IJOLAE
Indonesian Journal on Learning and Advanced Education
http://journals.ums.ac.id/index.php/ijolae

AI-Supported Outdoor Biology Learning: A Review of Opportunities, Challenges, and Pedagogical Tensions

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DOI: 10.23917/ijolae.v8i2.16264
Received: February 13th, 2026. Revised: April 28th, 2026. Accepted: May 4th, 2026
Available Online: May 25th, 2026. Published Regularly: May, 2026

Abstract

The study aims to present a global overview of how the application of artificial intelligence (AI) has been integrated into outdoor biology learning in secondary schools over the past decade (2015-2025). The main objective is to identify trends around the world, point out specific challenges and opportunities, and understand the pedagogical tensions arising from the use of AI in outdoor education, creating research gaps for future cognate research. To achieve this, a systematic review (following PRISMA guidelines) of peer-reviewed articles from Scopus, Web of Science, and Google Scholar was conducted. We searched for studies discussing AI, outdoor learning, and biology education. The findings reveal a sharp increase in relevant research publication since 2020. Early adoption is strongest in the East Asian region, followed by Europe, North America, and Oceania. Common AI tools, such as computer vision, AR-based species identifiers, and intelligent tutoring systems, have notably improved students' ecological engagement, conceptual understanding, and inquiry skills. Despite progress, significant gaps remain high-income regions benefit from strong digital infrastructure, whereas low- and middle-income countries face barriers like limited internet connectivity, inadequate devices, and teachers' lack of AI literacy. Pedagogical tensions also emerge regarding the balance between authentic nature engagement and AI-mediated guidance aligned with curricular goals. This review highlights emerging global trends and gaps in AI-powered outdoor biology learning, laying a foundation for equitable implementation from a pedagogical perspective, emphasizing the need for targeted teacher professional development, context-sensitive design, and future research on long-term impacts and cross-cultural differences.

Keywords: artificial intelligence in education, educational technology integration, AI-supported learning environments, digital learning ecosystems, advanced machine learning, instructional design innovation

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1. Introduction

Many studies state that learning biology in outdoor settings contributes to increased student engagement, critical thinking, and knowledge retention (Schilhab, 2021; Herodotou et al., 2019). This premise is reinforced by other findings that learning biology outside the classroom can provide more experience in terms of sensory and contextual value, thereby improving cognitive and affective outcomes (Rivet & Krajcik, 2007; Garner et al., 2009). Meanwhile, advances in AI are changing the map of STEM education, it shows that Learning can be more personalized and able to make abstract concepts more real (Liu-Galvin et al., 2025; Vries & Bakal, 2021).

In biology education, AI integration helps visualize abstract processes and provides guided inquiry for novice students at the primary or secondary levels (Pedersen et al., 2018; Patel et al., 2024). Cheung et al. (2024) states that the integration of AI in Learning such as exploring complex biological phenomena, ranging from automated, personalized virtual scientific investigations, to generative AI tools can open up a new path of the Education roadmap for students. These applications of AI, especially those rooted in constructivist theory, facilitate active exploration and collaborative learning, in harmony with the involvement of high order thinking skills as described by Bloom's taxonomy (Kesgin, 2025).

Therefore, AI integration not only supports conceptual learning but also raises important considerations in improving epistemic accuracy in science education (Kesgin, 2025). Given these advances, how important it is to understand how artificial intelligence is explicitly integrated into biology learning especially outdoors, especially in secondary education. However, when digital technology is incorporated into the outdoor context, a new question arises: (1) How do AI tools fit into outdoor and ecological pedagogy? (2) What pedagogical or technical problems arise? (3) Is there a conflict between nature-based learning objectives and the use of technology?

The purpose of this review was to discover the various artificial intelligence technologies used, to create a summary of the benefits and drawbacks of the use of AI, and to investigate activities that have the potential to give rise to pedagogical conflicts, as well as how to balance the technology with conventional outdoor pedagogy.

To ensure a transparent and replicable process, this review follows PRISMA guidelines. In the following, the Figure 1 provides an explanation of the methodology (search and selection process), as well as a structured synthesis of the findings regarding all the opportunities, difficulties, and pedagogical tensions discussed in the literature (AlMasri, 2024; Kesgin, 2025).

2. Literature Review

a. Artificial Intelligence in Education.

Artificial intelligence has developed rapidly in the world of education. It has evolved from theoretical models to practical applications, and the result is an improvement in student learning experience and administrative efficiency (Morić et al., 2024). With this integration, according to Kavitha & Joshith, (2024) education can be personalized, teaching is better, and new approaches to student engagement through various artificial intelligence technologies, such as machine learning, robotics, and chatbots. These technologies enable customized learning paths, adaptive instructional content, and predictive modeling of student performance.

This results in a more customized and effective educational experience. AI can influence science education by changing instructional methods, assessment strategies, and administrative procedures. This directly affects students' learning outcomes and perceptions. Additionally, AI tools could encourage personalized learning by accommodating students' unique needs and providing tailored feedback, which is an increasingly sought-after skill in STEM education (Li et al., 2025). This personalized method supports a wide range of learning styles and meets different stages in which students acquire new knowledge, especially in complex scientific fields (Kesgin, 2025).

To maximize the sustainable development of AI, which includes both generative and pre-generative AI, a broad perspective is needed. It also needs to address the ethical issues and consequences associated with these advances in education (Almasri, 2024). Despite these advances, many previous reviews often provided descriptive rather than predictive analysis, offered limited perspective for future research trajectories, or combined various methodologies, such as predictive and bibliometric modeling, to examine past trends and goals (Kesgin, 2025). As a result, to address these differences, a thorough analysis is required. This analysis should concentrate on how various AI paradigms, including the latest generative AI models, affect pedagogical frameworks and educational outcomes in outdoor biology learning environments.

b. Outdoor Biology Learning

Outdoor biology learning, also known as experiential learning, uses the natural environment as a dynamic classroom environment, allowing students to engage directly with environmental ideas and encourage environmental stewardship. This method of education puts students into the real world. Through hands-on observation and exploration, this method helps students understand and maintain deeper biological principles (Bruschi et al., 2024).

The outdoor learning is also essential for fostering literacy about the environment and sense of connection with nature, which may be difficult to achieve only in a traditional classroom setting. By incorporating artificial intelligence into these outdoor conditions, there is a tremendous opportunity to improve observation, data collection, and analytical capabilities (Morić et al., 2024). It enhances the learning process of biological experiences. Additionally, AI can help students find patterns and come to conclusions that may be difficult to reach with traditional techniques. For example, AI-powered tools can help in species identification, environmental monitoring, and real-time data visualization. This will change the way students interact and interpret the outdoor learning experience.

The integration process not only enhances scientific understanding but also enhances a sense of environmental responsibility and critical thinking about environmental issues (Taiye et al., 2024). Putting AI into outdoor biology learning has pedagogical consequences that have not been widely discussed, especially about student autonomy and data collection ethics. Therefore, a timely, systematic review is needed to synthesize the current literature, find gaps, and create research schedules for artificial intelligence-powered outdoor biology learning.

c. The Intersection of AI and Outdoor Biology Learning

However, the convergence of artificial intelligence (AI) with outdoor biology learning necessitates a substantial pedagogical shift. On the one hand, it presents novel opportunities to enhance student engagement and scientific inquiry by leveraging the interplay between technology and the natural environment. This enables the development of engaging and interactive learning experiences where artificial intelligence tools can offer hands-on feedback, tailor learning pathways, and facilitate data-driven inquiry in practical settings (Handziko & Suryadarma, 2021).

For instance, artificial intelligence can simulate environmental changes before students begin their fieldwork. On the other hand, virtual reality allows students to visit inaccessible places, sparking their curiosity and encouraging them to connect with nature (Calzada et al., 2025). By integrating advanced computing capabilities with the advantages of experiential learning, this fusion facilitates the continuous acquisition and analysis of in situ data, thereby enhancing environmental comprehension and scientific literacy (Calzada et al., 2025).

Generating hypotheses, designing experiments, and interpreting vast ecological data sets collected during outdoor biology research is now becoming possible with AI, especially through advanced machine learning algorithms (Erduran & Levrini, 2024). In the context of secondary education, this development holds significant importance as it enables students to interact with intricate biological phenomena through AI-driven tools that facilitate the design of their learning and critical thinking processes. These tools assist in achieving a harmonious balance between technological mediation and direct sensory engagement.

Nevertheless, the integration of AI into outdoor biology learning has been associated with pedagogical challenges, including the potential for excessive reliance on AI rather than the pursuit of a comprehensive understanding of biology (Lin & Liu, 2022). Therefore, to ensure responsible and practical integration, careful evaluation is needed to consider ethical issues such as data privacy, mitigation of algorithmic bias, and anticipation of the possibility of AI influencing students' understanding of nature, so that the presence of teachers is still indispensable to moderate these potential drawbacks (Almasri, 2024).

d. Pedagogical Tensions in Digital Learning Environments

The integration of digital technologies, particularly artificial intelligence (AI), into educational practices presents a multifaceted landscape of opportunities and challenges. Consequently, a comprehensive examination of pedagogical tensions is imperative (Bruschi et al., 2024). The research endeavors to explore strategies for harmonizing the utilization of AI capabilities to provide personalized instruction while preserving the nuanced human teaching elements. This approach is crucial for fostering critical thinking and socio-emotional development (Calzada et al., 2025).

Furthermore, fundamental learning science research is often neglected during the design of AI tools, leading to a disparity between technological sophistication and pedagogical alignment. This misalignment impedes the seamless integration of AI into the curriculum (Sajja et al., 2023). Although the demands for data-driven insights seem stringent, they risk instrumentalizing technology and ignoring the complexity of the educational process (Snee et al., 2016). This entails a thorough examination of how AI can be incorporated into the current pedagogical framework without diminishing the value of organic learning experiences and direct human interaction (Wei et al., 2025). In addition, the ethical consequences of AI, such as concerns about data privacy, algorithmic bias, and the possibility of a reduction in human interaction, pose serious pedagogical issues that must be carefully considered in a digital learning environment (Zimmerman et al., 2023). This is particularly significant because artificial intelligence (AI) technology frequently lacks a comprehensive comprehension of the human learning process and is not grounded in sound pedagogical principles.

Consequently, this can exacerbate educational disparities (Trevisan et al., 2024). In addition, the rapid deployment of digital tools in education, especially in the context of emergency distance education, has raised awareness of the importance of re-evaluating the role of technology. This requires a more conscious and capable integration, which takes into account the well-being of students and pedagogical principles (Bruschi et al., 2024). This shows how important it is to work together in a collaborative approach where educators, researchers, developers, and AI work together to ensure that technological advances are based on educational theory and practice rather than focusing solely on technological capabilities (Sajja et al., 2025).

3. Method

This study conducted comprehensive searches of multiple academic databases (e.g., Scopus, Web of Science, ERIC, IEEE Xplore, and education journals) for peer-reviewed articles published 2015–2025. Search queries combined terms for AI (e.g., "artificial intelligence," "machine learning," "augmented reality," "smart device," etc.), outdoor learning (e.g., "outdoor education," "field trip," "nature-based learning"), and biology education (e.g., "biology," "life science," "ecology"). Boolean operators and truncations were applied to capture variations (for example: ("artificial intelligence" OR "augmented reality" OR "VR" OR "smartphone") AND ("outdoor learning" OR "field trip" OR "nature education") AND ("biology" OR "life science" OR "environmental science") AND ("secondary" OR "high school" OR "middle school")). We also reviewed references of key articles and relevant systematic reviews (e.g., studies on AR in environmental education) to identify additional sources.

An example of a similar search strategy is found in Situmorang et al. (2024), who used targeted terms in Scopus to retrieve literature on technology in biology education. The search process and results at each stage will be summarized in a PRISMA flow diagram in Figure 1.

Following the search process, studies were eligible for inclusion if they met the following criteria. First, only peer-reviewed journal articles published between January 2015 and December 2025 were considered to ensure the review reflects contemporary developments in artificial intelligence and educational technology. Second, studies had to involve learners in formal secondary education, operationalized as students aged approximately 12–18 years, consistent with international definitions of lower and upper secondary schooling. Third, the research needed to be situated within biology, life science, ecology, or environmental science learning contexts. Fourth, the learning activities had to take place in outdoor, field-based, or nature-based environments, including school-organized fieldwork, ecological surveys, or structured outdoor inquiry activities. Fifth, the studies were required to report the use of artificial intelligence–based technologies, defined as systems incorporating machine learning, computer vision, intelligent algorithms, or adaptive decision-making components. Finally, only empirical studies employing quantitative, qualitative, or mixed-methods research designs were included to ensure evidence-based synthesis.

Nevertheless, studies were excluded if they focused exclusively on primary education, as differences in developmental stages, pedagogical aims, and forms of technological mediation would introduce conceptual heterogeneity. Research conducted solely in higher education was also excluded due to its distinct epistemic demands, levels of learner autonomy, and disciplinary specialization. Studies situated in informal or non-formal learning contexts such as citizen science programs, museum initiatives, or extracurricular nature clubs were omitted unless they were clearly aligned with formal curricular objectives. In addition, conceptual papers, editorials, systematic reviews, dissertations, and book chapters, were excluded to maintain consistency in study design and peer-review standards. Finally, only studies published in English were included to ensure feasibility and consistency in analysis.

4. Results and Discussion

a. Study Selection and Characteristics

This section will report the search outcome and a summary of the included studies. The selection was anticipated studies from a diverse range of countries, reflecting the global interest in environmental education. For example, previous research on environmental education has highlighted studies from various regions, including the US, Asia, and Australia, suggesting a broad geographical scope in the field (Kurtuluş & TATAR, 2021; Ninomiya-Lim et al., 2017).

Similarly, the review observes considerable geographical diversity in the literature concerning AI-supported outdoor biology learning within secondary education. Table 1 tabulates key characteristics of the included studies. The descriptors encompass country/region, year of publication, sample sizes, subject matter, and specific AI modality or tool used.

Preliminary scoping suggests that mixed-methods and experimental designs are frequently utilized in this area. This review also reports the distribution of these methodologies; for instance, prior reviews of mobile technology in outdoor learning have indicated a prevalence of mixed-method designs (approximately 45.5%), with qualitative and quantitative approaches constituting about 22.7% and 31.8% of studies, respectively (Kraalingen, 2021). This PRISMA systematic approach ensures a comprehensive overview of the research landscape as in Figure 2.

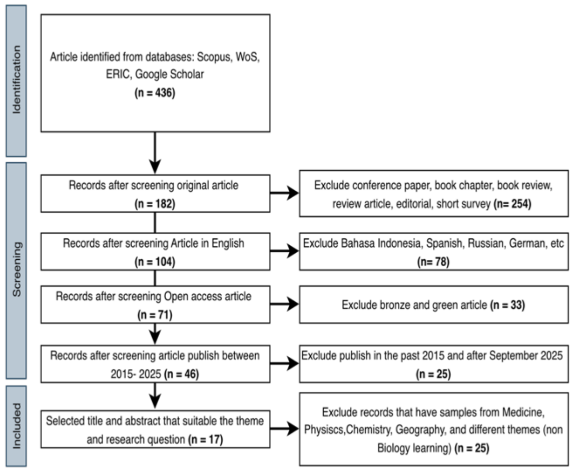

Figure 2. Implementation of PRISMA flow

b. Artificial Intelligence Tools and Activities

This subsection explores the types of AI-powered technologies being applied. Examples include: Augmented Reality mobile applications that overlay information on natural objects (Antoniadi, 2023; Bogosian et al., 2025; Cederqvist & Williams, 2023); Virtual Reality ecosystem simulation (Chandler et al., 2021; Cho & Park, 2023); Intelligent Tutoring System on tablets for field measurements (Cotič et al., 2020; Tong, 2017); Sensor and Robotics Platforms for Collecting Biological Data (Kelley & Grünbaum, 2018; Velasco-Montero et al., 2024); and AI-based Mobile Apps for species identification (Hognogi et al., 2023; Mäder et al., 2021; Schermer & Hogeweg, 2018). Summarizing how this tool is used, for example AR, can "make symbols and timelines visible" in outdoor settings (Arvola et al., 2021; Chin et al., 2020), or AI applications can assist students in identifying and learning about flora and fauna in situ (Chozas et al., 2023; Hognogi et al., 2023). Where available, it then notes the theoretical framework that guides the intervention.

This section also sets the stage for analyzing what opportunities these tools offer and what challenges arise. It also detailing how these AI applications facilitate specific learning activities, such as real-time data collection (Besson et al., 2022; Porter et al., 2005; Rathoure & Rathaur, 2024), interactive simulations (Calzada et al., 2025), and personalized feedback (Mnguni, 2024; Mulenga & Shilongo, 2024), in the context of outdoor biology. This includes exploring how AI integrates with various learning modalities, such as gamification (Bónus et al., 2024; Ferreira et al., 2025; Gupta et al., 2024; Lee et al., 2021) and inquiry-based learning (Bónus et al., 2024; Zhang et al., 2023), to increase student engagement (Errabo et al., 2024; Ng et al., 2024) and a deeper understanding of biological concept.

Table 1. Key Characteristics of the Included Studies

Country/ region	Year of publication	Sample sizes	Subject matter	Specific AI modality or tool used
Australia	2021 (Chandler et al., 2021)	27 participants	Learning about ecosystems, biology, sustainability	Immersive Virtual Reality
Austria (Europe)	2023 (Schmidthaler et al., 2023)	35 teachers	Teachers' perceptions of mobile AR in biology education	Mobile AR applications
Germany (Europe)	2022 (Bowler et al., 2022)	1,645 individuals	Citizen science, species observation, data variability, motivation	Citizen science data platforms
Germany	2025 (Mulders et al., 2025)	Not specified, "learners"	Biodiversity, Amazon rainforest environment	Virtual Reality learning application ("On Biodiversity's Tracks")
Germany (Europe)	2024 (Rzanny et al., 2024)	Not specified, "professional ecologists and plant enthusiasts"	Plant identification accuracy	Plant identification apps (automated image recognition)
Latvia (Europe)	2023 (Žaimis, 2023)	Not specified	Environmental protection in education, data acquisition, and virtual environment deployment	Self-propelled autonomous aquatic robot
Portugal (Europe)	2017 (Pombo et al., 2017)	Not specified, "students"	Enhanced engagement, motivation, cognitive load reduction	Augmented Reality
USA	2018 (Kelley & Grünbaum, 2018)	Elementary, middle, and high school students	Monitoring temperatures in classrooms/creeks, ecological relationships, eelgrass restoration	Environmental sensors
USA	2023 (Bodzin et al., 2023)	139 participants	VR experience, engagement, and learning about the local environment	Desktop Virtual Reality field trip (dVFT)
USA	2024 (Khan et al., 2024)	Not specified, "participants"	Citizen science, plant and animal species identification	SmartCS mobile app

Country/ region	Year of publication	Sample sizes	Subject matter	Specific AI modality or tool used
USA	2021 (Chakarov et al., 2021)	Middle school students	Inquiry science instruction, data collection/analysis/display	Physical computing system (Data Sensor Hub with BBC micro: bit and sensors)
USA	2024 (Wall et al., 2024)	Not specified	Ecosystem monitoring, research, and management	EarthRanger (open-source platform)
Malaysia (Asia)	2024 (Ying et al., 2024)	Secondary schools	Environmental citizenship competences	Virtual Reality module
Japan (Asia)	2021 (Sun et al., 2021)	Not specified, "participants"	Species identification, ecological data collection	Smartphone (deep learning)
Japan (Asia)	2024 (Atsumi et al., 2024)	Not specified, "citizen scientists"	Biodiversity monitoring, species distribution	Smartphone-driven community-sourced data
Taiwan (Asia)	2021 (Chiang, 2021)	Not specified, "students"	Environmental education, immersion, empathy, behavior change	Virtual Reality games
Taiwan (Asia)	2016 (Huang et al., 2016)	Not specified	Ecological learning, cognitive outcomes, reduced cognitive load	Augmented Reality

c. Opportuities (Benefits) for Outtdooor Biology Learning

This section explores the various enhancements and pedagogical benefits of integrating AI into outdoor biology education, focusing on how these technologies foster a deeper understanding and greater engagement among secondary school students. Enhancements and pedagogical benefits of AI-supported outdoor biology learning include personalized learning pathways, enhanced data analysis capabilities, and immersive experiential learning opportunities (Mann et al., 2022). The opportunities are listed as Table 2 follows.

Table 2. Opportunities (Benefits) for Outdoor Biology Learning

Opportunity Category	Description
Authenticated Learning Context	AI-mediated outdoor learning authenticates the learning context, as teachers use Augmented Reality to establish local places as the foundation for lessons, thereby enhancing real-world relevance (Arvola et al., 2021).
Enhanced Engagement and Motivation	Students frequently exhibit increased curiosity, attentiveness, enjoyment, and motivation when technology is integrated into outdoor learning environments (Coppola et al., 2021). For example, AR field trips have been shown to boost student interest and self-regulation in science learning (Pombo & Rodrigues, 2024).
Contextualized Learning	AI tools effectively bridge outdoor observations with classroom content, with AR particularly facilitating conceptualization by connecting outdoor and indoor learning experiences (Arvola et al., 2021). Consequently, detailed instructional material can be digitally integrated into particular sites, which serves to channel learners' focus and deliver relevant, situation-aware teaching at the precise moment of need (Kamarainen et al., 2013).
Improved Understanding and Achievement	The application of artificial intelligence tools in outdoor settings has proven to be effective in biology learning. Evidence from a number of quantitative studies shows a significant improvement in conceptual mastery, accompanied by better

Opportunity Category	Description
	cognitive achievement and a lighter mental load (Huang et al., 2016; Zimmerman et al., 2023).
Collaboration and Inquiry Skills	Digital technologies may successfully scaffold group work and data collecting, promoting active, inquiry-based learning, which is consistent with the goals of outdoor education (Porte et al., 2024).
Affective and 21st-century Skills	AI expands opportunities for student participation in environmental education. AR-driven field guides that ask location-specific questions, as well as intelligent data-logging technologies that connect students to real-time ecosystem data, are examples of how outdoor biology learning may be enhanced (Lim et al., 2024).
Expanded Educational Approaches	AI broadens options for student engagement in environmental education. Examples include AR-driven field guides providing location-specific questions and intelligent data-logging technologies that connect students with real-time ecosystem data, therefore magnifying the benefits of outdoor biology study (Tabuenca et al., 2023).

d. Challenges

Despite the considerable pedagogical potential of AI-supported outdoor biology learning, the implementation of these technologies is accompanied by multiple challenges that emerge across technical, pedagogical, infrastructural, and socio-economic dimensions. Existing studies consistently report that the integration of AI into outdoor environments requires not only technological readiness but also adaptive instructional strategies and institutional support. Moreover, the dynamic and unpredictable nature of outdoor learning environments often amplifies operational difficulties that are less visible in conventional classroom settings (Mäder et al., 2021). These challenges highlight the importance of examining how educators, learners, and institutions negotiate the practical constraints associated with AI-enhanced outdoor learning ecosystems.

This subsection details recurring difficulties reported by authors as Table 3 below.

Table 3. Challenges in outdoor learning enhanced by AI

Challenge Category	Description	Specific Examples / Details
Technical and Logistical	Operational difficulties with technology and connectivity in outdoor settings.	Device malfunctions, limited Internet access at remote sites, and equipment maintenance (Gal, 2019; Kraalingen, 2021; Ma et al., 2024).
Pedagogical	Educators' difficulties in adapting to and utilizing new technologies.	Teachers' learning curve with new technologies, a shortage of training or support (Kraalingen, 2021).
Pedagogical	Challenges in managing diverse student groups with varying technological aptitudes.	Managing mixed student groups with varying levels of tech proficiency (Kraalingen, 2021).
Pedagogical	Discrepancies between digital activities, curriculum objectives, and traditional outdoor pedagogy.	Teachers faced two primary hurdles: first, effectively using the landscape for instruction and aligning digital tasks with the curriculum, which created a conflict between tech-driven activities and traditional outdoor pedagogy; and second, managing the practicalities of

Challenge Category	Description	Specific Examples / Details
		structuring the AR experience, organizing students, and ensuring content directly supported learning goals (Arvola et al., 2021).
Content Preparation	Difficulties in creating or selecting appropriate digital content and integrating it effectively.	Deciding what AR/AI content to create or select, and when to integrate it during a field lesson (Arvola et al., 2021).
Research Gap	Limited detailed examination and reporting of practical obstacles in the existing literature.	Only a few studies have deeply examined obstacles; for instance, Arvola et al. (2021) specifically listed challenges; in Arici et al.'s review, only 2 of 20 papers reported on AR challenges, highlighting a gap in the literature.
Broader Operational	General logistical and safety concerns that are frequently mentioned but rarely quantified.	Safety and classroom management.
Societal	Disparities in access to advanced AI tools among different educational institutions.	Not all schools can afford advanced AI tools, potentially widening inequalities (Mangubat & Mangubat, 2025).

e. Pedagogical Tensions

Beyond practical and technical challenges, the integration of artificial intelligence into outdoor biology learning also generates a series of pedagogical tensions that influence how learning experiences are designed and interpreted. These tensions emerge because outdoor education traditionally emphasizes authentic, experiential, and student-centered interaction with nature, whereas AI technologies often introduce structured guidance, algorithmic mediation, and standardized learning pathways (Bahmani et al., 2025). As a result, educators are required to continuously negotiate the balance between technological enhancement and the preservation of meaningful ecological experiences. Understanding these tensions is essential for ensuring that AI functions as a pedagogical support system rather than a replacement for direct engagement with the natural environment.

The tensions as conflicts or dilemmas emerging from AI integration is identified by some key tensions as Table 4 below.

Table 4. Pedagogical tensions emerging from AI integration

Pedagogical Tension	Description
Authenticity vs. Technology Mediation	Outdoor education values direct sensory experience, yet AI tools introduce virtual elements. Teachers face the tension of enhancing reality without overshadowing it, balancing the 'authentic place' of learning with digital overlays. This involves balancing the reductionist nature of AI models with the inherent variability of natural systems (Calzada et al., 2025), and ensuring technology is seamlessly integrated to enrich learning contexts without creating a barrier (Kraalingen, 2021; Rosenbaum et al., 2006).
Teacher Control vs. Student Autonomy	AI can guide students through tasks, but outdoor learning often emphasizes student-led exploration. Instructors must decide how much to let algorithms direct the learning path. Personalized instruction via AI can inadvertently isolate learners from collaborative social dynamics (Mangubat & Mangubat, 2025) and hinder the

Pedagogical Tension	Description
	development of collective problem-solving skills and appreciation for diverse perspectives (Calzada et al., 2025). This also involves the broader tension between AI systems guiding individual trajectories and preserving the student's own initiative (Donskikh, 2019; Goodwin, 2022), as well as the question of whether teachers or AI agents should create learning activities (Alm, 2024; Gardner & Elliott, 2014).
Standardization vs. Contextualization	Curricula set standardized objectives, but outdoor learning is inherently contextual and local. Integrating generic AI content across diverse outdoor sites creates tension with educational standards. This involves a trade-off between standardized learning outcome supported by AI assessments and the pedagogical emphasis on localized, context-dependent inquiry inherent in outdoor biology education, which often resists universal metrics (Almasri, 2024).a This highlights the paradox of personalizing while standardizing through AI assessments (Ferreira et al., 2023), and the assumption that AI's utility is consistent across varied contexts (Porayska-Pomsta, 2024).
Technical Complexity vs. Curriculum Simplicity	There is a risk of cognitive overload if students focus more on operating an AI system than on biology content. Technical issues and the inherent complexity of AI applications can distract from learning goals, impacting students' mental capacities (Dauer & Dauer, 2016) and potentially compromising depth of engagement with content (Stadler et al., 2024).

The pedagogical tensions our analysis revealed resonate with broader discussions in digital education. Scholars like Smith have observed that new technologies often "entangle" established teaching methods a dynamic clearly reflected in our data, where educators described technology as a source of both potential and complication. For example, the documented struggle to seamlessly weave augmented reality into local settings Calzada et al., (2025) exemplifies the core tension between Authenticity and Technological Mediation. The objective is to use digital tools to augment not replace the immediate, sensory experience of the natural world (van Kraalingen, 2023; Rosenbaum et al., 2006).

A key insight from this tension is that while AI tools can personalize learning, their integration must be deliberate. Without careful design, there is a risk of oversimplifying intricate ecological systems into static digital models, which may ultimately foster a fragmented or incomplete understanding of environmental processes (Adil, 2025).

f. Synthesizing Opportunities and Challenges

The integration of Artificial Intelligence (AI) into outdoor biology learning represents a paradigmatic transformation in science education, particularly at the secondary education level. The synthesis of opportunities and challenges indicates that AI is not merely a supporting tool but acts as an epistemic agent reshaping how students understand biological phenomena in contextualized and data-driven ways (Nachtigall et al., 2022).

On one hand, AI enhances student engagement, enables personalized learning pathways, and strengthens inquiry-based learning through real-time data analysis and visualization. On the other hand, significant barriers remain, including infrastructural limitations, digital inequality, and pedagogical challenges in maintaining a balance between authentic outdoor experiences and technology-mediated learning.

Table 5. Synthesis of Opportunities and Challenges in AI-Supported Outdoor Biology Learning

Dimension	Opportunities	Challenges
Pedagogical	Contextualized learning, inquiry-based approaches, personalization	Curriculum misalignment, over-reliance on technology
Technological	AR, VR, computer vision, real-time sensors	Connectivity limitations, device constraints
Cognitive	Improved conceptual understanding, data literacy	Cognitive overload
Social	Collaboration and citizen science	Digital divide
Environmental	Enhanced ecological awareness	Reduced authenticity of direct experience

This table illustrates that opportunities and challenges in AI-supported outdoor biology learning are inherently dualistic and interconnected. From a pedagogical perspective, AI reinforces constructivist approaches by providing scaffolding, adaptive feedback, and data-driven insights, which have been shown to improve conceptual understanding (Huang et al., 2016). However, these advantages often conflict with standardized curricula, creating tension between flexible AI-supported learning and rigid educational frameworks.

Technologically, innovations such as augmented reality (AR) and environmental sensors enrich experiential learning. Nevertheless, limited connectivity in outdoor environments remains a critical bottleneck (Kraalingen, 2021). This issue is exacerbated by disparities in technological access between high-income and low-income regions.

From a cognitive standpoint, AI reduces cognitive load through visualization and automation of data processing. However, poorly designed systems may instead increase cognitive burden due to technological complexity (Koć-Januchta et al., 2022). Socially and environmentally, AI promotes collaboration through citizen science initiatives but risks diminishing authentic interactions with nature (Calzada et al., 2025). Thus, careful pedagogical design is essential to balance these competing dimensions.

Table 6. Integrative Model of Opportunities–Challenges in AI Outdoor Learning

Layer	Description	Implication
Technology	AI tools (AR, VR, ML)	Enhancing vs. disrupting learning
Pedagogy	Inquiry & experiential learning	Requires alignment
Infrastructure	Devices & connectivity	Equity concerns
Human Factor	Teacher competence	Critical success factor
Outcome	Learning achievement	Dependent on integration quality

This integrative model demonstrates that successful implementation of AI in outdoor biology learning depends on the interaction among multiple layers rather than technology alone. The technological layer provides affordances such as visualization and analytics; however, without appropriate pedagogical alignment, these tools may become distractions rather than facilitators.

The pedagogical layer ensures that AI supports experiential and inquiry-based learning rather than replacing direct engagement with nature. This requires teachers to extend their pedagogical content knowledge toward technological pedagogical content knowledge (TPACK) (Santhosh et al., 2024).

Infrastructure remains a major limiting factor, particularly in developing regions, where lack of devices and connectivity may widen the digital divide (Mangubat & Mangubat, 2025). The human factor highlights the central role of teachers as orchestrators of learning. Without adequate training, even advanced technologies cannot be effectively utilized.

Ultimately, learning outcomes are contingent upon the quality of integration across these layers. This model emphasizes that AI should be viewed as part of a broader educational ecosystem rather than a standalone solution.

g. Coping the Challenges

While the integration of artificial intelligence (AI) into outdoor biology learning presents significant pedagogical opportunities, its practical implementation is accompanied by a range of complex and interrelated challenges that must be addressed systematically. These challenges extend beyond purely technical issues and encompass pedagogical alignment, teacher readiness, infrastructural constraints, and broader socio-economic disparities (Almasri, 2024). As identified in the preceding synthesis, the success of AI-supported outdoor learning is highly contingent upon the ability of educators and institutions to navigate these constraints without compromising the authenticity of experiential learning.

Importantly, coping with these challenges requires a multi-layered strategy that integrates technological adaptation, instructional design innovation, and institutional policy support. Rather than viewing these barriers as limitations, they should be reframed as design considerations that inform the development of more resilient and context-sensitive learning ecosystems. For instance, addressing connectivity issues in outdoor environments necessitates not only technical solutions such as offline-capable systems but also pedagogical adjustments that optimize learning activities under constrained conditions (Zeuss et al., 2023). Similarly, the issue of teacher competence highlights the urgent need for professional development models that go beyond technical training to include pedagogical integration and reflective practice.

Furthermore, equity considerations play a critical role in shaping how these challenges are addressed. Without deliberate intervention, the adoption of AI technologies risks exacerbating existing educational inequalities, particularly between well-resourced and under-resourced institutions (Schmidt & Steinecke, 2020). Therefore, strategies for coping with challenges must be inclusive, scalable, and adaptable to diverse educational contexts. The following section presents a structured overview of key strategies and frameworks designed to mitigate these challenges and support sustainable implementation of AI in outdoor biology learning.

Table 7. Strategies for Addressing Challenges in AI-Supported Outdoor Learning

Challenge	Strategy
Limited connectivity	Offline mode, edge computing
Access inequality	Device subsidies, shared devices
Teacher competence	TPACK-based training
Pedagogical misalignment	Blended outdoor learning design
Cognitive overload	Simplified interfaces and scaffolding

The coping strategies identified indicate that technical solutions alone are insufficient.

For instance, offline modes and edge computing provide practical solutions for connectivity issues in outdoor environments (Ma et al., 2024), but these must be complemented by pedagogically sound instructional design.

Access inequality can be mitigated through institutional policies such as device subsidies and shared device models, ensuring equitable participation. From a pedagogical perspective, blended learning approaches combining direct exploration with AI-supported inquiry have proven effective in maintaining balance between technology and authentic experience (Arvola et al., 2021).

Teacher training is critical, particularly through TPACK frameworks that integrate technological, pedagogical, and content knowledge. Furthermore, cognitive overload can be minimized through user-friendly interface design and adaptive scaffolding, ensuring that students remain focused on biological concepts rather than technological complexity.

Table 8. Adaptive Implementation Framework for AI Outdoor Learning

Component	Description
Preparation	Content and device planning
Execution	Blended exploration
Support	Real-time AI assistance
Reflection	Discussion and evaluation
Iteration	Continuous improvement

This framework emphasizes a cyclical and adaptive approach to implementing AI in outdoor learning. During the preparation phase, teachers design context-relevant activities and ensure technological readiness. The execution phase integrates direct exploration with selective AI support. The support phase allows AI to provide real-time feedback while remaining under teacher supervision (Fayzullina et al., 2023). Reflection is critical for consolidating learning, enabling students to articulate their findings through discussion and analysis.

The iteration phase supports continuous improvement based on prior evaluations, aligning with design-based research principles. This framework ensures that AI integration remains pedagogically grounded and context-sensitive.

h. Comparison with Existing Literature

To situate the findings of this review within the broader academic discourse, it is essential to conduct a comparative analysis with existing literature on artificial intelligence in education, particularly within STEM and environmental learning contexts. Over the past decade, a growing body of research has examined the impact of AI technologies on student learning outcomes, engagement, and instructional practices (Mnguni, 2024). However, much of this literature has been concentrated in formal classroom settings or generalized STEM domains, with relatively limited attention given to the unique characteristics of outdoor biology learning environments.

This distinction is critical, as outdoor learning introduces additional layers of complexity, including environmental variability, logistical constraints, and the need for direct sensory engagement with natural phenomena. Consequently, the integration of AI in such contexts cannot be fully understood through frameworks developed for traditional classroom settings (Satria WD et al., 2025). By comparing the findings of this study with prior research, it becomes possible to identify both convergences and divergences in terms of theoretical perspectives, methodological approaches, and empirical outcomes (Li et al., 2025).

Moreover, this comparative analysis serves to highlight the specific contributions and novelties of the present study, particularly in its emphasis on pedagogical tensions, contextual implementation challenges, and the interplay between technological mediation and authentic learning experiences. It also enables the identification of critical research gaps that persist across the literature, such as the lack of longitudinal studies, insufficient attention to ethical considerations, and limited exploration of cross-cultural variations (Koć-Januchta et al., 2022; Saputri et al., 2025). Through this lens, the following section provides a structured comparison that not only validates the current findings but also positions them within a broader trajectory of ongoing research in AI-supported education.

Table 9. Comparison with Existing Literature

Aspect	Existing Literature	This Study
Focus	General AI in STEM	AI in outdoor biology learning
Methodology	Predominantly quantitative	Mixed-method dominant
Findings	Improved learning outcomes	Pedagogical tensions identified
Limitations	Lack of contextual analysis	More context-sensitive

Previous literature predominantly focuses on AI applications in general STEM or classroom-based settings (Li et al., 2025). This study extends the scope by situating AI within outdoor biology learning, which involves higher contextual complexity.

The dominance of mixed-method approaches provides a more comprehensive understanding compared to purely quantitative studies. While quantitative data measure learning outcomes, qualitative insights reveal the dynamics of implementation and learner experiences.

A key contribution of this study is the identification of pedagogical tensions, which are rarely addressed in prior research. This highlights that AI integration is not solely about effectiveness but also about balancing technological affordances with pedagogical values.

Table 10. Research Gaps and Future Directions

Area	Gap	Recommendation
Longitudinal studies	Limited	Conduct long-term studies
Ethical issues	Underexplored	Develop AI ethics frameworks
Context diversity	Limited	Cross-cultural studies
Teacher readiness	Insufficient data	Develop training models

Despite rapid advancements, significant research gaps remain. Longitudinal studies are scarce, limiting understanding of long-term impacts of AI on learning outcomes (Wu et al., 2025). Ethical concerns such as data privacy and algorithmic bias are also underexplored, despite their importance in educational contexts (Almasri, 2024).

Additionally, most studies are conducted in high-income countries, necessitating cross-cultural research to understand diverse implementation contexts. Teacher readiness remains a critical yet under-researched factor, highlighting the need for practical and scalable training models.

i. Implications for Practice and Policy

For teachers trying to bring technology into the outdoors, the key is to start small. Before rolling something out to an entire grade, pilot it with one class or a single field trip group. The most important question to ask is: "What specific learning goal is this tool helping us achieve?" Professional development should move beyond just how to use the device, focusing instead on strategies for weaving it seamlessly into an outdoor lesson plan.

For school and district leaders, this isn't just about buying gadgets. True enablement means investing in the foundation: reliable outdoor connectivity, enough charged devices, and critically policies that ensure access isn't just for well-resourced schools. Equity in opportunity has to be a priority from the start.

Finally, for the people designing these educational technologies, our findings point to one major need: flexibility. Tools shouldn't come as a rigid, one-size-fits-all package. The best ones will be designed for easy localization think augmented reality platforms that let a teacher swap in images and information from their own schoolyard or local park. If the tech can't adapt to the infinite variety of the natural world, it will struggle to find a lasting place in it.

j. Limitations

A principal limitation of this review arises from the considerable heterogeneity in the research designs and outcome measures across the included studies. This diversity precluded a formal meta-analysis, limiting our ability to quantify overall intervention effectiveness (Morimoto & Ponton, 2021). Consequently, our synthesis is necessarily qualitative. While this approach yields valuable contextual understanding, it may constrain the generalizability of specific results.

Further limitations stem from the nature of the evidence. Many studies depend on self-reported data, which introduces potential biases; future work would benefit from incorporating more objective, direct measures of learning (Jatmiko et al., 2023). The predominance of short-term investigations also presents a challenge, as it leaves the long-term effects on knowledge retention, conceptual change, and attitude development largely unexplored.

The rapidly evolving landscape of AI technology itself poses a significant challenge for research, making it difficult to establish durable conclusions as tools and applications continuously advance (Morić et al., 2024). This is compounded by an inconsistent attention to critical ethical dimensions such as data privacy and algorithmic bias within the extant literature. Future investigations must integrate more robust ethical frameworks to address these concerns comprehensively (Calzada et al., 2025).

5. Conclusion

This review comprehensively examined the extant literature on Artificial Intelligence-supported outdoor biology learning, revealing a nascent yet rapidly expanding field characterized by innovative pedagogical approaches and technological integration. Our analysis elucidates significant opportunities for enhanced engagement and personalized learning, alongside persistent challenges in infrastructure, teacher training, and ethical considerations. It underscores the pedagogical tensions inherent in blending authentic outdoor experiences with technologically mediated instruction, particularly concerning the balance between technological utility and the preservation of genuine ecological interaction.

The review also highlights that, despite the potential benefits, a significant portion of the literature does not delve into the nuances of different AI technologies or their specific applications across varied learning contexts. Specifically, there is a clear need for research that differentiates between various AI methodologies, such as machine learning, natural language processing, and computer vision, and explores how each uniquely contributes to or detracts from outdoor biology education, moving beyond generic discussions of "AI".

Looking ahead, several key priorities emerge for future research. First, studies must move beyond measuring short-term engagement and begin to assess the long-term effects of AI tools. Longitudinal research is needed to evaluate how these technologies shape lasting student outcomes and the development of deeper ecological literacy over time.

Concurrently, the ethical dimensions of deploying AI outdoors require urgent scholarly attention. This includes examining critical issues such as data privacy, student consent, and the potential for algorithmic bias, all of which must be addressed to ensure responsible use. Furthermore, the technical reliability of AI systems in educational contexts needs rigorous evaluation. Researchers should focus on mitigating known challenges such as AI "hallucinations," embedded biases, and a lack of contextual relevance to build more trustworthy and pedagogically sound applications. Another essential direction is the study of teacher preparation. Future work should identify the most effective professional development models to empower educators with both the technical competency and the pedagogical insight needed to integrate AI thoughtfully into outdoor curricula.

Finally, a truly comprehensive understanding demands a global perspective. Comparative studies across diverse cultural, socioeconomic, and geographical contexts reveal how factors like access, infrastructure, and local educational values influence implementation and effectiveness. This work should include the development of culturally responsive AI tools that honor indigenous knowledge and local ecological practices, ensuring technology amplifies rather than overrides diverse ways of knowing. Ultimately, the field must strive for a deeper understanding of AI's long-term academic impact, looking past initial gains in efficiency or engagement to assess its enduring contribution to learning.

6. Acknowledgement

The authors would like to express their sincere gratitude to DiktiLitbang PP Muhammadiyah for the generous support provided through the Hibah Riset Nasional Muhammadiyah Batch IX year 2025 (Grant Number: 0259.685/I.3/D/2025). This funding enabled the completion of the research project and facilitated the dissemination of its findings. The authors also acknowledge the institutions and individuals who contributed valuable insights and assistance throughout the study.

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