From Play to Conservation: Leveraging Video Games and Artificial Intelligence for Eco-Cultural Emancipation in Sub-Saharan Africa

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Abstract: - This article examines the pedagogical potential of video games and artificial intelligence (AI) in fostering ecological literacy among secondary students in Sub-Saharan Africa. As mobile technologies and digital play become increasingly embedded in youth culture, these tools offer immersive and adaptive pathways to engage with pressing environmental challenges. Grounded in theories of flow and situated learning, the paper proposes a dual approach: using culturally resonant games to cultivate systems thinking and ethical reflection and leveraging AI to personalize ecological simulations and support context-sensitive learning. Design principles emphasize cultural relevance, infrastructure sensitivity, and alignment of ethical artificial intelligence. This article concludes with a research agenda aimed at mapping, testing, and evaluating game-based and AI-enhanced learning environments, inviting interdisciplinary collaboration to transform digital play into a tool for ecological preservation.

Key-Words: - Artificial Intelligence (AI), Culturally Responsive Pedagogy, Ecological Education, Indigenous Knowledge, Video Games (VG), Participatory Learning, Contextualized ecological solutions

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1 Introduction

Africa boasts the world's youngest population, [1]. Often called "digital natives," these young people are naturally drawn to technology, showing a preference for computer and mobile language and games that can sometimes overshadow more traditional learning methods, [2]. Given that youth is a period of personal and emotional development as well as independence and exploration, [3], [4], this represents a unique and innovative opportunity to learn. By reimagining teaching strategies and integrating digital tools, the learning process can potentially be enhanced for African youth.

In Sub-Saharan Africa, the increasing accessibility of mobile technology, digital gaming, and artificial intelligence (AI) is profoundly shaping how young people learn and interact with the world. The increasing penetration of mobile phones and Internet access in urban centers in Africa has enabled widespread engagement with digital games among adolescents, [5], [6]. In fact, according to the Ericsson Mobility Report, [7], by 2020, 70% of the global population was expected to use smartphones, while mobile subscriptions were projected to increase from 85% in 2020 to 105% in 2022, exceeding 1 billion users in Sub-Saharan Africa.

Urban adolescents aged 11–18 show a marked interest in video games (VG) and AI-driven applications, yet most of their engagement occurs outside formal educational settings, [8], [9]. While often perceived as distractions, [10], [11], these technologies offer substantial pedagogical value. AI significantly enhances inclusive education by improving accessibility, facilitating personalized learning, and lowering obstacles for students with disabilities, [12]. Digital games, especially serious games, use familiar formats and multiple types of stimuli to boost motivation and emotional growth, [13], [14], [15]. Children are increasingly inclined to learn through interactive digital environments rather than traditional methods, [13]. Serious games activate diverse cognitive processes and sustain attention, making them powerful tools for multifactorial learning, [14]. According to [16], youngsters in Africa do not distinguish between playing and working, as well as between participating and learning. This belief is established in African tradition. Play is more than just a recreational activity in many African societies; it is an educational tool that is integrated into song, narrative, and symbolic engagement with the surroundings. Indigenous games frequently provide problem-solving skills, social conventions, and ecological awareness, [17]. In ecological education, these affordances are especially relevant, as they allow for immersive, contextualised exploration of environmental issues, [18], [19]. Harnessing VG and AI within culturally responsive frameworks may thus transform African classrooms into inclusive, engaging ecosystems for ecological awareness and action.

Sub-Saharan Africa faces an unprecedented convergence of ecological and cultural challenges, [20]. Rapid environmental degradation (deforestation, climate change, and unsustainable resource management) threatens biodiversity, food security, and the livelihoods of millions, [21]. Beyond the visible ecological crisis lies a quieter, more systemic challenge: many young people remain disconnected from environmental education. For decades, well-intentioned efforts to promote ecological awareness have relied heavily on Western scientific frameworks, often overlooking local knowledge and culturally embedded ways of understanding the natural world, [22], [23], [24]. Traditional approaches, typically abstract and confined to the classroom, fail to reflect learners' lived realities or spark meaningful engagement. As a result, an entire generation growing up amid ecological upheaval is left without the tools, language, or agency to make sense of their changing environment, [25].

In fact, existing curricula frequently fail to connect with the sociocultural realities of African communities, neglecting indigenous knowledge and fostering a sense of disconnection from local ecosystems. Traditional methods of ecological education are not sufficient to motivate and engage youth, [23], [26], [27]. This results in a lack of awareness and action towards environmental protection.

This challenge is particularly acute given the demographic landscape of Africa: a young population increasingly immersed in digital culture, [28], [29].

Although this generation of "digital natives" represents a powerful force for change, their potential remains largely untapped in the context of ecological stewardship. Conventional educational methods struggle to compete with the allure of digital entertainment and personalized experiences. Therefore, a paradigm shift is urgently needed. Innovative approaches are required to bridge the gap between environmental awareness and actionable engagement, leveraging the power of digital technologies to connect with African youth on their own terms.

This paper proposes a framework for harnessing the immersive potential of VG and the adaptive capabilities of AI to foster eco-cultural emancipation in Sub-Saharan Africa, offering a novel pathway towards a more sustainable and equitable future, [30]. Drawing on interdisciplinary literature and emerging African innovations, we argue that digital play and intelligent systems can become catalysts for ecological preservation and curricular transformation, [27], [31], [32].

The remainder of this paper is organized as follows. Section 2 outlines the theoretical framework underpinning the study. Section 3 introduces the design principles for contextual integration, while Section 4 presents implementation scenarios and the proposed modeling approach. Main limitations and challenges of the conceptual framework and implementation model are presented in Section 5 and discussed in Section 6, highlighting its relevance and potential impact. It's finally followed by Section 7 which concludes the paper with final remarks, perspectives, and future directions.

2 Theoretical Framework

The integration of VG and AI into educational practice is rooted in a diverse set of pedagogical theories that demonstrate how learners construct meaning, engage with complexity, and develop agency, [33], [34]. These tools, when thoughtfully designed and contextually grounded, offer immersive and interactive learning experiences, [35]. They may represent new pathways for experiential learning, collaborative inquiry, and ecological awareness. In African educational settings, where ecological challenges intersect with cultural and infrastructural realities, digital play and intelligent systems present unique opportunities to revolutionize science learning and ecological engagement.

This section is therefore divided into two parts. The first one, drawing on socio-constructivist, cultural, and design-based models, explores the theoretical foundations that underpin game-based learning and AI in education. The second reviews recent literature on how these digital tools are being mobilized to foster ecological literacy and environmental agency among learners.

2.1 Theoretical Foundations of Game-Based Learning and Artificial Intelligence in Education

The pedagogical integration of VG and AI into environmental education is grounded in a constellation of contemporary learning theories that emphasize immersion, agency, and contextual relevance. At the heart of this convergence lies the Flow Theory, [36], which explains how learners enter states of deep engagement and intrinsic motivation when challenges are balanced with skill – an essential condition for sustained motivation in educational games.

Indeed, these immersive environments foster situated learning, [37], problem solving, [38], and identity exploration, [39], which train learners for science education, where knowledge is co-constructed through authentic and context-rich experiences, mainly when related to local ecological realities.

Complementing this, Self-Determination Theory, [40], highlights how digital play can nurture intrinsic motivation by supporting autonomy, competence, and relatedness. Moreover, the competitive dynamics embedded in many game-based environments can amplify persistence and engagement, particularly when framed as constructive challenge rather than exclusionary ranking, [41].

In African contexts, where ecological challenges intersect with cultural identity, game-based learning offers a dynamic space for eco-cultural construction. VG can support problem-solving, systems thinking, and narrative-based exploration, [35], [42].

Moreover, [43], highlights contradictions in traditional schooling that often limit environmental education, and argues for learning experiences that are more hands-on and transformative. In this perspective, embedding generative AI within educational games offers new possibilities. Such systems can adjust the content, difficulty, and type of feedback in real time, based on learners' profiles, motivations, and cultural backgrounds, [19], [44]. When VG responds to who the learner is and what they value, it becomes a more personal and meaningful pedagogical experience.

Recent work also highlights the role of participatory culture, [45], where learners are not passive recipients but active creators of meaning. This aligns with constructivist and design-based approaches, [46], which advocate for learning environments that are iterative, collaborative, and socially grounded. In the realm of ecological education, such frameworks support the development of environmental agency, critical reflection, and community engagement. These theoretical currents support a vision of ecological education that is immersive, inclusive, and emancipatory. So, according to this, African youth should engage with digital tools not just for entertainment or learning about conservation, but mainly to participate meaningfully in shaping sustainable futures.

2.2 Digital Play and AI for Ecological Learning in African Contexts

Serious games increasingly support environmental education worldwide, [47]. In Sub Saharan Africa, AI shows transformative promise, [48], yet research directly connecting video games, AI, and ecological learning remains scarce, highlighting significant opportunities and gaps, [49].

This paper presents an exploratory study on the convergence of VG and AI to advance eco-cultural emancipation in Sub-Saharan Africa. A semi-systematic review was conducted to map this emerging field, consulting the Google Scholar, ERIC, and MDPI databases, alongside the research tool *Elicit AI* and personal academic databases. The core search string integrated five conceptual clusters: ("video games" OR "serious games" OR "game-based learning" OR "digital play"), ("artificial intelligence" OR "AI" OR "machine learning"), ("environmental conservation" OR "ecological preservation" OR "sustainability" OR "climate change" OR "ecological education"), ("Sub-Saharan Africa" OR "Africa" OR "African youth"), and ("cultural heritage" OR "indigenous knowledge" OR "eco-cultural learning" OR "emancipation"). This string was meticulously adapted for the specific syntax of each research engine.

The search was constrained to English-language publications from 2021 to 2025, yielding a total of 138 records. The PRISMA-guided screening process, as shown in Figure 1 (Appendix), applied strict inclusion criteria.

Papers were required to have a primary focus on the Sub-Saharan context, with VG and/or AI as a central thematic. They also needed to address ecological or environmental culture, integrate indigenous knowledge, and be relevant to secondary education. Furthermore, only peer-reviewed journal articles with accessible PDFs were considered, excluding preprints, books, and book chapters. This rigorous filtering, which also excluded works for methodological opacity or thematic misalignment, resulted in eight high-quality studies for final synthesis. These selected papers are summarized in Table 1 (Appendix), providing a foundational overview of how VG and AI are being leveraged for eco-cultural learning and empowerment across the region.

Table 1 (Appendix) synthesizes the literature into three convergent themes that leverage digital play and artificial intelligence for eco-cultural emancipation in Sub-Saharan Africa. The first theme, "Games for Engagement," demonstrates how serious games and robotic gamification transform climate education. These tools boost motivation and pro-environmental values, fostering actionable green innovation through interactive, context-specific play, even in offline settings. The second theme, "Indigenous Knowledge & AI", addresses the critical tension between technological advancement and cultural preservation. It reveals how AI, when co-created with communities, can merge with indigenous games and heritage to develop computational thinking and validate local knowledge. This centers cultural content in education, empowering self-determination and resilience against cultural erosion. Finally, the "Ethical AI Frameworks" theme highlights the foundational need for context-aware and ethically guided AI integration. Studies identify significant barriers—including infrastructure deficits, algorithmic bias, and the underrepresentation of African voices—while advocating for community-centered models. This prevents a neocolonial imposition of technology, ensuring that AI and gaming initiatives are equitable and directly serve local needs and values, thereby solidifying the path toward meaningful eco-cultural emancipation.

3 Design Principles for Contextual Integration

This section outlines design principles for integrating game-based learning with local ecological and cultural content, ensuring relevance and appropriate technology for resource-constrained settings (See Figure 2 (Appendix)).

3.1 Infrastructure Sensitivity

Designs must take into account the material realities of many Sub-Saharan classrooms, including limited connectivity, low-spec devices, and unreliable power. This requires offline functionality, mobile-first development, and compatibility with locally available hardware. Rather than being a limitation, this approach serves as a creative catalyst for inclusive and resilient educational tools, ensuring they operate effectively where they are needed most, [50], [51].

3.2 Ethical AI

AI systems in education must be transparent, fair, and culturally sensitive from the ground up, [52]. This requires robust protection of learner data, proactive measures to prevent algorithmic bias, and clear explanations for automated feedback. The authors in [51] highlight the nuanced ethical challenges of generative AI in game-based learning, urging developers to embed safeguards from the outset. In parallel, the authors in [53], emphasizes the importance of critically examining the constraints and risks associated with ChatGPT and similar tools. These include concerns about the accuracy of generated content, ethical issues such as plagiarism, and the potential impact on students' learning autonomy and critical thinking. Such reflections are particularly relevant in Sub-Saharan Africa, where the integration of generative AI into game-based ecological education must not only respect local epistemologies but also ensure responsible pedagogical use. Addressing these risks is essential to support eco-cultural emancipation through digital tools without reproducing epistemic or cognitive dependencies.

3.3 Participatory Co-Design

Beyond consultation, participatory design invites learners and educators to become co-creators. This democratic approach fosters ownership, relevance, and pedagogical agency. Studies such as [54], [55], show how participatory game-based learning, exemplified by *MinecraftEdu*, empowers future teachers and deepens disciplinary understanding. In a similar spirit, the authors in [56], illustrate how integrating citizen observatories like *Pl@ntNet* and *OdourCollect* digital tools into school-based environmental education cultivates ecological values and democratic engagement. By linking learners to real-world environmental issues, such approaches not only build scientific literacy but also nurture a sense of responsibility and belonging, which is essential for designing sustainable futures from the ground up.

3.4 Cultural Relevance

Science education gains depth when it speaks the language of learners' lived worlds—ecological, linguistic, and symbolic. In African contexts, knowledge is often transmitted through stories, rituals, and play. Integrating local narratives, proverbs, and environmental symbols into educational games allows learners to engage with science through familiar cultural frames. Culturally grounded design enhances motivation and conceptual retention in STEM learning, [55]. The authors in [57], further argue that folk stories are powerful pedagogical tools that support children's thinking and concept development, especially when rooted in communal experience. These stories carry ecological wisdom, moral reasoning, and social values. The study, [17], show that traditional African play fosters cognitive and emotional growth, making it a natural bridge to scientific inquiry. When learners decode sayings from elders, collect symbolic items (like calabashes or medicinal bark), or navigate myth-based dilemmas, they are not just playing: they are reasoning, remembering, and relating. Cultural relevance is not an accessory; it is a foundation. It affirms identity, deepens understanding, and invites learners to see science as part of their own story.

3.5 Teacher Empowerment

Teachers are not just facilitators: they are designers, mediators, and cultural interpreters. In resource-constrained environments, their pedagogical agency is central to meaningful digital integration. Empowerment must go beyond simple access to devices. It requires collaboration with teachers to co-design game-based activities, incorporate indigenous knowledge systems, and build ongoing feedback loops where educators reflect on learner engagement and ecological reasoning.

As noted in [58], decolonizing technology education means recognizing teachers as knowledge brokers who translate local ways of knowing into practical learning experiences, especially when working with systems and control concepts in the curriculum.

In [59], the author further highlights the importance of formative processes that support teachers as they adapt STEM curricula using community technologies, cultural practices, and indigenous problem-solving strategies. Similarly, in [54], the authors show that game-based learning becomes truly transformative only when teachers are trained and trusted to tailor digital games to their own teaching styles and to the cultural realities of their students.

Operationally, this requires a supportive ecosystem that includes offline training modules, community-based workshops, and peer mentoring structures to foster collective innovation. Teachers should also be equipped to interpret in-game analytics, support students in reflective journaling, and help them make cultural sense of ecological issues.

Ultimately, empowerment is not a one-off intervention, but an ongoing, dialogical process built on trust, relevance, and reciprocity.

3.6 Adaptive Learning

AI-powered learning systems must respond to diverse learner profiles by offering personalized pathways and differentiated feedback grounded in ecological and cultural relevance. As [60], demonstrate, generative models can scaffold ecological concepts based on individual progress and misconceptions. Other studies, [19], [44], emphasize that adaptive game mechanics strengthen Inquiry-Based Learning (IBL) and metacognition when personalization reflects learners' cultural identity and lived experiences.

In practice, this begins with profiling each learner—capturing their local traditions, prior ecological knowledge, and cognitive style. Based on this profile, the system generates contextualized quests that respond to learners' choices, errors, and motivations. For instance, if a student struggles to understand freshwater sustainability, the system may introduce an inquiry question such as: "Why are fish disappearing from our river?" The learner then investigates local sources of river pollution, analyzes impacts on fishing livelihoods, and proposes community-aligned solutions. Throughout the quest, the game adapts dynamically: offering narrative cues grounded in cultural practices, simplified visualizations, or eco-mentor guidance when needed. Feedback is differentiated and culturally relevant, delivered in real time or asynchronously, and may include support from eco-mentors or peer facilitators.

Learners engage in reflective eco-journaling and self-assessment, revisiting their strategies and ecological reasoning. This iterative loop culminates in the reintegration of situated knowledge and dynamic updates to the learner profile. At its core, adaptive learning moves beyond personalization toward contextualization. This ensures that local ecosystems, cultural values, and environmental realities become central to ecological understanding and agency.

Figure 2 (Appendix) illustrates the adaptive learning loop, highlighting how learner profiling, contextualized quests, differentiated feedback, and iterative reflection converge to support ecological understanding in culturally diverse and resource-constrained environments.

4 Implementation scenarios and modeling

4.1 Contextually Adapted Scenarios for Sub-Saharan Africa

To operationalize the integration of VG and AI into ecological education in sub-Saharan Africa, we propose three contextualized implementation scenarios. These scenarios are based on the design principles outlined earlier and aim to illustrate how digital tools can be deployed in a realistic and sustainable manner. Each of these scenarios is described in Table 2 (Appendix).

These scenarios were designed by adapting established Western serious game models such as *Minecraft*, *The Farmers*, *Terraria* or *Clim'way*, whose pedagogical efficacy is well-documented, [61], [62], [63], to the sub-Saharan African context through deliberate cultural and infrastructural contextualization.

4.2 Context-Adaptive Ecological VG with AI

The proposed implementation model, visualized in Figure 1, is a systematic and iterative workflow for developing and deploying contextually adapted, game-based learning environments for ecological education in Sub-Saharan Africa. This model is grounded in a design-based research approach, emphasizing co-creation, contextualization, and continuous improvement. The process is structured into five core phases and one critical sub-step, which together ensure that the final product is pedagogically sound, culturally relevant, and technically feasible.

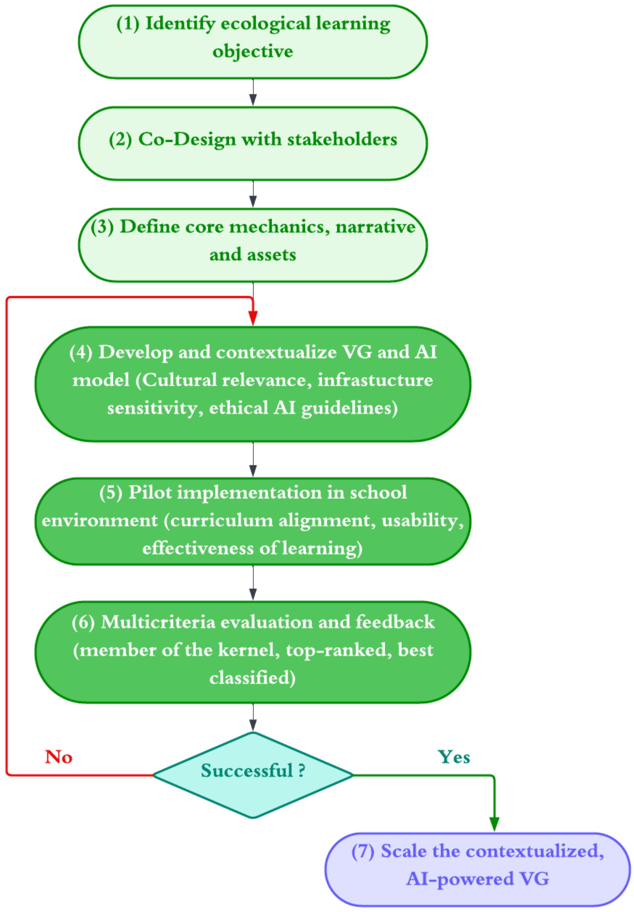

Fig. 1: Iterative development workflow for contextualized and AI-powered serious games. Source: created by the authors.

The workflow proceeds as follows: The process begins by identifying a core ecological learning objective through collaboration with local educators (1). This objective is then fleshed out through co-design workshops with stakeholders (teachers, students, community members, etc.) to ensure relevance and ownership (2). These workshops benefit from the active involvement of diverse actors—including educators, researchers, policymakers, psychologists, and game developers—whose collaboration is essential for designing emotionally intelligent and pedagogically inclusive games, [15]. Moreover, integrating principles from Citizen Science fosters meaningful connections between learners and scientific inquiry, reinforcing ecological awareness through participatory engagement, [64]. The ideas from these workshops will be formalized into a concrete design document defining the core mechanics, narrative, and assets (3).

This blueprint guides the development phase, which is strictly governed by three principles: cultural relevance, infrastructure sensitivity, and ethical AI (4). The resulting prototype is deployed in a pilot implementation in schools (5), followed by a multi-criteria evaluation using both quantitative and qualitative data (6).

The results lead to a decision: scale the successful intervention or iterate by returning to the development phase (4) for refinement based on feedback, ensuring continuous improvement before wider deployment (7). Multicriteria analysis is essential to holistically evaluate the impact of pedagogical tools, going beyond cognitive gains alone by integrating key dimensions such as curriculum alignment, usability, cultural relevance, and technical feasibility, [65], [66], [67].

4.3 Mechanical Integration of Indigenous Knowledge into Game-Based Learning

The mechanical integration of indigenous knowledge into game-based learning requires both linguistic and cultural grounding. In what follows, the terms used to designate elements of the local culture will be drawn from Kikongo, a language spoken by several million people in Central Africa, notably in the Democratic Republic of the Congo, the Republic of the Congo, Angola, and Gabon. Beyond this linguistic dimension, a core pillar of the design is the deliberate embedding of indigenous knowledge systems into game mechanics, fostering a contextualized epistemological hybridization. In the proposed scenarios, the player embodies a character named *Mpanzu* (boy) or *Nkenge* (girl), drawn from Central African oral traditions.

The game can be experienced in first-, second-, or third-person perspective, depending on the desired level of immersion. Each perspective is aligned with a distinct pedagogical intention. First-person view promotes sensory immersion and emotional engagement with ecological challenges; second-person framing reinforces personal responsibility and reflection; and third-person perspective supports systemic reasoning and the analysis of ecosystem interactions. An adaptive AI agent may dynamically switch perspectives to scaffold learning based on the player's needs, context, and performance.

The gameplay unfolds across a sequence of ecosystems representative of Sub-Saharan Africa (dense forests, savannas, wetlands, or mangroves) where the player encounters two main types of challenges:

- *Symbolic and narrative challenges*: Throughout the game, the player encounters two distinct types of cultural figures—Elders and "*bisimbi*"—-each offering unique symbolic challenges. Elders are wise human characters, often portrayed as village sages or custodians of oral tradition. They engage the player through proverbs, tales, ecological sayings, and reflective questions rooted in lived experience and communal wisdom. Their role is to guide, provoke thought, and transmit ancestral knowledge. In contrast, "*bisimbi*" are mythological entities from Kongo tradition—spirits of the forest, water, or mountains. These supernatural beings present riddles, symbolic dilemmas, or metaphoric trials that draw on ecological themes. Interacting with "*bisimbi*" requires the player to interpret layered meanings, often tied to local myths and environmental ethics. Progress in the game depends on the player's ability to navigate both types of encounters—reasoning with Elders and decoding the symbolic language of Spirit entities. This dual engagement valorizes oral transmission, ecological literacy, and culturally embedded ways of knowing.
- *Contextualized ecological challenges*: Following a Problem-Based Learning (PBL) approach, the player faces real-world environmental issues such as poaching, bushfires, invasive species, wildlife depletion, illegal logging, or disruptive infrastructure projects. Each decision leads to a gain or loss of "Eco-points" with narrative feedback provided by Elders or Spirit entities to reinforce learning.

Three additional mechanics deepen this integration (these elements are partially reflected in Table 2 (Appendix) under the column "Components & specificities" illustrating how local epistemologies are embedded within the game's narrative and mechanics):

1. Indigenous knowledge as in-game resources: Players collect symbolic items (e.g., medicinal bark, ritual statuettes, calabashes) that unlock ecological knowledge or regenerative powers.
2. Mentorship system: A Non-Playable Character (NPC) embodies a local Elder who guides the player, shares stories, and assigns quests tied to ecological memory.
3. Adaptive storytelling: The game's narrative and consequences evolve based on player choices,

reflecting the diversity of worldviews and relationships with nature.

These implementation scenarios demonstrate the transformative potential across diverse ecological and cultural settings. However, translating these designs into practice entails a range of pedagogical, infrastructural, and ethical challenges that warrant critical reflection.

4.4 Assessment Mechanisms and Indicators of Learning

Building on the contextual, narrative, and epistemological foundations of the VG design, this subsection details how learning outcomes are assessed across the proposed scenarios. The evaluation framework is grounded in Problem-Based Learning (PBL) and integrates both cognitive and cultural dimensions through multimodal indicators. Each indicator is designed to be SMART and linked to a context-sensitive reward system.

In Scenario 1, learners who complete at least 75% of ecological challenges and decode four traditional sayings posed by Elders and "*bisimbi*" spirits earn eco-points. Inspired by [68], every 150 eco-points accumulated correspond to 1 symbolic carbon credit, representing approximately 1.5 kg of avoided CO_2-equivalent emissions. This metaphorical conversion reinforces the link between cultural knowledge, environmental responsibility, and climate impact. Eco-points or Carbon credits may be used to unlock tools, episodes, or regenerative powers. Time-on-task ($\geq$ 30 minutes/session) and strategic use of indigenous items—such as medicinal bark/roots/leaves, ritual statuettes, or calabashes—in at least three quests are tracked as indicators of ecological reasoning and cultural engagement. Reflective journals are evaluated for depth and cultural insight, with high-quality entries rewarded by mentorship bonuses.

In Scenario 2, creativity is scored via a rubric assessing originality and ecological depth ($\geq$ 75%), while cultural relevance is validated by integrating three local myths or symbols. Collaborative design is tracked through peer feedback and co-design logs, with exemplary teamwork unlocking special actions and symbolic carbon credits. Projects scoring above threshold are showcased in virtual galleries or school competitions.

In Scenario 3, a minimum 25% improvement in post-test scores and successful completion of two scenario-based tasks yield thematic badges (e.g., "Water/Forest Guardian"). Retention is measured across three sessions, and autonomous learners demonstrating consistent self-assessment and adaptive feedback use receive eco-points for in-game advantages.

A synthetic overview of the SMART indicators, associated evaluation tools, and reward mechanisms is provided in Table 3 (Appendix).

5 Limitations and Implementation Challenges

This framework presents promising avenues for eco-cultural education through VG and AI. Yet, its successful implementation in Sub-Saharan Africa requires addressing several challenges related to contextual relevance, ethical integrity, and long-term sustainability.

First, teachers' training and perceived self-efficacy are critical. Although VG can enhance learners' motivation through immersive and interactive experiences, their pedagogical impact depends heavily on the confidence and competence of educators. According to Self-Determination Theory, [40], perceived competence is a key driver of motivation. This remains true for both learners and teachers. Without adequate training, educators may feel disempowered or overwhelmed. Moreover, the Theory of Planned Behavior, [69], suggests that negative attitudes or perceived lack of control can lead to resistance, especially if teachers view digital games as culturally inappropriate or pedagogically superficial. Capacity-building programs must therefore address both technical and attitudinal dimensions.

Second, infrastructural and financial constraints remain significant. Limited access to electricity, internet connectivity, and digital devices—especially in rural schools—can hinder implementation. Moreover, the cost of acquiring and maintaining such tools may be prohibitive without external support. Scalable solutions such as solar-powered kits, offline-compatible platforms, and community-based digital hubs are essential, [64], [70].

Third, social acceptability must be cultivated. Technologies must resonate with local values and be co-designed with communities to ensure legitimacy. Integrating indigenous narratives, symbols, and ecological knowledge into game mechanics enhances cultural alignment and learner engagement, [71], [72].

Fourth, ethical risks must be anticipated. This framework aligns with selected principles from the European Commission's Trustworthy AI framework, [73], notably:

1. Human oversight: Teachers must retain control over AI-generated feedback.

2. Privacy and data governance: Student data must be anonymized and securely stored.
3. Societal well-being: AI tools should promote ecological awareness and avoid reinforcing digital divides.
4. Finally, risks of overexposure or addiction among young learners must be mitigated through design safeguards such as time limits, reflective pauses, and adult supervision protocols.

These challenges call for multi-stakeholder collaboration, flexible design, and policy frameworks tailored to local realities.

6 Discussion

This study demonstrates that the intersection of VG and AI offers fertile ground for reimagining ecological education in Sub-Saharan Africa. Anchored in theories such as Flow, [36], Situated Learning, [37], and Participatory Culture, [45], our framework positions digital play as a culturally responsive and cognitively engaging medium. The selected African studies reveal a growing ecosystem of innovation—from intelligent tutoring systems to generative indigenous games—each contributing to climate literacy, cultural transmission, and computational thinking, [74].

The six design principles distilled (Infrastructure Sensitivity, Ethical AI, Participatory Co-Design, Cultural Relevance, Teacher Empowerment, and Adaptive Learning) are not abstract ideals but operational levers. For instance, the principle of participatory co-design is embodied in the scenario where learners and teachers co-create serious games addressing local environmental challenges. This approach, supported by ”low-cost” tools and generative AI like ChatGPT, fosters agency, creativity, and ownership – echoing [56], emphasis on democratic engagement through citizen observatories.

The flowchart implementation model reflects, [46], design-based research ethos: iterative, context-sensitive, and grounded in real-world feedback. It ensures that educational tools evolve through cycles of co-creation, piloting, evaluation, and scaling. The scenario of an adaptive ecological simulation game exemplifies this model, merging local ecosystem data with AI-driven personalization to cultivate systems thinking and ecological awareness.

Moreover, the intelligent tutoring system scenario highlights the potential of AI to scaffold STEM learning in multilingual and resource-constrained environments. Through adaptive feedback and culturally relevant content, such systems can democratize access to quality ecological education while recognizing learners' diverse backgrounds.

Rather than limiting innovation, contextual integration acts as a generative force. It aligns VG and AI tools with the ecological, cultural, and infrastructural realities of African learners, ensuring they resonate with lived experience. By embedding ecological values, cultural narratives, and ethical safeguards into game-based environments, this framework offers a compelling pathway toward sustainable futures rooted in local knowledge and global citizenship.

7 Concluding Remarks, Perspective and Future Directions

In an era of ecological urgency and digital transformation, African science education must evolve to meet the needs and realities of its learners. By harnessing the immersive power of VG and the adaptive AI, educators can cultivate ecological literacy that is both rigorous and resonant.

This study has explored the transformative potential of VG and AI as tools for eco-cultural emancipation in Sub-Saharan Africa. By weaving together theoretical foundations (such as flow theory, situated learning, and participatory culture) with emerging African innovations, we have proposed a framework that positions digital play and intelligent systems not as imported novelties, but as culturally responsive instruments for ecological education and curricular renewal.

The six design principles identified (Infrastructure Sensitivity, Ethical AI, Participatory Co-Design, Cultural Relevance, Teacher Empowerment, and Adaptive Learning) offer a roadmap for developing inclusive, resilient, and locally grounded educational technologies. The implementation model and contextualized scenarios presented in this study demonstrate how iterative, co-created, and ethically guided game-based environments can foster systems thinking, climate literacy, and learner agency. These principles are not static; they invite continuous reinterpretation in dialogue with local communities, ecological realities, and technological shifts.

Looking ahead, several avenues merit further exploration. First, longitudinal studies are needed to assess the long-term impact of AI-powered games on learners' ecological knowledge, values, and behaviors. Second, more attention should be given to the role of indigenous knowledge systems and oral traditions in shaping game narratives and AI feedback loops. Third, the integration of citizen science platforms into school curricula offers promising opportunities for democratizing ecological data and fostering community-based learning.

Finally, future research should prioritize capacity-building among educators, ensuring they are not only users but co-designers and stewards of these technologies. This calls for transdisciplinary collaboration among researchers, developers, teachers, and learners. These partnerships should be rooted in African epistemologies and oriented toward sustainable futures.

This agenda calls for interdisciplinary collaboration across education, computer science, environmental studies, and African cultural research.

By embracing the convergence of play and AI within ethical, contextual, and participatory frameworks, we can ignite a new era of ecological education — one that empowers learners to imagine, design, and inhabit more just and sustainable worlds.

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Contribution

Conceptualization: JRMB, RBMN, GKK; Formal analysis: ENM, PMI, RMB; Methodology: JRMB, RBMN; Supervision: BNM, RBMN, GKK; Validation: ENM, BNM, PMI, GKK, JRMB; Writing — original draft: JRMB, RBMN; Writing — review and editing: JRMB, RBMN. All authors have read and approved the final version of the manuscript.

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Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

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Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

The authors equally contributed in the present research, at all stages from the formulation of the problem to the final findings and solution.

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Conflict of Interest

The authors have no conflicts of interest to declare that are relevant to the content of this article.

APPENDIX

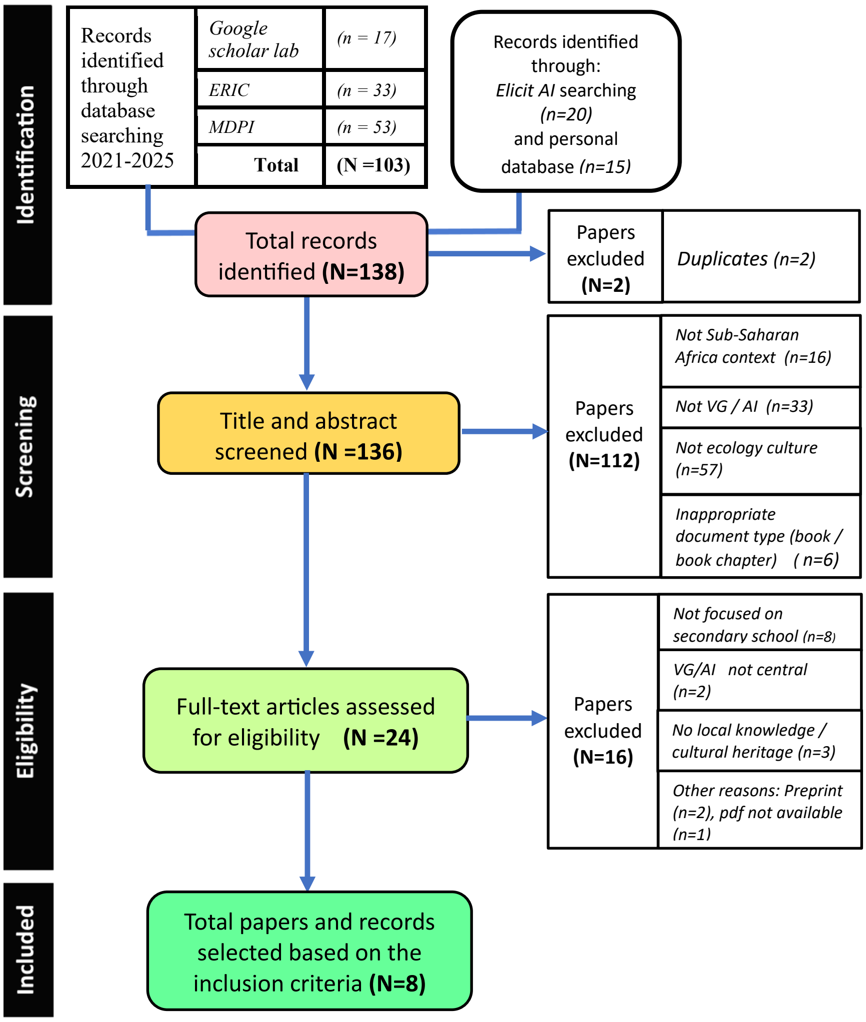

Fig. 1: Flow Diagram of Study Selection Process. Source: created by the authors.

Table 1: Summary of Selected Studies on VG and AI for Eco-Cultural Education in Sub-Saharan Africa

Thematic focus	Context/setting	Focus area	Key findings	Contribution to Eco-Cultural Emancipation
1.Games for Engagement. [49], [75], [76]	Climate crisis & need for engaging pedagogy in SSA	Using serious games and robotics to promote environmental literacy and motivation	- Games boost engagement and pro-environmental values - Gamification sustains motivation in complex topics - Offline and context-specific solutions	Fosters environmental agency and green innovation through interactive "play" enabling actionable learning
2.Indigenous Knowledge & AI. [77], [78], [79]	Tension between AI advancement and preservation of African indigenous knowledge	Merging AI with indigenous knowledge (games, heritage) for culturally resonant education	- Indigenous games develop computational thinking. - AI can preserve or threaten heritage - Community co-creation is vital.	Centers and validates indigenous knowledge, empowering cultural self-determination and resilience
3.Ethical AI Frameworks. [79], [80], [81]	AI adoption in SSA amid infrastructure gaps and ethical concerns	Developing context-aware, ethical AI for education that reflects African values	- Barriers (infrastructure, teacher training, algorithmic bias) - Underrepresentation of African voices in AI ethics - Need for community-guided AI.	Prevents neocolonial tech imposition; advocates for equitable, community-centered AI that serves local needs.

Source: created by the authors.

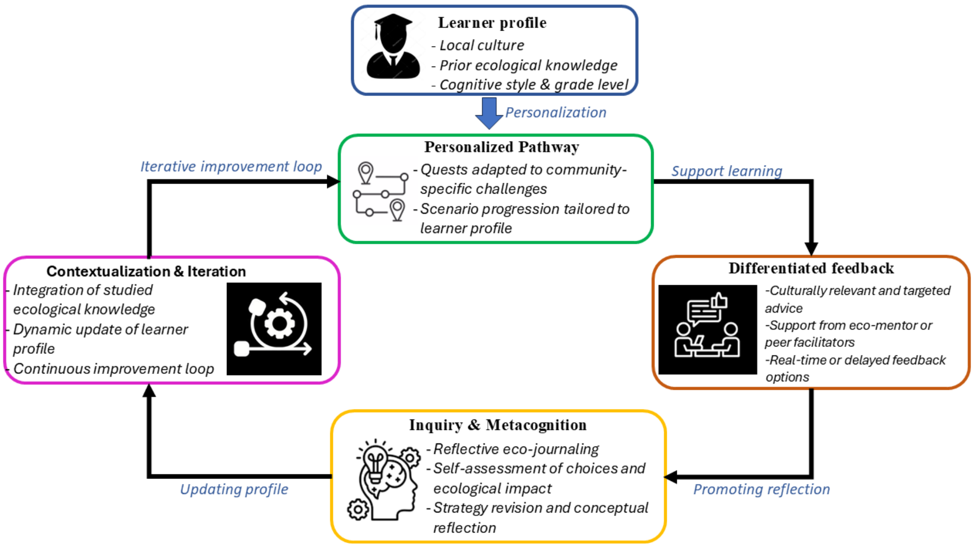

Figure 2: Adaptive learning loop. Source: created by the authors.

Table 2: Contextualized Scenarios for Integrating VG and AI into African Ecological Education

Scenario	Highlights	Components & Specificities	Assessment	Reward
Adaptive Ecological Simulation Game with GenAI	(1) Promote systems thinking and local ecosystem understanding. (2) Contextualized simulation (forest, savanna, wetlands) adapting challenges to learner profiles, [19].	Offline-first, mobile-compatible; cultural storytelling (proverbs, myths). GenAI for adaptive scenarios, [60].	Indicators of conceptual mastery and engagement (problem-solving, mission completion).	Eco-points converted into carbon credits to unlock content/tools.
Co-creation of Serious Games by Teachers and Learners	(1) Strengthen agency and ownership of ecological issues. (2) Participatory design of local challenges (deforestation, water, invasive species), [54].	Teacher training; low-code tools; AI-assisted generation of landscapes/dialogues.	Qualitative evaluation: creativity, cultural relevance, community resonance.	Unlocking special actions/episodes; symbolic carbon credits showcased publicly.
Intelligent Tutoring System (ITS) for Sustainability Learning	(1) Support STEM acquisition through personalized coaching. (2) ITS enriched with eco-cultural content and game mechanics, [82].	Badges, non-competitive rankings; content aligned with national curricula and Indigenous knowledge, [58]. AI adapts difficulty and feedback.	Learning gains: pre/post tests, retention analysis.	Thematic badges (e.g., "Water Guardian"), eco-points for milestones.

Source: created by the authors.

Table 3: Summary of SMART Indicators, Evaluation Tools, and Reward Systems

Scenario	SMART Indicators	Evaluation Tools	Reward System
1. Simulation Game	≥75% ecological challenges solved ≥4 sayings decoded (elders + "bisimbi" spirits) ≥30 min/session + 3 symbolic items used Reflective journal quality	In-game analytics Journal review NPC feedback logs	Eco-points + carbon credits Unlock tools/episodes Mentorship bonuses
2. Co-creation	≥75% creativity score ≥3 myths/symbols integrated Peer feedback + co-design logs Elder interviews	Rubric scoring Observations Interviews	Special actions unlocked Symbolic carbon credits Virtual gallery/showcase
3. Tutoring System	≥25% post-test improvement 3-session retention tracking 2 scenario tasks completed Self-assessment consistency	Pre/post-tests Scenario logs Feedback analytics	Thematic badges Eco-points for in-game advantages

Source: created by the authors.