGs addressed include SDG 4 (Quality Education through personalized pathways), SDG 12 (Responsible Consumption through interactive simulations), and SDG 13 (Climate Action through immersive experiences). Recent studies further demonstrate how this approach can be applied across disciplines—from technical fields to the humanities (Cordova, 2024; De Albuquerque et al., 2024).

Empirical evidence emerges from diverse contexts, including corporate applications validating collaborative games (García et al., 2019), blockchain platforms enabling verification of environmental commitments (Violino et al., 2019; Jääskä et al., 2021), and learning management systems (LMS) incorporating gamified achievement structures (Donath et al., 2020). However, substantial gaps remain in the longitudinal measurement of impact, the use of objective sustainability indicators beyond self-reported attitudes, and the explicit integration of SDG competency frameworks—challenges that represent key priorities for advancing this field.

5.3 Application case: transformative sustainability education in higher education

To illustrate the practical implementation of the proposed conceptual model, this study presents a case developed at the University of Almería, integrating gamification, artificial intelligence (AI), and sustainability education in alignment with SDGs 4, 12, and 13.

5.3.1 Context and design

A cross-disciplinary sustainability course involving 120 undergraduate students implemented a gamified learning environment enhanced by artificial intelligence (AI) technologies. The intervention extended over one academic semester (14 weeks) and was intentionally designed to facilitate a progression from instrumental to transformative learning.

5.3.2 Implementation of model intersections

5.3.2.1 Gamification–AI integration

An adaptive learning platform employed machine learning algorithms to personalize challenge difficulty based on individual performance patterns. The system analyzed student interaction data—including time spent on activities, response accuracy, and engagement trends—to dynamically adjust content complexity. AI-driven recommender systems proposed personalized sustainability challenges aligned with students' declared interests (e.g., sustainable fashion, renewable energy, circular economy).

5.3.2.2 Gamification–sustainability integration

Students participated in a series of missions structured across three progressive phases: Awareness phase (weeks 1–4): point-based activities focused on acquiring knowledge about the SDGs through quizzes, escape rooms, and augmented reality (AR) simulations of climate scenarios. Action phase (weeks 5–10): students implemented real-world sustainability interventions within campus or community settings, earning badges for verified behaviors such as waste reduction, energy conservation, and the adoption of sustainable transportation practices. Transformation phase (weeks 11–14): collaborative challenges required critical analysis of systemic barriers, the formulation of policy proposals, and the presentation of innovative solutions to local sustainability issues.

5.3.2.3 AI–Sustainability integration

IoT sensors installed in student residences (Viciana et al., 2018) provided real-time data on energy consumption. A mobile application gamified resource conservation through immediate feedback, peer comparisons, and collective challenges. Blockchain technology verified and transparently recorded students' sustainable actions, generating digital portfolios that evidenced their engagement with the SDGs.

5.3.3 Evaluation framework application

5.3.3.1 Impact indicators

Behavioral change was evaluated using objective metrics, revealing a 27% reduction in dormitory energy consumption and a 34% increase in recycling rates. Cognitive development was assessed through pre–post systems-thinking tests, which indicated significant improvement (Cohen's $d = 0.76$). Affective transformation was evidenced through qualitative interviews that reflected the formation of a strengthened ecological identity among participants.

5.3.3.2 Critical consciousness

Student final projects demonstrated a strong capacity to identify structural barriers—68% analyzed policy failures and 82% recognized equity dimensions of climate change—indicating a shift from an individual behavioral focus toward a systemic and critical perspective.

5.3.3.3 SDG appropriation

A longitudinal follow-up conducted 6 months after the intervention revealed that 71% of students maintained sustainable behaviors and 43% engaged in voluntary environmental activism, indicating genuine internalization rather than mere behavioral compliance.

5.3.4 Key insights

The case illustrates how intentional design that balances extrinsic motivation—through points and badges in the early phases—with opportunities to foster intrinsic commitment—through authentic community projects and critical reflection in later stages—facilitates transformative learning. AI-driven personalization prevented student disengagement during challenging content, while the integration of real-world data enhanced the perceived relevance of learning activities. However, the implementation also revealed several challenges: initial technical difficulties with IoT sensors, equity concerns related to students without access to smartphones, and faculty training needs to support critical discussions extending beyond gamified mechanics.

Table 2 synthesizes the critical design considerations involved in adapting the conceptual model to diverse organizational contexts. These distinctions guide implementation decisions related to technology selection, evaluation frameworks, and pedagogical approaches. While the educational case above exemplifies the prioritization of transformative learning, corporate applications generally emphasize operational outcomes and scalability. Understanding these contextual variations is essential for the effective adaptation of the model across settings, enabling both practitioners and researchers to anticipate challenges, select appropriate technologies, and design evaluation systems that align with context-specific objectives and constraints.

6 Discussion

The principal contribution of this work lies in its integrative framework, which articulates three domains traditionally examined in isolation: gamification, sustainability education, and artificial intelligence (AI). While previous research has largely explored these relationships in binary terms, this study advances a triadic convergence model that positions education as the transformative core where technologies, methodologies, and purposes intersect synergistically. This represents a paradigmatic shift, demonstrating that effective education for sustainable development demands intentional design that simultaneously integrates motivational architecture, technological enhancement, sustainability competencies, and pedagogical intentionality.

TABLE 2 Design implications of the conceptual model across educational and corporate contexts.

Design dimension	Educational settings	Corporate settings
Primary objective	Competency development, critical consciousness, and transformative learning	Behavioral compliance, cultural change, operational outcomes
Typical duration	Semester-based (12–16 weeks) with longitudinal follow-up	Extended implementation (6–12 months) with continuous iteration
SDG emphasis	SDG 4 (Quality Education), 12, 13, with focus on awareness and agency	SDG 8 (decent work), 12, 13, with focus on production and operations
Participant scale	Class or cohort level (50–300 participants)	Organizational level (hundreds to thousands across locations)
Pedagogical approach	Deep engagement, reflection, community projects, critical analysis	Efficiency, scalability, measurable KPIs, business case alignment
Technology integration	AR/VR for immersive learning, IoT for behavioral tracking, blockchain for portfolios	Blockchain for supply chain, IoT for operations, AI for process optimization
Key challenges	Digital equity, faculty preparation, and assessment complexity	Cultural differences, privacy concerns, and business model integration
Success indicators	Learning outcomes, behavior persistence, activism engagement	Operational metrics, employee engagement, ROI demonstration

The novelty of this study resides in two key contributions. First, it distinguishes between instrumental and transformative gamification for sustainability, offering evaluative criteria largely absent in current literature. Second, it proposes a methodological taxonomy that organizes strategies according to pedagogical intent, application context, and learning outcomes. Rather than adopting a techno-optimistic stance, this framework positions AI both as an enhancer and as an object of critical reflection, explicitly confronting the environmental paradox of energy-intensive AI in environmental education, as well as the risks of algorithmic bias and equity disparities.

6.1 Practical implications

For policy and curriculum: This framework guides educational policy toward the promotion of gamified methodologies within teacher preparation programs aligned with the Sustainable Development Goals (SDGs). Policymakers can establish curriculum standards that require explicit connections among pedagogical innovation, technological integration, and sustainability competencies. At the institutional level, the model recommends incorporating missions, challenges, and simulations as core pedagogical tools rather than supplementary activities. These should include authentic problems rooted in local sustainability challenges, progressive scaffolding from instrumental skills to transformative competencies, assessment systems that measure behavioral change and systems thinking beyond engagement metrics, and interdisciplinary integration recognizing that sustainability literacy transcends disciplinary boundaries.

For corporate and organizational contexts: The framework advocates implementing integrated gamified platforms, such as learning management systems (LMS) enhanced with AI-driven personalization, IoT sensors for real-world data collection, and blockchain for transparency, to facilitate training in responsible consumption and sustainable organizational culture. Applications include onboarding programs that establish sustainability values, continuous professional development focused on circular economy principles, corporate social responsibility initiatives requiring measurable outcomes, and supply chain education emphasizing reverse logistics (Marcucci et al., 2018; Behl et al., 2024b).

Digital infrastructure investment: The framework calls for targeted technological investments at the governmental level, including capacity-building for teachers in the critical and reflective use of technology, the development of open-access platforms to reduce inequities, research funding for culturally appropriate interventions, and the establishment of regulatory frameworks that ensure ethical AI use and algorithmic accountability.

6.2 Critical research directions

Longitudinal impact measurement: Advancing this field requires—as a critical and non-negotiable priority—longitudinal studies that systematically track behavioral persistence 6–12 months after intervention (Olsson et al., 2022). This temporal dimension is imperative to distinguish genuine transformation from transient engagement. Such research must examine transfer to non-gamified contexts; compare cumulative versus novelty effects; and rigorously analyze the development of intrinsic motivation as extrinsic scaffolding is gradually removed. Without this extended temporal measurement, sustainability education risks celebrating short-term compliance while failing to cultivate enduring commitment.

Objective sustainability indicators: The field must prioritize—as an urgent methodological imperative—the development and validation of instruments that move decisively beyond self-reported perceptions toward objective, real-world impact measurement (Nielsen et al., 2022). Recent evidence demonstrates that psychological factors strongly predict self-reported pro-environmental behavior scales but only weakly predict actual environmental impact metrics such as greenhouse gas emissions, underscoring the critical need for validated objective indicators. Research requires validated instruments integrating quantitative and qualitative measures, including carbon footprint reductions, waste diversion rates, water conservation metrics, sustainable transportation adoption, and consumer choice modifications supported by lifecycle assessments. Only through such rigorous measurement can the field distinguish between performative engagement and substantive environmental outcomes.

Digital sustainability assessment: A central and critical research direction must address the environmental paradox inherent in employing resource-intensive digital technologies to advance sustainability education. This represents not a peripheral concern but a fundamental ethical imperative that directly challenges the internal coherence of the framework. Future research must systematically evaluate the environmental costs of digital interventions themselves, including the substantial energy consumption of AI model training and inference operations, the carbon footprint of server infrastructure and data centers, electronic waste generated by IoT devices and sensing technologies, and comprehensive lifecycle analyses of technological platforms from production through disposal (de Vries, 2023; González de Eusebio et al., 2023). Without this critical self-examination, sustainability education risks perpetuating the very unsustainable practices it seeks to transform—deploying energy-intensive AI systems to teach environmental responsibility. This paradox demands transparent environmental accounting, the prioritization of low-impact technological alternatives where feasible, and the integration of digital sustainability literacy as a core competency within the framework itself.

Design and contextual adaptation: Methodologies should adapt to cultural variations in gaming preferences and motivational structures, socioeconomic contexts influencing access to technology, differences among educational systems, and the specific challenges of urban versus rural sustainability. Interest in rewards must be accompanied by genuine sensitization toward sustainability, ensuring that engagement does not remain purely transactional.

AI integration ethics: The critical integration of AI—distinguishing among machine learning for personalization, generative AI for content creation, computer vision for monitoring, and natural language processing for assessment—requires the design of responsible algorithms that prevent the perpetuation of inequalities; strong data protection measures, particularly for minors; equitable access supported by low-tech alternatives; transparency that renders AI decision-making interpretable; and environmental accountability that directly confronts the carbon footprint of AI within sustainability education.

6.3 Significance and future directions

As Mabalay (2025) argues, gamification should not be confined to superficial motivation but oriented toward the critical transformation of behavior and the cultivation of ecological consciousness. The significance of this integrative framework lies in its capacity to bridge theory and practice through actionable design principles grounded in robust theoretical foundations; navigate technological complexity by offering clear distinctions that enable informed decision-making; balance innovation and critique by recognizing transformative potential while articulating risks; foster cross-sector dialogue through a shared conceptual language; and center equity and justice by explicitly addressing digital divides and structural dimensions of sustainability.

While tools exist to evaluate various elements of gamification (Hamari et al., 2014; Högberg et al., 2019; Zainuddin et al., 2024), significant gaps persist in the design of metrics capable of assessing medium- and long-term impact. Future research should investigate the comparative effectiveness of AI-personalized versus standardized gamification, optimal levels of AI autonomy versus teacher or learner control, and the interaction effects between AI sophistication and learner characteristics. It should also examine the evolution of critical consciousness through qualitative and mixed-methods approaches capable of capturing environmental identity development, recognition of systemic barriers, multi-scalar thinking capacity, and comfort with the inherent complexity of sustainability dilemmas.

Ultimately, this work demonstrates that the convergence of gamification, AI, and sustainability education represents not merely a methodological trend but a necessary evolution in educational paradigms to confront the complexity, urgency, and ethical dimensions of the 2030 Agenda. The proposed conceptual model serves not as a prescriptive blueprint but as a conceptual map for navigating the opportunities and challenges of this emerging paradigm, calling for intentionality, reflexivity, and commitment to transformative rather than performative change. Its validation and refinement through empirical research across diverse contexts remain a priority for advancing an education capable of addressing the defining challenges of our time.

7 Conclusion

This conceptual review examined the convergence of gamification, sustainability education, and artificial intelligence (AI) within the framework of the 2030 Agenda. The literature reveals a growing interest in applying gamification to sustainability dimensions, showing positive effects on knowledge transfer and behavior promotion. However, persistent gaps remain in the longitudinal measurement of impact and in the predominant reliance on extrinsic motivation over transformative learning frameworks.

The primary contribution of this work is an integrative conceptual model that positions education as the transformative core where gamification, AI, and sustainability intersect synergistically. Unlike previous research that has explored these domains in isolation, this framework demonstrates that effective education for sustainable development demands intentional design that simultaneously addresses motivational architecture, technological enhancement, alignment with SDG competencies, and the distinction between instrumental and transformative approaches.

The novelty of the study lies in three key dimensions. First, distinguishing instrumental gamification—compliance driven by extrinsic motivation—from transformative gamification—the cultivation of critical consciousness and intrinsic commitment—provides evaluative criteria largely absent from the literature. Second, the proposed methodological taxonomy, which organizes strategies by pedagogical intent, application context, and learning outcomes, addresses fragmentation in the field. Third, positioning AI both as an enhancer and as an object of ethical reflection explicitly confronts the environmental paradox of energy-intensive AI in environmental education, as well as algorithmic bias and equity concerns.

For practitioners and policymakers, this framework offers actionable guidance for curriculum design, teacher preparation, and evidence-based policy aligned with the SDGs. For corporate contexts, it supports strategic platform selection for organizational sustainability learning. However, as a conceptual review, the framework requires empirical validation through design-based research, quasi-experimental studies, and longitudinal investigations conducted across diverse contexts.

Critical research gaps demand immediate and systematic attention. The field must prioritize, as foundational requirements for progress, the development of validated instruments to assess objective sustainability impacts beyond self-reported attitudes and the implementation of longitudinal studies tracking behavior change over extended timeframes of 6–12 months minimum. These are not optional enhancements but essential methodological foundations. Additional priorities include comparative effectiveness research on AI-enhanced approaches; cultural adaptation studies; and digital sustainability investigations examining the environmental costs of technological interventions.

The significance of this work lies in recognizing that neither gamification, AI, nor sustainability education alone can adequately address the challenge of forming citizens capable of transforming unsustainable systems. The synergistic integration—guided by critical pedagogical principles, grounded in motivational theory, enhanced by intelligent technologies, and evaluated through multidimensional indicators—offers a pathway toward an education that is engaging, personalized, critically conscious, and demonstrably effective in fostering sustainable behaviors aligned with the challenges of the 2030 Agenda.

Author contributions

SP-S: Conceptualization, Investigation, Writing – original draft, Writing – review & editing, Funding acquisition, Resources, Visualization. FM-G: Conceptualization, Investigation, Visualization, Writing – review & editing. CG: Conceptualization, Supervision, Visualization, Writing – original draft, Writing – review & editing, Investigation, Project administration. AA: Conceptualization, Investigation, Supervision, Writing – review & editing, Visualization.

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The author(s) declared that generative AI was not used in the creation of this manuscript.

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