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How Immersive Digital Technology Learning in Ecology and Environmental Education: A Systematic Literature Review

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Abstract: This study investigates research trends in immersive digital technologies in ecological and environmental education. It also examines how immersive learning environments impact student learning outcomes and engagement across various educational contexts. A systematic literature review was conducted using the PRISMA protocol and the SPIDER framework. Publications were searched for between 2015 and 2025. The data obtained were analyzed descriptively. An initial search of the Scopus database identified 253 publications, and the ERIC database identified 43 publications, of which 26 studies met the inclusion criteria and were selected for in-depth analysis. The results indicate that research interest in immersive digital technologies in ecological and environmental education began in 2019. Most research on immersive digital technologies was conducted in 2025. VOSviewer analysis revealed that the identified keywords were technology, learning, and environmental substance. Among the identified technologies, virtual reality (VR) was the most dominant keyword. Furthermore, the study found that research on virtual reality technologies outnumbered research on augmented reality. Immersive digital technologies are used to enhance learning outcomes across affective, cognitive, behavioral, and engagement domains. This technology helps improve students' affective skills, such as environmental awareness, ecological empathy, positive attitudes toward conservation, and connectedness to nature. Game-based and narrative-based learning contribute to increased affective engagement and learning motivation. In the learning process, immersive digital technology is facilitated by contextual learning designs, such as experiential, inquiry-based, and situated learning. This review shows that immersive digital technologies in ecology and environmental education depend on the learning approach and objectives, enabling these technologies to support learning outcomes such as cognitive, affective, behavioral, and engagement. In addition, learning outcomes are influenced by immersive modality and learning approach.

Keywords: augmented reality, virtual reality, virtual field trips, ecology education, environmental education

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INTRODUCTION

Immersive digital technologies, including virtual reality (VR), augmented reality (AR), and virtual field trips (VFT), have gained significant traction in education (Indayati et al., 2024; Lestari & Rohmani, 2024; Sviridova et al., 2023; Zain et al., 2022). The use of this technology is increasingly recognized for creating interactive learning environments that feature engaging visualizations and are experience-based, enabling students to interact with content/material in a more meaningful, contextual way. (Lampropoulos et al., 2021). This widespread use reflects a shift from traditional learning to technology-based learning and, more specifically, to digital media-supported and multimodal learning. Therefore, immersive digital technology is not just a tool but also a learning medium to improve the quality of learning through simulation, visualization, and contextual interaction (Sedlák et al., 2022; Walkington et al., 2024).

The development of immersive digital technology demonstrates that it is not merely a technological innovation, but also part of a learning transformation. The use of immersive digital technology is becoming increasingly common due to the need for interactive and contextual learning (Lampropoulos et al., 2021; Walkington et al., 2024). Therefore, the relevance of immersive digital technology is becoming increasingly apparent, especially in contextual learning. One area that requires immersive digital technology is ecology and environmental education. In recent years, this connection has become more apparent, as ecology and environmental education demand learning experiences that link abstract scientific concepts to authentic environmental contexts and human-environment interactions.

Ecological and environmental education requires students to master complex concepts such as the relationships between ecosystem components and environmental change (Carmi & Alkaher, 2019; Riva et al., 2023). In many cases, the concepts of ecology and environment are abstract and related to the surrounding environment, so they cannot be explained through theory in class (Bleier, 2023). Therefore, immersive digital technology has the potential to enhance learning experiences and engage students in ecological and environmental issues (Buchanan et al., 2019; Cho & Park, 2023; Mallam et al., 2019). This is very important because ecological and environmental learning often involves dynamic systems, spatial relationships, ecological processes, and environmental changes that are difficult to observe directly through traditional classroom teaching.

Immersive digital technology overcomes the shortcomings of traditional learning and ensures student safety while learning (Marinelli et al., 2023; Pande & Jepsen, 2024). Virtual reality (VR) and augmented reality (AR) are examples of immersive technologies that allow students to explore and interact with simulated environments (Oriti et al., 2023; Walkington et al., 2024). Through this technology, students can learn about ecosystems, objects, and ecology without having to consider safety (Safitri et al., 2025). Compared to conventional learning, which still relies on verbal explanations or static media, immersive technology provides a more interactive, contextual, and safer experience. However, the learning effectiveness of immersive technology is determined not only by the sophistication of the technology but also by the suitability of the learning design and learning objectives, and by the extent to which the technology supports meaningful student interactions.

Immersive digital technologies are particularly relevant to ecology and environmental education because their educational value can be understood not only from a technological perspective but also through their support for learning processes (Ardoin et al., 2020; Vercelloni et al., 2021). Immersive digital technology helps present information in a more concrete, visual, and interactive way (Alene et al., 2023; Walkington et al., 2024). Immersive technology can help reduce the difficulty in processing abstract concepts by allowing students to observe environmental relationships, processes, and phenomena in more meaningful and contextual ways (Fromm et al., 2021; Wang et al., 2020). In addition, this technology does not necessarily increase extraneous cognitive load when the content, interactions, and sensory elements align with the learning objectives (Cavanaugh et al., 2023; Huang et al., 2023).

In addition, ecology and environmental education emphasize active exploration, contextual understanding, and meaningful interaction with real-world issues (Ardoin et al., 2020). Therefore, immersive technology is highly relevant to a student-centered approach where students acquire knowledge through inquiry, experience, and reflection. Furthermore, with this technology, learners can engage with environmental phenomena not only by receiving information but also by navigating, observing, and responding to simulated ecological situations (Asino et al., 2022; Badilla-Quintana & Sandoval-Henríquez, 2021). Such experiences can strengthen conceptual understanding and foster emotional engagement, environmental awareness, empathy for nature, and a stronger sense of connection to ecological issues (Lumber et al., 2017; Mäkelä & Aktaº, 2023; Yang et al., 2018).

Research on immersive technology in education is increasing. Several studies have been conducted (Klippel et al., 2019; Mohsen & Alangari, 2024; Selvakumar & Sivakumar, 2025; Su et al., 2022). Moreover, several systematic literature reviews (SLRs) have been conducted on immersive technologies in education (Cardenas-Valdivia et al., 2023; Dewanto et al., 2024; Masmuzidin et al., 2022; Meronda et al., 2025; Turan & Karabey, 2023). This shows that this technology is a topic of study in educational research, including the development of learning media. Existing studies indicate that immersive technologies have been associated with a variety of educational benefits, including improved conceptual understanding, engagement, motivation, and affective responses. Nevertheless, the research landscape remains fragmented because many studies focus on specific educational levels, particular subject areas, or a single immersive modality.

Although many SLRs have discussed the use of immersive technology in education, these studies are oriented towards specific learning contexts, subjects, or types of technology. For example, the use of augmented reality to enhance Quechua language learning (Cardenas-Valdivia et al., 2023), reviewed the role of AR on student engagement and learning outcomes at various levels of education (Dewanto et al., 2024), and the use of AR in young people (Masmuzidin et al., 2022). Other studies focus on the impacts and limitations of virtual laboratories (Meronda et al., 2025) and on the application of immersive technology to distance learning. However, this study provides important knowledge regarding the benefits of using immersive technology in learning (Turan & Karabey, 2023). However, there has been little specific research into the use of this technology in ecological and environmental education. Ecological and environmental education requires contextual learning. Therefore, focusing on immersive digital technology in ecological and environmental education represents a research gap that needs to be filled. This is because it can provide insight into research trends in immersive technology, the impact of learning outcomes, and engagement in ecological and environmental education. More importantly, previous SLRs generally do not critically examine how immersive technologies function within the distinctive characteristics of ecology and environmental education, which emphasize contextual understanding, environmental literacy, emotional engagement with nature, and pro-environmental awareness or behavior. In other words, earlier reviews have provided valuable general insights, but they have not sufficiently positioned immersive technology within the specific pedagogical and conceptual demands of ecological and environmental learning.

Based on this gap, this article is limited to studies that focus on the application of immersive learning technologies in formal and informal educational contexts, including ecological and environmental education. This limitation was implemented to focus the analysis on the research objectives of ecological and environmental education. Furthermore, the synthesis will be more in-depth. Thus, a focused scope will yield more valuable and relevant contributions to ecological and environmental education.

Based on this scope, this systematic literature review aims to comprehensively synthesize the use of immersive digital technology in ecological and environmental education. This review is expected to provide an overview of research trends, types of technology used, and reported learning outcomes. Thus, it provides useful suggestions for educators, stakeholders, and researchers who wish to apply immersive technologies in ecological and environmental education. This contribution differs from prior literature reviews and can advance the development and application of immersive technology in ecology and environmental education across educational levels. The following are the research questions used in this literature review.

1. What research trends on immersive digital in ecology and environmental education?
2. How do immersive technology and its use in learning impact learning outcomes and engagement across different levels of education and immersion?

METHOD

Research Design

This systematic literature review followed the PRISMA standard (Marzi et al., 2025; Samala et al., 2023). The Sample, Phenomenon of Interest, Design, Evaluation, and Research Type (SPIDER) framework was used to develop a research question. This framework is often used for reviews of qualitative, mixed-methods, and educational research (Korstjens & Moser, 2017; Methley et al., 2014; Petersson-Bloom et al., 2023).

The SPIDER framework contributed to the formulation of questions and the development of a literature search strategy. The framework guided the study's focus as follows: a. A sample was used to identify subjects or participants. b. The phenomenon of Interest was used to select articles that focused on immersive digital technology in ecological education and research. c. Design was used to record the research design in the selected articles. d. Evaluation was used to record the research results/findings. The research type was used to record the research approach used.

Search Strategy

The author chose Scopus and ERIC as the primary data sources for the search article. The search strategy utilized key terms from the research question, examined keyword terminology, and examined abstracts for specificity. The final search query was ("virtual field trip" OR "VR field trip" OR "virtual excursion" OR "immersive learning" OR "immersive environment" OR "immersive media" OR "virtual reality" OR "VR" OR "augmented reality" OR "AR") AND (ecology OR ecological OR "environmental education" OR "environmental learning" OR biodiversity OR "biodiversity education" OR conservation OR "ecosystem education" OR "ecosystem learning") AND ("learning outcome" OR "cognitive outcome" OR "affective outcome" OR engagement OR "student engagement" OR motivation OR "learning experience") AND (experiment OR "quasi experiment" OR empirical OR evaluation OR "case study" OR survey OR "mixed method"). The filter menu is not used in the initial search string.

The procedure for selecting articles was conducted transparently and in a replicable manner using the PRISMA steps (Figure 1). The initial search found 296 articles. We then used automation tools to filter the following: 2015-2025, document type: article, publication stage final, source type: article, language: English, and open access: all open access. This filtering resulted in 150 articles for screening.

Inclusion and Exclusion Criteria

The selection of articles in a systematic review is guided by inclusion and exclusion criteria

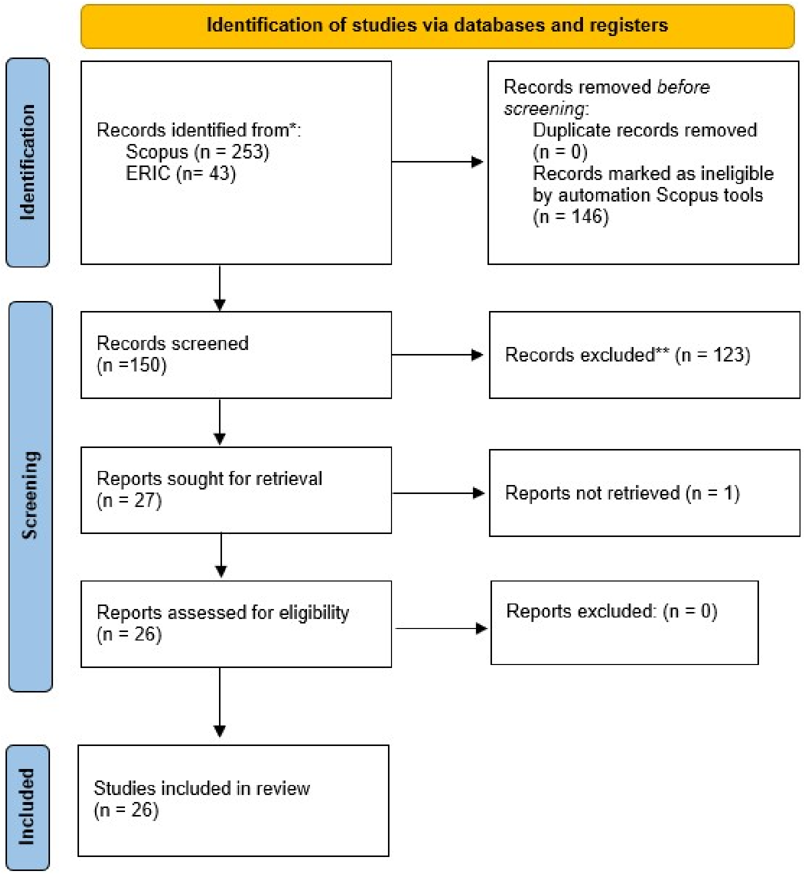

Figure 1. Study selection procedures using PRISMA

to ensure relevance, consistency, and methodological rigor. The inclusion and exclusion criteria are in Figure 2. The selection process resulted in 26 articles meeting the inclusion criteria.

Data Extraction

Systematic extraction was used to ensure the retrieval of relevant and consistent information from articles. The extraction grid included the

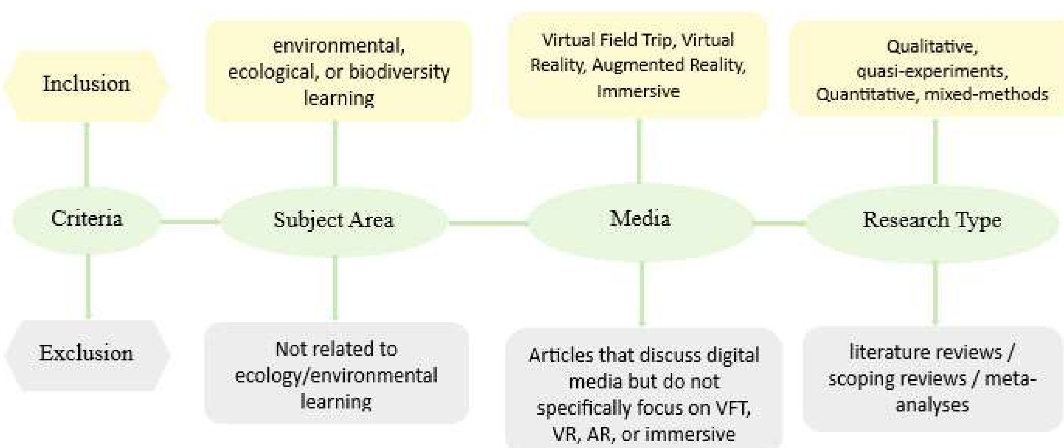

Figure 2. Criteria for inclusion and exclusion

bibliographic details, sample characteristics, ecological or environmental focus of the media, research design and methodological choices, measurement instruments, analytical approach, VR/AR or online media features used, presence of mediating or moderating variables, reported learning outcomes, key findings, and stated limitations. This extraction structure was directly informed by the SPIDER framework and the conceptual focus of the research questions, ensuring that all relevant dimensions were represented. Data extraction was performed using Scispace. The results were reviewed by the first and second authors. Any discrepancies were discussed until a consensus was reached. If no agreement were reached, a third author would determine the best course of action.

Data Synthesis

Data synthesis involved two stages. The first stage was a bibliometric analysis using VOSviewer. This analysis identified research trends, emerging keywords, and clusters within immersive technology and ecological and environmental education research.

The second stage involved narrative synthesis using 26 selected articles. This synthesis focused on identifying patterns, relationships, and mechanisms linking immersive digital technologies, pedagogical design, and learning outcomes.

Data Analysis

Data from the VOSviewer analysis were analyzed descriptively.

RESULT AND DISCUSSION

What Research Trends are Emerging in Immersive Digital Ecology and Environmental Education?

Network Visualization with VOSviewer

The network visualization presented in Figure 3 shows four focus clusters and research directions in immersive technology, ecology, and the environment. The first cluster (green) comprises the keywords environmental education, learning, teaching, and game-based learning. This cluster demonstrates the relationship between environmental education and technology-based learning media. Furthermore, game and technology-based learning is also a strategy for improving learning outcomes, particularly in environmental education. Figure 3 shows that environmental issues are used not only as material but also as a contextual learning approach in environmental education. The second cluster (yellow) contains keywords such as virtual reality and biodiversity. Meanwhile, the third cluster (blue) contains keywords such as augmented reality, educational technology, gamification, and digital games. The fourth cluster (red) contains keywords such as education, humans, climate change, procedures, and metaverse. Virtual reality connects several clusters, including biodiversity and climate change. In addition, this network visualization uses immersive technology to facilitate learning about environmental issues such as climate change and humanitarian issues. Furthermore, the relationship between augmented reality and gamification reflects the trend of using interactive technology to enhance learning engagement.

Figure 3 shows three main keywords formed by conceptual proximity: technology, learning, and environmental substance. The technology cluster emerged from research on media and platforms, including augmented reality, virtual reality, and digital games. The learning cluster emerged from numerous studies that place immersive digital technology in the context of learning design, teaching, and student engagement strategies. Meanwhile, the environmental cluster developed from the use of immersive technology in topics such as environmental education, biodiversity, and climate change. This visualization indicates that the research trend in immersive technology is interdisciplinary, connecting

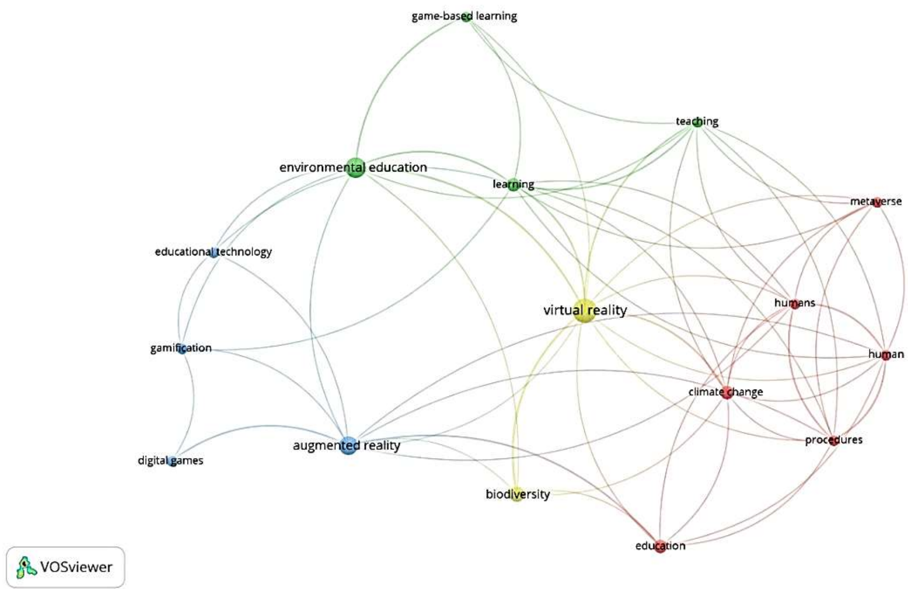

Figure 3. VOSviewer analysis results

technological innovation, learning, and environmental issues. Furthermore, this visualization demonstrates that research trends are not solely focused on technological developments but also on their use as learning media.

The visualization from VOSviewer shows that the keyword virtual reality occupies a central position, indicating that this technology is a dominant focus of research. The connection between virtual reality and the keywords learning, teaching, biodiversity, climate change, and augmented reality indicates that virtual reality is understood not only as a technological device but also as a learning medium on ecological and environmental topics. Figure 3 shows that the research landscape is still dominated by virtual reality, while augmented reality and digital games are supporting themes that are still developing.

The results of this network visualization analysis illustrate a strong relationship between immersive technology and environmental education. This relationship illustrates that education is one way to address environmental issues such as climate change and biodiversity loss. Virtual reality and gamification are innovative media that facilitate increased understanding of environmental issues (Chuang et al., 2025; Mulders & Träg, 2023; Ou et al., 2021b). Then, the results of this study show that immersive technology-based learning can increase species knowledge, environmental awareness, and experiences with nature (Bogerd et al., 2023; Chiang, 2021; Lo et al., 2021; Stone et al., 2022).

Distribution of Articles Based on Publication Year

Figure 4 illustrates the trend in research publications from 2016 to 2025. The distribution of the number of articles per year fluctuated throughout the 2016–2025 period. In 2016, the number of articles published was relatively low, at one article. Meanwhile, the highest number in 2025 was eight articles.

Overall, this research area is still developing and will only show strong acceleration in 2025. The increasing amount of research on immersive technology in ecology and environmental education is aiding conservation efforts. Students gain real-time visuals of ecological systems and environmental processes (Safitri et al., 2025). Moreover, immersive technology is an engaging learning medium that facilitates students' understanding of environmental concepts (Juergensmeier et al., 2024; Mercier, Ertz, et al., 2025).

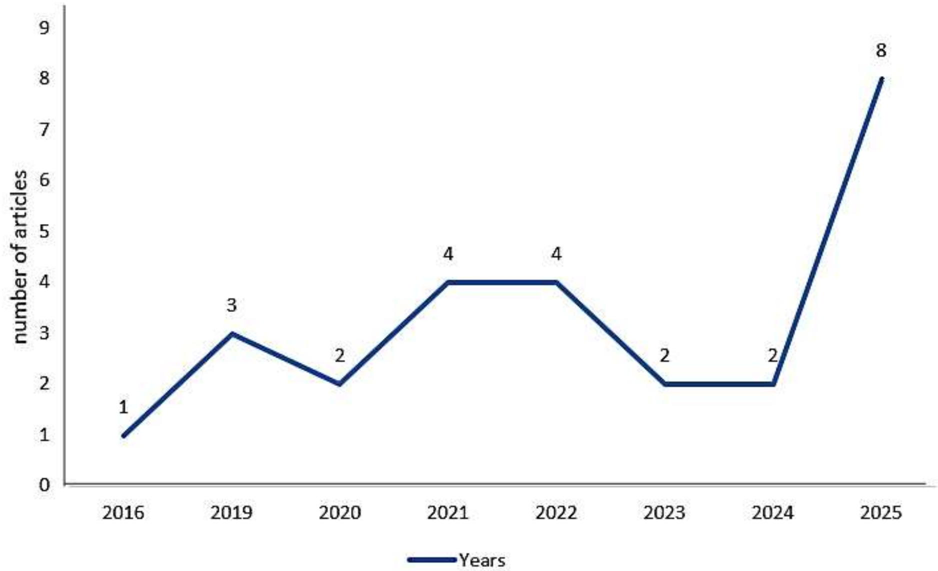

Figure 4. Distribution of articles by year

Research Focus

The output of the visual overlay analysis is shown in Figure 5. This analysis suggests that virtual reality (VR) is a major keyword in research on immersive technology in ecology and environmental education. This node has a strong connection to the concepts of learning, teaching, and environmental education. This indicates that some research uses VR as a primary technology in learning environmental and biodiversity issues.

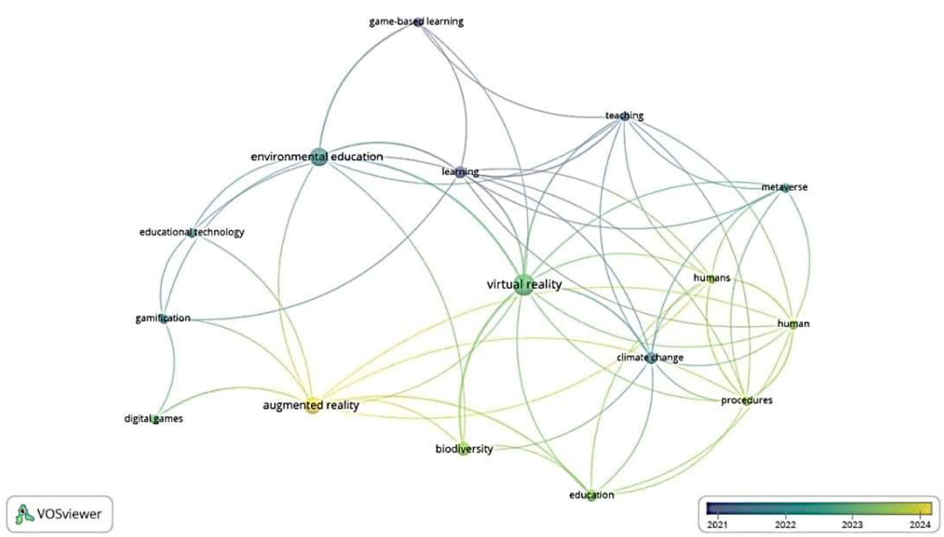

Figure 5. Overlay visualization mapping

Based on the year of publication, the research topic changed. In the 2021–2022 period, research topics such as educational technology, gamification, and game-based learning tend to be in darker shades. Then, in the 2023–2024 period, the topics are augmented reality, biodiversity, education, and humans. The second year shows an increase in a more contextual and experiential learning approach. The reality of AR, shaped by biodiversity issues, shows that immersive technology is seeking to incorporate real-world situations into its development.

Based on analysis through VOSviewer, digital immersive research in ecology and environmental education has evolved from exploring technology and game-based pedagogical approaches to utilizing immersive technologies to facilitate meaningful, student-centered learning about environmental issues. In the development of immersive technology, VR is dominant, but current research focuses on AR to address diversity issues and human aspects in the learning process. From Figure 6, it can be seen that VR research is conducted more frequently, with 15 articles, while AR has only 8.

The results of the analysis showed that research on immersive technology not only emphasizes the effectiveness of technology but also addresses ecological concepts, environmental issues, student characteristics, and learning experiences (Mulders & Träg, 2023; Ou et al., 2021b; Park et al., 2025). This aligns with the environmental education framework, in which learning outcomes encompass not only cognitive but also affective and engagement aspects (Lovren & Jablanovic, 2023). Learning that involves emotions, such as learning in an environmental context, is more meaningful (Jia & Wang, 2024). Furthermore, learning that engages emotions is more meaningful (Lovren & Jablanovic, 2023).

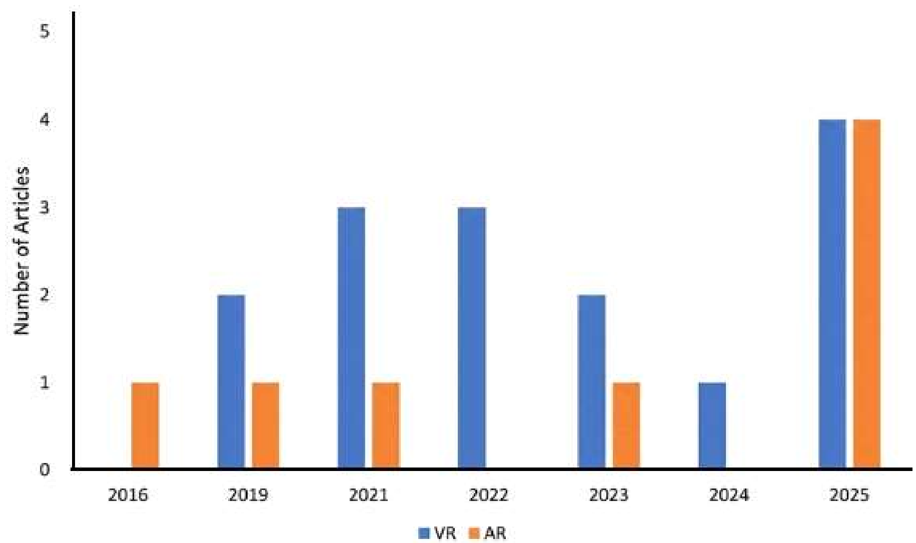

Figure 6. Comparison of the number of AR and VR publications

How Do Immersive Technology and its use in Learning Impact Learning Outcomes and Engagement Across Different Levels of Education and Immersion?

The extraction results are in Table 1. Using this table, each study can be systematically compared by type of immersive technology, pedagogical approach, and learning outcome domain.

Learning Outcomes in the use of Immersive Technology

A study of learning outcomes from immersive technology is presented in Table 1. The results of the literature review show that learning outcomes using immersive technology are connected across domains. The combination of the cognitive and engagement domains had the highest value at 27% (Figure 7), indicating that

Table 1. Article extraction results

Author (years)	Types of Immersive Technology	Pedagogical Approach	Learning Outcome Domain
Aivelo & Uitto (2016)	Augmented Reality	Experiential Learning	Cognitive & Behavior
Duwan et al. (2019)	Virtual Reality	Experiential Learning	Cognitive & Affective
Buchanan et al (2019)	Virtual Reality	Experiential Learning	Cognitive, Affective & Engagement
Mei & Yang (2019)	Mobile AR	Game-based learning	Cognitive & Engagement
Aguayo et al. (2020)	Augmented Reality and Virtual Reality (XR)	Experiential Learning	Cognitive
Dunn et al. (2021)	AR mobile game	Game-based learning	Behavior
Chiang (2021)	Virtual reality game	Game-based learning	Affective & Behavior
Essokolo & Robino (2022)	Immersive Educational Video Game	Narrative-based learning	Affective
Ou et al. (2021a)	Virtual reality 360 panoramic technology	Inquiry-Based Learning	Cognitive & Engagement
Ou et al. (2021b)	Virtual reality	Situated learning and game-based learning	Cognitive
Stone et al. (2022)	Virtual reality	Collaborative and Participatory learning	Cognitive & Engagement
Lo and Tsai (2022)	3D Virtual reality	Inquiry-Based Learning	Cognitive & Engagement
Chandler et al. (2022)	Virtual reality	Inquiry-Based Learning	Cognitive & Engagement
Adjanin & Brooks (2023)	Virtual Reality	Experiential Learning	Cognitive
Mulders and Träg (2023)	Augmented Reality and Virtual Reality (XR)	Inquiry-Based Learning	Cognitive & Affective
Harrington (2023)	Augmented Reality and Virtual Reality (Digital twin)	Experiential Learning	Cognitive & Engagement
Juergensmeier et al. (2024)	Virtual Field Trip	Experiential Learning	Affective
Masruroh et al. (2024)	Mobile virtual tour	Experiential Learning	Engagement
Safitri et al. (2025)	Augmented Reality	Inquiry-Based Learning	Cognitive
Mercier et al. (2025)	Augmented Reality	Inquiry-Based Learning	Cognitive
Chuang et al (2025)	Virtual Reality-based game	Game-based learning	Cognitive & Affective
Park et al. (2025)	Virtual Reality	Experiential Learning	Affective & Engagement

Schneideret et al. (2025)	Augmented Reality	Situated learning	Affective & Behavior
Mulders et al. (2025)	Virtual reality	Inquiry-Based Learning	Cognitive
Roy et al. (2025)	Cardboard virtual reality	Experiential Learning	Affective & Behavior
Sandbrook et al (2025)	Augmented Reality-based gamification	Game-based learning	Affective & Engagement

the learning process places a strong emphasis on understanding the material and active student engagement. The relatively high frequency of the cognitive and engagement domains in the reviewed studies suggests that immersive technologies in ecology and environmental education are most frequently used to support conceptual understanding through active student engagement.

The interplay between the cognitive domain and engagement is evident in several studies, including Harrington (2023), Mei & Yang (2019), Stone et al. (2022), and Chandler et al. (2022). his trend is understandable because ecological and environmental topics often involve complex systems, such as spatial relationships and dynamic processes within ecosystems, which are difficult to observe directly in conventional classroom settings. Therefore, immersive technology is used not only to facilitate understanding of concepts and relationships but also to sustain students' attention, participation, and engagement during exploration. Furthermore, this combination frequently appears in studies employing inquiry-based learning and experiential learning, indicating that immersive environments are highly effective when students are required to investigate, observe, and interact with ecological phenomena rather than passively receiving information.

Figure 7 shows that the cognitive domain accounts for 19%. The cognitive domain in the reviewed studies indicates that immersive technology serves as a tool to enhance students' understanding of ecological concepts, biodiversity, and environmental systems. This can be seen in studies such as Safitri et al. (2025), Mercier et al. (2025), and Mulders et al. (2025), which report cognitive outcomes as the primary domain in their research variables. This domain frequently appears in the reported studies because ecology and environmental education require students to understand the complex relationships among ecosystem components, biodiversity, and environmental changes—concepts that are often difficult to visualize through conventional teaching methods alone. Immersive technologies such as VR and AR provide more concrete, spatial, and interactive representations of these concepts, thereby supporting conceptual exploration and knowledge construction (Lo & Tsai, 2022; Safitri et al., 2025).

The affective domain accounts for 8% (Figure 7). After using immersive technology, there was an increase in aspects of environmental awareness, ecological empathy, positive attitudes towards conservation, and connectedness with nature (Buchanan et al., 2019; Chuang et al., 2025; Mulders & Träg, 2023). This increase is due to the use of immersive technologies, such as realism, narrative, simulation, and virtual field trips, which connect students' experiences and emotions to learning.

A learning process that prioritizes students' experiences and emotions will encourage them to behave in pro-environmental ways (Lovren & Jablanovic, 2023). Students not only get concepts but also direct experience, such as feeling and reflecting on the impact of environmental problems (Brick et al., 2023; Olsen et al., 2024). Furthermore, this learning creates an emotional

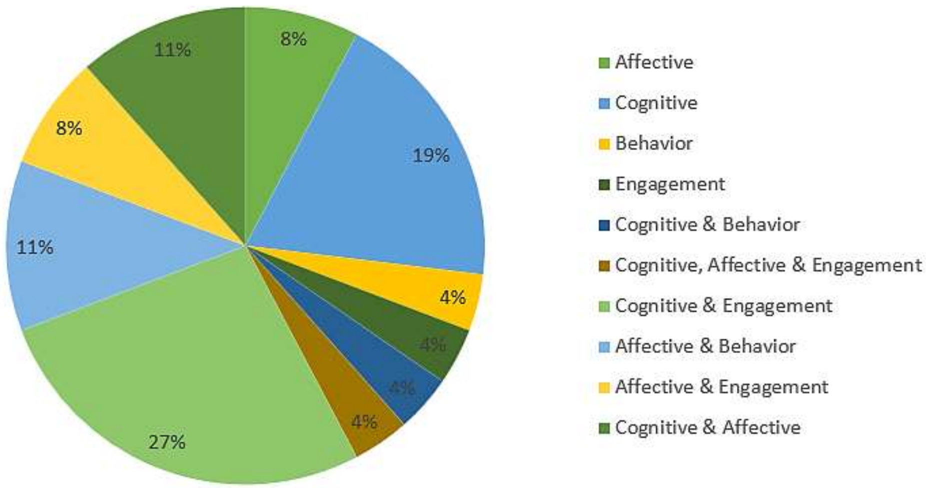

Figure 7. Outcome learning domain proportion

connection between students and their environment. This connection fosters concern, a sense of responsibility, and awareness of the need to protect and preserve the environment (Ison & Bramwell-Lalor, 2023; Pasca, 2022). Overall, Figure 7 illustrates that learning tends to focus on cognitive mastery supported by active engagement, while integration with the affective and behavioral domains remains relatively limited.

Learning Outcomes in Immersive Modality and Immersion Level

To provide a clearer overview of the relationship between immersive technology and learning outcomes, the selected studies were mapped in a technology–learning outcome matrix. Based on the analysis, variations in learning outcomes are presented in Table 1. Different learning outcomes are determined not only by the type of technology but also by the level and quality of immersion within that technology. High-level immersive technologies, such as VR, can facilitate the simultaneous achievement of cognitive and affective learning outcomes (Chiang, 2021; Park et al., 2025). This is due to immersive simulations' ability to enable learners to explore complex ecological systems while simultaneously fostering a strong sense of emotional involvement and presence (Ou et al., 2021b). As shown in Figure 8, VR was associated with the broadest combination of learning outcome domains. This indicates that highly immersive modalities tend to support multiple learning experiences.

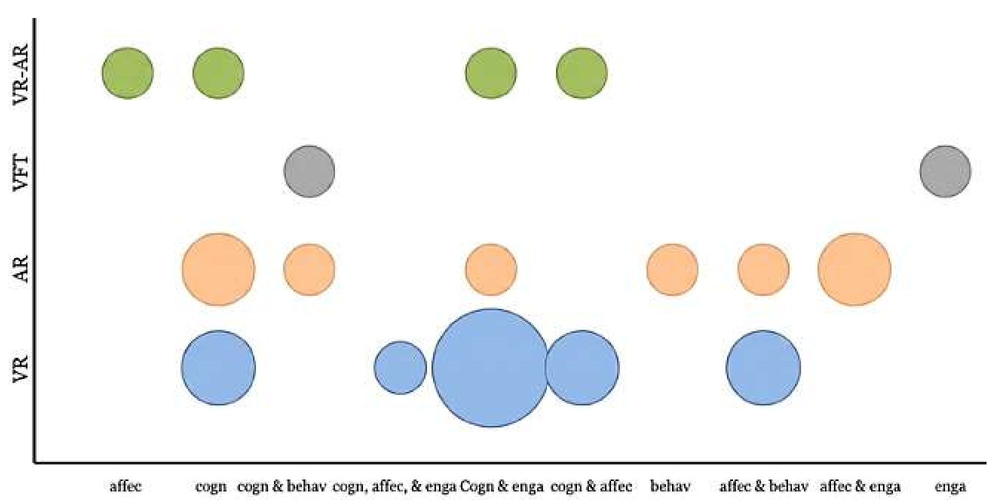

Figure 8. Matrix connecting technology types and learning outcome domains

In the meantime, AR, an immersive technology with a moderate level of immersion, focuses on cognitive domains and increasing environmental awareness (Mercier et al., 2025b; Safitri et al., 2025). The approach used in AR leverages contextual and location-based interactions to connect environmental data with real-life situations students face (Lo et al., 2021). Virtual Field Trips (VFT) and 360° environments are often associated with the affective domain and increased learning engagement, particularly in primary education and non-formal learning settings (Lo & Tsai, 2022; Ou et al., 2021b). This trend is also supported by Figure 9, which shows that research on immersive technology has been conducted across various levels of education. However, it remains concentrated in university and junior high school settings, while primary and non-formal education environments remain relatively limited. Immersive technology types on exploration and storytelling experiences (Bogerd et al., 2023; Juergensmeier et al., 2024).

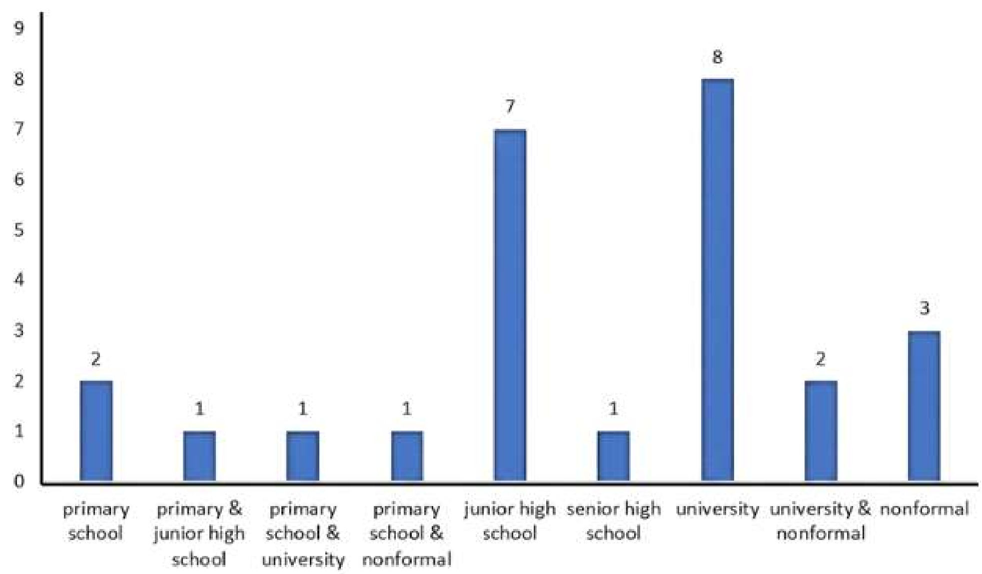

Figure 9. Educational levels in immersive technology research on ecological and environmental education

This study shows that immersive learning outcomes are influenced by the interaction between the level of immersion, experience design, and learning objectives, and are not solely determined by the technology modality. The results of the study indicate that differences in learning outcomes after using immersive technology are related not only to the technology but also to the level of immersion, learning design, and the learning objectives to be achieved. Overall, Figures 8 and 9 reinforce the interpretation that modality type, immersion level, and learning approach collectively shape reported learning outcomes in ecology and environmental education.

Pedagogical Mediation of Immersive Learning Outcomes

In the studies reviewed, immersive technology was not only implemented as a tool but also integrated with specific learning approaches. Of the 26 selected articles, immersive technology was used alongside learning approaches such as experiential learning, inquiry-based learning, game-based learning, contextual learning, collaborative and participatory learning, and narrative-based learning (Table 1). This pattern indicates that the contribution of immersive technology to ecology and environmental education depends not only on the modality's technological features but also on the learning experiences designed with specific learning approaches. Thus, immersive technology in the reviewed studies generally serves as part of instructional design rather than merely as a learning medium.

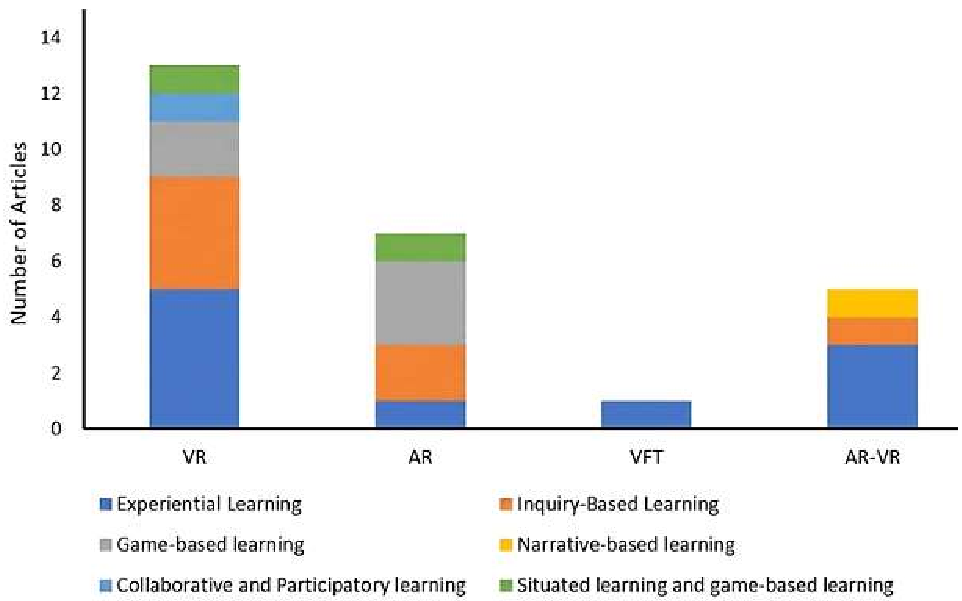

Figure 10. Comparison of immersive technology types and learning approaches

The results of the analysis in Figure 10 show that virtual reality technology was implemented through experience-based learning (5 articles) and inquiry-based learning (4 articles). VR technology was implemented through experiential designs that emphasized exploration and direct encounters with simulated ecological situations (Adjanin & Brooks, 2023; Buchanan et al., 2019; Duwan et al., 2019). Additionally, VR is used in inquiry-oriented activities that encourage students to investigate ecological relationships and environmental processes (Chandler et al., 2022; Mulders et al., 2025; Ou et al., 2021; Lo & Tsai, 2022). This indicates that VR is generally used for learning that requires the exploration of ecological content or the structured investigation of complex environmental phenomena that are difficult to access directly in a traditional classroom.

Augmented reality (AR) technology appears more frequently in studies that utilize game-based learning (3 articles) and inquiry-based learning (2 articles) (Figure 10). This suggests that AR aligns with learning approaches that emphasize contextual interaction, task-based engagement, and the relationship between digital information and the real-world environment (Dunn et al., 2021; Sandbrook et al., 2025). In the reviewed studies, AR was not only used to support concept exploration but also to facilitate interactive and context-sensitive learning experiences (Safitri et al., 2025). AR is positioned to enrich students' interactions with real-world objects, places, or environmental contexts (Ou et al., 2021; Safitri et al., 2025).

In addition, virtual field trip (VFT) technology is often used in inquiry-based learning, particularly when direct access to the field is limited (Juergensmeier et al., 2024). Overall, these findings suggest that the implementation of learning approaches using immersive technology is strongly influenced by the alignment between the modality, learning objectives, and the desired learning experience.

The review showed that the learning approach plays a significant role in determining how immersive technology influences learning outcomes. Contextual learning facilitated by immersive technology allows students to connect abstract concepts with their experiences (Lo & Tsai, 2022; Ou et al., 2021; Safitri et al., 2025). Game-based and narrative-based learning contribute to increased affective engagement and learning motivation (Blair et al., 2021; Chuang et al., 2025; Mulders & Träg, 2023). Inquiry-based learning strengthens cognitive outcomes through exploration, hypothesis generation, and collaboration in an immersive environment (Mercier et al., 2025b; Stone et al., 2022).

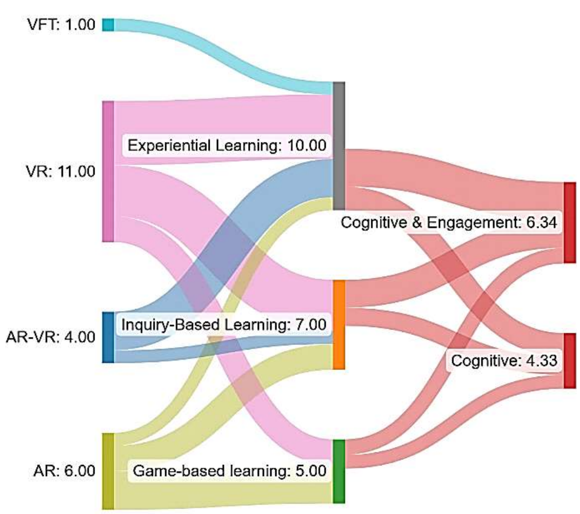

Figure 11. Sankey diagram linking immersive technology types, pedagogical approaches, and the most frequently reported learning outcome domains

Figure 11 illustrates the pathways connecting the most frequently reported types of immersive technologies, pedagogical approaches, and domains of learning outcomes. The Sankey diagram shows that VR is most strongly associated with experiential learning, which then flows primarily toward cognitive outcomes and engagement. Inquiry-based learning also emerges as a major pathway, particularly in linking VR and AR-VR modalities to cognitive and cognitive engagement outcomes. Conversely, AR appears more strongly linked to game-based learning, suggesting that this modality is often implemented through interactive, task-oriented designs that support active learner participation. Overall, the figure reinforces the argument that learning outcomes are not generated by technology alone; rather, learning outcomes emerge through pedagogical approaches embedded within each modality. This implies that the educational impact of immersive technologies in ecological and environmental education is shaped by the alignment between modality type, learning approach, and desired learning outcomes.

Despite these pedagogical strengths, the reviewed studies also indicate several implementation challenges. One recurring issue is that immersive technology may be used for novelty rather than for clearly defined instructional purposes, thereby reducing its educational value. In highly immersive environments, learners may also experience distraction or excessive cognitive load when the technology's sensory richness is not matched by sufficient guidance or task structure. In addition, implementation may be constrained by practical limitations such as device availability, technical readiness, and differences in learners' familiarity with digital tools. These findings suggest that the success of immersive learning depends not only on the modality itself but also on the quality of pedagogical planning and support.

At the same time, the reviewed literature suggests several strategies that support successful implementation. Immersive technologies appear to be more effective when they are aligned with specific learning objectives, integrated with active pedagogical approaches, and supported by structured tasks, discussion, and reflection. The use of authentic environmental issues and contextually meaningful activities also seems to strengthen learner engagement and the relevance of the learning experience. Thus, the impact of immersive technology is optimized when instructional design, modality choice, and learner support are carefully coordinated.

Overall, this literature synthesis suggests that while immersive technologies have excellent features for education, instructional design plays a key role in achieving learning outcomes. This statement aligns with Blair et al. (2021): integrating immersive technology into learning requires adjustments to learning objectives and technological capabilities. This is to ensure that students' learning experiences align with learning objectives.

CONCLUSION

This study shows that the use of immersive digital technology in ecology and environmental education has increased in the past year. Research into immersive technology has evolved rapidly, moving from a focus on developing technology to facilitating learning experiences and improving learning outcomes and student engagement. Virtual reality has become a key keyword in research on environmental education, biodiversity, and climate change. Augmented reality and virtual field trips are being used to facilitate learning experiences. Furthermore, the synthesis results show that pedagogical approaches such as experiential learning, inquiry-based learning, and game-based learning contribute to achieving learning objectives in the cognitive, affective, behavior, and student engagement domains. The results of this study confirm that immersive digital technology plays a significant role in ecology and environmental education by providing contextual learning experiences and facilitating students' understanding of concepts. These findings suggest that the educational value of immersive technology depends not only on the modality used but also on the alignment between the type of technology, the learning approach, the level of immersion, and the desired learning outcomes.

This research implies that the use of immersive digital technology in education is not only about adopting new technology, but also about developing learning designs that are appropriate to student needs and the characteristics of contextual learning materials. Furthermore, the results of this study serve as a basis for educational stakeholders in curriculum development and designing learning that emphasizes not only knowledge but also behavior and pro-environmental aspects. For teachers, immersive technologies should be selected based on learning objectives, where VR supports the exploration of complex ecological and environmental concepts, AR facilitates contextual and discovery-based learning, and virtual field trips enable experiential exploration when direct access to the field is limited. For curriculum developers, immersive technologies should be integrated through clearly defined outcomes, structured learning tasks, reflection, and assessment that encompass conceptual understanding, environmental awareness, engagement, and pro-environmental orientation. For researchers, these findings underscore the need for more in-depth investigation into the long-term effectiveness of AR on pro-environmental behavior change, particularly in primary schools.

DECLARATION OF GENERATIVE AI USAGE IN THE WRITING PROCESS

During the writing of this manuscript, the authors used Scispace to assist with data extraction. The authors have reviewed and edited the content generated by this tool and assume full responsibility for the content of the published article.

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