

ARTIFICIAL INTELLIGENCE AND ECOLOGICAL PEDAGOGY: A THEORETICAL FRAME FOR DESIGNING INCLUSIVE AND SUSTAINABLE OUTDOOR LEARNING ENVIRONMENTS

INTELLIGENZA ARTIFICIALE E PEDAGOGIA ECOLOGICA: UN QUADRO TEORICO PER PROGETTARE AMBIENTI DI APPRENDIMENTO OUTDOOR INCLUSIVI E SOSTENIBILI

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ABSTRACT

This article explores how AI can support inclusive and sustainable outdoor education through an ecological pedagogy lens. Drawing on the Ecological Pedagogy Framework, it positions AI as a relational tool that complements embodied learning. Case studies on wearables, environmental monitoring and adaptive platforms illustrate opportunities and risks, stressing inclusivity, sustainability and teacher mediation.

L'articolo analizza come l'intelligenza artificiale possa sostenere l'educazione outdoor inclusiva e sostenibile attraverso la pedagogia ecologica. Riprendendo l'Ecological Pedagogy Framework, l'IA è presentata come strumento relazionale che integra l'esperienza corporea. Casi su wearable, monitoraggio ambientale e piattaforme adattive mostrano potenzialità e rischi, evidenziando inclusività, sostenibilità e ruolo docente.

KEYWORDS

Artificial Intelligence in Education; Ecological Pedagogy; Outdoor Learning; Inclusive Education; Sustainability.

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Introduction

Education today faces intertwined challenges of ecological crisis, urbanisation, and a growing disconnection from nature (Mueller, 2009; Tarantino et al., 2023). Scholars have documented the decline in opportunities for outdoor learning across Europe, with significant implications for learners' health, socio-emotional development, and ecological awareness (Fägerstam & Blom, 2013; Lugg, 2007). The spread of urban lifestyles and the reduction of green spaces contribute to what Tarsi et al., themed as nature-deficit, a condition linked to diminished well-being, creativity, and environmental stewardship (Tarsi et al., 2024). In parallel, the sustainability crisis, climate change, biodiversity loss, and ecological degradation demand that education be reimagined to enact it in pedagogical practice (Patera & Del Gottardo, 2022). Reconnecting education with natural environments thus becomes an ecological and a pedagogical imperative. This resonates with recent Italian contributions emphasising sinecological pedagogy as a dynamic interaction among people, environments, and educational events (Tarantino et al., 2023; Tarsi et al., 2024). The Ecological Pedagogy Framework (EPF) offers a holistic model for responding to these challenges, figure 1.

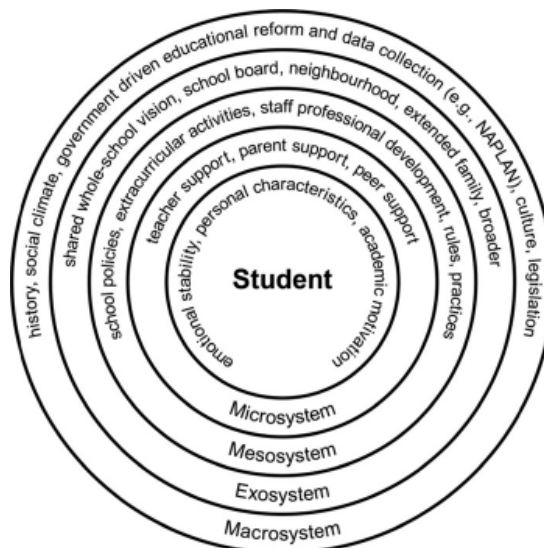


Figure 1. The socio-ecological framework of school belonging, modified from (Allen et al., 2016)

The EPF aims to create a dynamic interplay of humans, environments, and events, where interdependences are central (Lee, 2017). Outdoor and experiential learning research confirms that such ecological and relational approaches enhance student motivation, deepen learning, and foster long-term ecological responsibility (Beames et al., 2012; Gadotti, 2010). Through sensory engagement and embodied interaction, this approach reframes the relationship between learner and environment as reciprocal, in which growth occurs through meaningful exchanges with peers, educators, and ecological systems. However, in parallel to this it is necessary to acknowledge that Artificial Intelligence (AI) is rapidly entering the educational landscape (Palma & Amatori, 2025).

While debates often emphasise the risks of automation and substitution, emerging research stresses the relational potential of AI. Indeed, Bearman argues that AI functions as a “black box” in many contexts, raising concerns about the erosion of critical thinking (Bearman & Ajjawi, 2023). Yet when deployed within well-designed pedagogical frameworks, AI can support reflection, scaffold personalised learning, and augment teachers’ capacity for inclusivity (Ciccarelli et al., 2024; Ciccarelli & Tafuri, 2024). Adaptive learning platforms, intelligent tutoring systems, and data-driven feedback mechanisms are examples of how AI can enhance personalisation and accessibility (Aggarwal, 2023). This aligns closely with EPF principles, as both approaches value relationality and contextual responsiveness.

However, issues of algorithmic bias, surveillance, and data privacy are particularly acute in educational settings (Selwyn, 2021; Williamson & Eynon, 2020). Moreover, without adequate AI literacy among teachers, there is a risk that technology becomes imposed rather than integrated (Zawacki-Richter et al., 2019). The sustainability dimension also cannot be ignored. The environmental footprint of AI infrastructures must be considered when aligning them with ecological pedagogies (Ghosh, 2025). Bringing these debates together, the central research problem addressed in this paper is whether AI can be meaningfully integrated into EPF for outdoor education in ways that reinforce, rather than undermine, the relational and ecological aims of such pedagogy.

The argument advanced here is that AI has the potential to map interactions between learners, teachers, and natural environments, thereby generating insights into engagement, collaboration, and ecological impact. It can also support

inclusivity by adapting outdoor activities to the needs of diverse learners, including those with physical or cognitive impairments and it enhances sustainability through data-driven monitoring of environmental conditions, ensuring that learning activities minimise ecological disruption.

Theoretical Framework

1. Nature-based education

At the heart of the present argument is the EPF view of education: learning emerges from dynamic, reciprocal relations among people, practices and places. In this perspective, outdoor education is a living system in which learners' embodied activity, peer relations, teacher mediation and ecological affordances co-produce understanding and values (Stanger, 2011). Recent work in environmental and sustainability education underlines how field-based experiences cultivate ecological literacy, observational acuity and collaborative reasoning when designed with small, discussion groups and guided reflection (Barrette et al., 2025). Recommendations typically include tight coupling between practical sessions and theoretical input, and group sizes of roughly 15–20 to maximise attention, dialogue and situated problem-solving, all of which agree with the EPF model (Ferraro, 2023).

Within subject disciplines, there is accumulating evidence that re-embedding curriculum content in local ecologies strengthens conceptual grasp and civic responsibility. For secondary biology, Moore-Anderson proposes a framework to reintegrate nature into the teaching of physiological and developmental systems, moving from classroom abstraction towards place-responsive inquiry in living environments (Anderson & Moore, 2021). Such designs resonate with broader European practice in environmental communication and ecological culture, which emphasises that students' competencies grow when universities orchestrate networks of activities (e.g., fieldwork or eco-projects) linking classroom knowledge, local ecosystems and community initiatives oriented to sustainability (Mohd Ali Khan et al., 2025). Within the Italian context, sinecological pedagogy has been advanced as an educational paradigm that integrates corporeality, ecological responsibility, and relational dynamics (Tarantino et al., 2023; Tarsi et al., 2024).

2. Artificial intelligence as a relational technology

Positioning AI appropriately requires clarity about its pedagogical role. Bearman discussed that in each interaction, a computational artefact offers a judgement about the best possible action, but the process is fundamentally opaque (Bearman & Ajjawi, 2023). The task for higher education is to help learners work with AI, orient to quality standards and engage critically as part of a sociotechnical ensemble. From a practitioner standpoint, this means designing learning where AI augments human judgment rather than replacing it. Qureshi argues for a collaborative human-AI pedagogy where intelligent tutoring, adaptive platforms and automated feedback can personalise learning and offload routine tasks (Qureshi et al., 2023). Still, the distinctly human work, ethical discernment, relational atonements, and formative diagnosis remain irreducible.

3. Principles for outdoor learning design

AI-supported sensing (e.g., wearables, environmental sensors, geospatial logging) can map patterns of engagement (movement, collaboration, attention to features) and ecological impact (trampling, microclimate, biodiversity indicators), providing educators with formative insight, figure 2.

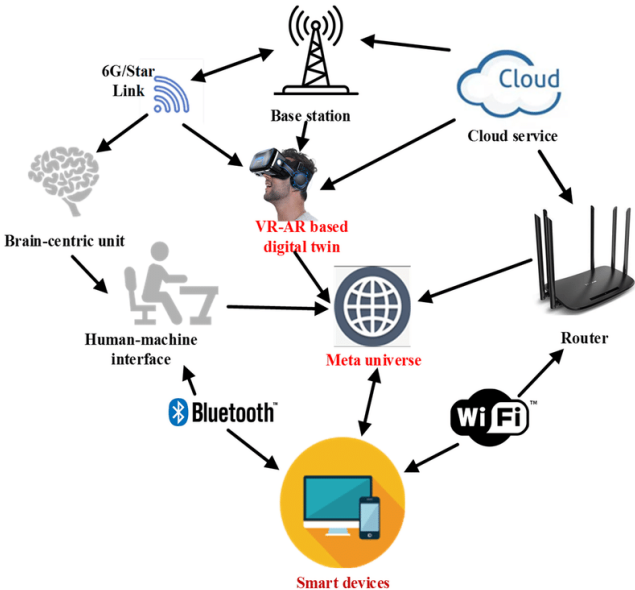


Figure 2. Intelligent ecology of AI-based wearable and immersive systems. The diagram illustrates the interconnected ecosystem through which brain-centric

units, human–machine interfaces, smart devices, and immersive VR/AR digital twins interact with cloud services and the metaverse via high-speed communication technologies (6G/Starlink, Wi-Fi, Bluetooth). This flow highlights how digital infrastructures, cognitive interfaces, and networked environments co-evolve to support data storage, interaction, and transformative learning processes. Modified from (Long et al., 2022).

These data can scaffold evaluative judgement without displacing first-hand experience. The pedagogical imperative, also according to Bearman and Ajjawi (2023), is to make such AI interactions visible as value-laden judgements and to teach students how to weigh them alongside situated observations. A synecological approach regards inclusion as tuning activities to the evolving learner–environment system (Sofo & Maragno, 2015). AI can assist with anticipatory adaptation (e.g., suggesting route variants, adjusting task difficulty) while teachers maintain ethical oversight and relational care. This mirrors Qureshi’s (2023) model in which AI augments planning and feedback, but educators remain responsible for meaning making and equity, particularly where algorithmic bias or data gaps might disadvantage learners. Real-time indicators (soil moisture, canopy temperature, species counts) can help classes enact low-impact practice and reflect on human–environment feedback loops.

4. Pedagogical designs that operationalise the framework

Studies in outdoor education show that small groups, explicit observation protocols, post-activity dialogue and iterative artefact creation (e.g., ecological diagrams) deepen learning and scientific reasoning. Instructors act as mediators who navigate the landscape and help students make ecological sense; AI can contribute as a second reader that surfaces patterns for discussion (Eames & Aguayo, 2019) bringing nature back into core topics offers a concrete structure for such sequences (Anderson & Moore, 2021).

K-12 evidence suggests that problem-based and collaborative pedagogies are associated with more advanced AI literacy outcomes; therefore, outdoor projects should incorporate explicit work on model limits, bias and data provenance, with teachers cultivating the metacognitive skill of weighing AI judgements against field evidence. Parallel work in curriculum design proposes holistic, cross-disciplinary approaches to AI education in schools, useful templates when mapping outdoor

activities that cut across science, design and citizenship (Chiu, 2021). A synecological–AI synthesis must confront three risks. i) Opacity and over-trust: if learners treat algorithmic outputs as authoritative, relational inquiry can collapse into deference. Pedagogies should therefore stage critical interactions with AI and emphasise quality standards and uncertainty (Bearman & Ajjawi, 2023). ii) Bias and surveillance: differential error rates and datafication can marginalise already under-served students (Iavarone, 2025); design must foreground human oversight, transparent criteria and minimal data collection (Qureshi, 2023). iii) Digital and ecological footprints: initiatives should be proportionate, selecting low-energy methods and minimum viable data consistent with sustainability aims (Suryanarayana et al., 2024).

To explore how the synecological framework can be operationalised in practice, it is possible to conceive conceptual scenarios in which AI complements rather than replaces outdoor and embodied learning. Each scenario draws on recent peer-reviewed literature, illustrating the concrete ways in which technology can support ecological, inclusive, and reflective pedagogies. The integration of wearable technologies in physical education has been widely investigated to provide real-time feedback and enhance embodied awareness (Lindberg et al., 2016). The crucial point highlighted by Lindberg is that technology must not reduce bodily experience into fragmented data but should be intentionally embedded in pedagogy to stimulate reflection and embodied learning (Molavian et al., 2023). In outdoor contexts, this allows students to see how their bodies adapt to environmental affordances; Several authors demonstrated that when teachers employ digital tools to support autonomy and competence, students perceive AI feedback as empowering rather than reductive (Ciccarelli & Tafuri, 2024; Iavarone & Aruta, 2023).

Similarly, outdoor learning environments provide unique opportunities to connect students with sustainability challenges. Rundel et al., demonstrated that environmental sensor networks integrated with AI enable real-time monitoring of biodiversity and microclimate, bridging empirical observation with predictive modelling (Rundel et al., 2009). Involving students in such projects aligns with synecological learning by situating knowledge within human–environment relations. Hence, the synecological lens helps ensure technology is used to enrich, not substitute, embodied ecological experience. In particular, inclusion represents one of the most compelling opportunities for AI integration. Digital tools can adapt

tasks to diverse learner needs, providing alternative challenges or multimodal instructions (Knox et al., 2019) differentiating activities based on sensor data, enabling students with motor impairments to participate fully in outdoor group tasks.

Research on digital corporeality stresses that inclusive education is about integrating body, environment, and digital mediation (Marzullo, 2024); Teacher mediation is again key. When teachers emphasise autonomy and relational care, AI becomes an enabler of inclusion rather than a source of deficit (Ciccarelli et al., 2024). Education policies must prepare teachers to design AI-supported, synecological outdoor learning, going beyond technical competencies to include AI literacy and ecological sensitivity. Italian contributions, such as Di Tore and Raiola, stress that corporeality and well-being must remain central, with AI acting as a co-facilitator (Capodanno et al., 2025; Viola et al., 2024).

Discussion

The case studies illustrate the diverse ways in which AI can be integrated within outdoor learning contexts, but they also highlight the need for a critical appraisal of its pedagogical and societal implications. Based on the review of the above literature the following this discussion develops three interrelated dimensions: the pedagogical opportunities, the ethical challenges, and the broader implications for teacher training, governance, and future research.

1. Pedagogical Opportunities

AI technologies demonstrate the potential to enhance bodily awareness, personalise participation, and foster sustainability-oriented learning. These findings are consistent with recent literature emphasising that AI should be considered a relational technology, not a replacement for teachers or direct experience (Bearman, 2023). Synecological pedagogy provides a conceptual safeguard against technocentric reductionism, reframing AI as a mediator of relations between body and environment, student and peer, or learner and ecological system. Research in applied learning sciences further confirms this direction. Roll and Wylie argue that adaptive systems can promote metacognitive awareness when embedded in pedagogical frameworks that value reflection and dialogue (Roll & Wylie, 2016). This resonates with the findings from outdoor sustainability projects where AI-enabled monitoring catalyses ecological reflection rather than replacing embodied inquiry (Holstein et al., 2019).

The convergence between AI and synecology thus points towards an expanded pedagogy of eco-digital corporeality, where technology augments rather than supplants embodied practice. This direction is consistent with the tradition of transformative learning, where educational experiences are not limited to knowledge acquisition but involve deep shifts in perspective (Scuotto et al., 2023). By situating AI within outdoor and synecological education, learners are encouraged to critically reassess their assumptions, engage in dialogue, and develop new ecological and social responsibilities. In this sense, AI-supported outdoor practices can serve as catalysts for transformative learning, fostering both personal growth and collective sustainability.

2. Ethical Challenges

Despite these opportunities, significant challenges arise. Central among these is the issue of explainability and the danger of “black-box” (Bearman & Ajjawi, 2023). Studies in human–AI interaction warn that opaque AI systems risk undermining teacher agency and student trust if their outputs are presented as unquestionable (Akgun & Greenhow, 2022). Within outdoor learning, this could manifest in an uncritical acceptance of AI-derived ecological data, potentially displacing embodied knowledge and lived experience. Another key concern is data ethics. Outdoor AI systems frequently involve multimodal data capture, from biometric sensors to geo-location. This raises questions of privacy, consent, and surveillance, especially in the case of vulnerable learners (Selwyn, 2019, 2021). The ecological settings of outdoor education amplify issues such as personal data are not only tied to the body but also to specific places, creating risks of environmental and cultural commodification. The call for responsible AI governance in education is therefore urgent, requiring protocols that ensure transparency, inclusivity, and data minimisation. AI systems carry the risk of narrowing the educational gaze to what is measurable. Hence, AI must be appropriated as a partial perspective that complements, but does not dominate, ecological and relational knowledge.

3. Implications for Teachers, Governance, and Future Research

Teachers remain the key mediators between AI systems and learners. The literature consistently demonstrates that the effectiveness of AI-supported education depends less on the sophistication of the technology and more on how teachers embed it pedagogically. Training programmes should therefore cultivate technical and AI literacy, equipping educators to interrogate algorithmic biases, challenge black-box outputs, and integrate AI tools in relationally meaningful ways. At the

level of governance, AI in education raises structural questions. Selwyn (2019) argues that educational AI is never neutral it encodes particular values and priorities. In outdoor and synecological learning, governance frameworks must therefore protect ecological integrity, inclusivity, and teacher agency. This entails resisting commercial pressures to impose standardised AI systems and instead fostering participatory co-design with educators, learners, and communities. Hence, technologies should enhance, not diminish, the mutual co-adaptation of learners, teachers, and environments. This principle challenges prevailing narratives of efficiency and optimisation, insisting instead on inclusivity, sustainability, and embodied engagement as guiding values. In this sense, AI is not a technological innovation imposed on pedagogy, but as a co-evolutionary process where digital systems, ecological environments, and human actors continually shape each other.

Conclusion

This article has proposed a synecological theoretical framework for understanding how AI may be integrated into outdoor learning environments. By situating AI within relational and ecological pedagogies, the analysis demonstrates that technology can act as a mediator of connections between learners, teachers, bodies, and environments, rather than as a substitute for embodied experience.

The review of case studies has illustrated the diverse applications of AI: enhancing corporeal awareness through wearables, supporting sustainability learning via environmental monitoring, enabling inclusive participation through adaptive systems, and strengthening teacher education with critical AI literacy. Taken together, these scenarios suggest that AI's most valuable contribution lies in its capacity to amplify synecological learning processes, fostering reflection, inclusivity, and ecological responsibility. At the same time, the discussion has emphasised the challenges: risks of technocentrism, black-box opacity, data ethics, and the danger of reducing learning to quantifiable metrics. Addressing these issues requires teacher mediation, responsible governance, and participatory design processes that keep pedagogy, not technology, at the centre.

Future research should extend the conceptual contributions of this paper through empirical validation and interdisciplinary development. Longitudinal field studies in schools, universities, and community-based contexts are needed to assess whether AI-supported outdoor learning effectively enhances ecological literacy, bodily

awareness, and inclusivity compared to traditional pedagogical models. Such work should adopt mixed-method approaches, combining quantitative indicators (e.g., biodiversity knowledge, physical performance metrics) with qualitative accounts of embodied and relational learning. Equally important is the need for cross-cultural and equity-focused investigations. Much of the existing research originates from higher-income contexts, which limits its applicability to under-resourced or culturally distinct settings. Such studies should examine how professional identities, pedagogical practices, and ecological sensitivities evolve as teachers engage with AI-supported outdoor learning.

Limitations

This study is primarily conceptual and draws on secondary literature rather than empirical evaluation. The case studies presented are illustrative scenarios derived from existing research, not direct field trials. As such, while they demonstrate the feasibility and potential of AI-supported synecological pedagogy, their impact remains to be tested in real educational settings. Furthermore, much of the evidence on AI in education derives from higher-income contexts, raising questions of applicability in under-resourced or culturally distinct settings.

Author contributions

Prof Francesco V. Ferraro conceived the study, conducted the literature review, developed the theoretical framework, and wrote the manuscript.

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