The Impact of Extended Reality Environmental Learning on Students' Eco-Literacy: A Systematic Review

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ABSTRACT

Current environmental challenges such as climate change, pollution, and loss of biodiversity demonstrate the need for an educational approach that fosters deep understanding and sustainable behavior. Schools play a central role in developing ecological literacy, awareness, and environmental responsibility in students. This study aims to explore how the use of Extended Reality (XR) affects students' knowledge, attitudes, and behavior towards the environment, as well as to identify the types of Extended Reality technology that have been applied in environmental literacy education. The research method used was a Systematic Literature Review following PRISMA 2020 guidelines, analyzing 24 empirical articles published between 2020 and 2025 from Scopus and Google Scholar databases on the application of XR-based environmental learning at various educational levels. The results show that the integration of XR, particularly Virtual Reality (VR), can improve students' understanding of environmental concepts, empathy, and motivation to behave in an environmentally friendly manner. Augmented Reality (AR) is effective in supporting conceptual learning and increasing learning engagement, while 360° videos and serious games provide an interactive learning experience that is easily accessible to young learners. However, Mixed Reality (MR) remains under-explored, and most studies have not examined the long-term behavioral impact. Overall, XR-based learning not only improves cognitive and affective aspects but also encourages emotional connection and behavioral change towards nature. From the research results, it can be concluded that Extended Reality is a promising learning medium to strengthen students' environmental literacy and awareness. Further research is recommended to investigate the long-term impact of XR on real environmental actions and its application in the Indonesian educational context to make it more inclusive and sustainable.

Keywords: *Augmented Reality, Eco-Literacy, Environmental Education, Extended Reality, Virtual Reality*

1. INTRODUCTION

Environmental issues, such as global warming and biodiversity loss globally (Shcheblyakov et al., 2019), and deforestation and rising sea levels nationally in Indonesia (Fatimah et al, 2024), present serious threats to human welfare. These large-scale impacts often stem from accumulated daily human behaviors. A core challenge in addressing this crisis is widespread public indifference, largely because environmental education is often delivered in an informative, non-contextual manner, failing to convey the real-world urgency of these issues. Environmental education, therefore, tends to be viewed as a complementary topic rather than a crucial subject.

To bridge this gap and promote meaningful environmental engagement, a new, impactful pedagogical approach is needed. Extended Reality (XR), an umbrella term encompassing Virtual Reality (VR) and Augmented Reality (AR) (Rauschnabel et al., 2022), offers a solution. XR allows students to move beyond passively reading about environmental damage by enabling them to explore it in realistic, interactive, and emotional virtual or augmented scenarios. VR immerses users in fully simulated spaces, while AR overlays digital elements onto the real world. This technology is uniquely aligned with key educational principles. By providing direct, sensory-rich, and interactive experiences, XR supports Experiential Learning (Kolb), where knowledge is gained through direct action; Contextual Learning, by placing concepts in a real-life framework; and Constructivism (Piaget and Vygotsky), where students actively build understanding through interaction (Do, Do & Nguyen, 2023). Furthermore, the Multisensory Learning approach engaging sight, hearing, and movement creates a richer, deeper, and more lasting impact on students' memories (Chandramouli, Zafar & Williams, 2025).

This process contributes directly to the development of Ecoliteracy, defined as the awareness and ability to understand ecological systems and act sustainably (Desmarais, 2024). Through its immersive nature, XR has the potential to influence the full scope of this literacy: the cognitive (understanding), the affective (concern), and the behavioral (pro - environmental actions).

Thus, this study seeks to investigate the transformative potential of XR in environmental education. This study addresses the following questions: 1) How does the use of Extended Reality (XR) affect students across the cognitive, affective, and behavioral domains of environmental learning?; 2) What types of XR technology (VR, AR, MR) have been applied in ecoliteracy education?

2. METHODOLOGY

2.1. Research Design and Framework

This study employs a Systematic Literature Review (SLR) with a qualitative–quantitative synthesis to analyze research on Extended Reality (XR), particularly Virtual Reality (VR) and Augmented Reality (AR) in environmental education. The review aims to identify how XR contributes to students' ecological literacy across cognitive, affective, and behavioral dimensions. This study follows the PRISMA 2020 (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines to ensure transparency, replication, and academic rigor in the review process.

Database searches were conducted using Scopus and Google Scholar. Keywords used included ("Virtual Reality" OR "Augmented Reality" OR "Extended Reality" OR VR OR AR OR XR) AND ("Environmental Education" OR "Eco-Literacy" OR "Pro-

Environmental Behavior"). The search was limited to English and Indonesian articles published between 2015 and 2025.

Articles were excluded if they (1) did not have student participants, (2) did not analyze eco-literacy components (cognitive, affective, behavioral), (3) had no full-text available, or (4) were outside environmental education context. Although the search covered 2015-2025, all articles meeting inclusion criteria were published between 2020 and 2025, indicating that XR research in environmental education is a relatively new and rapidly developing topic in the last five years.

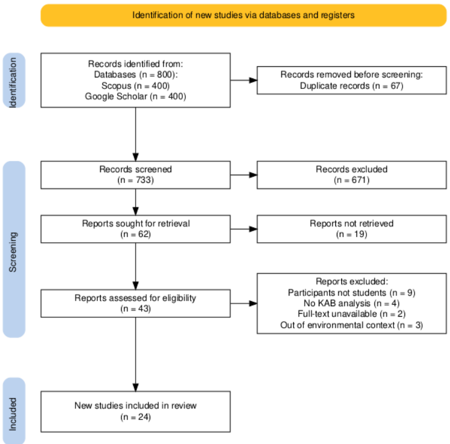

Figure 1. Research method following the PRISMA strategy (prepared by the authors).

2.2. Data Extraction and Synthesis

Data extracted included author, year, XR type, research design, participants, and key findings related to ecological literacy. Analysis used thematic and narrative approaches grouping results according to research questions.

3. RESULTS AND DISCUSSION

RESULT

3.1 Utilization of XR Technology

The diversity of XR technologies, which includes Virtual Reality (VR) and Augmented Reality (AR) provides different experiences for students.

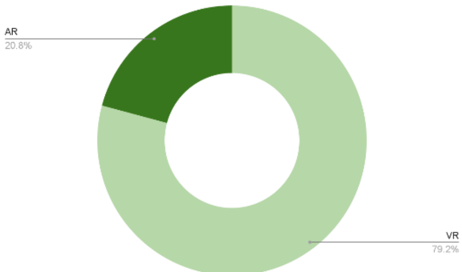

Figure 2. Proportion of VR and AR Utilization in Environmental Education

Analysis shows a significant dominance of Virtual Reality (VR) over Augmented Reality (AR) in environmental education interventions, with 19 studies (79.2%) primarily utilizing VR due to its immersive potential for visualizing complex or inaccessible scenarios. Conversely, AR accounted for only 5 studies (20.8%), generally focusing on real-world integrated digital content. This disparity suggests that VR's immersion and spatial presence are currently perceived as the stronger mechanisms for influencing pro-environmental attitudes and behaviors.

3.4 Synthesis of XR's Impact on Eco-Literacy

The synthesis was conducted by grouping the impacts of XR based on the three main dimensions of eco-literacy, namely knowledge (cognitive), attitude (affective), and pro-environmental behavior.

3.4.1 The Influence of XR on Cognitive aspect

The cognitive dimension is the initial foundation for building students' ecological literacy. Of the 24 studies analyzed, 16 studies showed that the use of XR significantly improved students' conceptual understanding of complex environmental issues. This improvement occurred not only in terms of memorization or factual knowledge, but also in students' ability to understand cause-and-effect relationships in ecological systems.

Table 1. Summary of the impact of XR on the cognitive aspect

Source	Cognitive Focus
Adjanin & Brooks (2023); Tyski & Henderson (2024); Tabbu et al. (2024); Tan et al. (2024)	Significant improvement in climate literacy, self-efficacy, and understanding of climate change.
Liu & Yeh (2022); Liao et al. (2025); Gestiada et al. (2025); Fokides & Arvaniti (2020)	VR enhances conceptual understanding of ecology, learning motivation, and moves students to a higher level of conceptual mastery.
Simsek (2024); Chen et al. (2024); Michel-Acosta et al. (2024)	AR enhances understanding of life cycles, aurora-climate, and tropical cyclones with higher post-test scores and lower cognitive load.
Suryati et al. (2025); Lo and Tsai (2022); Fokides & Chachlaki (2020)	VR-PBL enhances critical thinking, climate awareness, and long-term knowledge retention about conservation.
Manoharan, A. P. S. (2025); Chen (2022)	VR enhances awareness of marine ecosystems; AR improves understanding of environmental concepts.

The cognitive effectiveness of Extended Reality (XR) is technology-dependent. Virtual Reality (VR) facilitating the understanding of macro and systemic concepts through immersive, spatial, and experiential learning. Conversely, Augmented Reality

(AR) is optimal for grasping specific and microscopic phenomena by reducing cognitive load via real-world integrated 3D visualization. Crucially, XR's cognitive benefits are often mediated by its integration with structured pedagogical models, promoting higher-order thinking and the construction of a deep understanding of complex environmental challenges.

3.4.2 The Influence of XR on Environmental in Affective aspect

In addition to increasing knowledge, XR has also been shown to have a strong impact on shaping students' positive affective toward the environment. Of the 24 studies analyzed, 20 showed significant affective changes, including increased ecological empathy, sense of place, and awareness of responsibility for nature conservation.

Table 2. Summary of the impact of XR on the affective aspect

Source	Affective Focus
Adjanin & Brooks (2023); Tyski & Henderson (2024); Tan et al. (2024); Chiang (2021); Plechatá et al. (2022); van Horen et al. (2024)	Increased engagement, sense of place, emotional attachment to the environment, and empathy through immersive VR experiences.
Spangenberger et al. (2024); Manoharan, A. P. S. (2025).	VR enhances connectedness to nature, feelings of awe, and transforms negative attitudes into positive ones toward environmental issues.
Liu & Yeh (2022); Liao et al. (2025); Fokides & Arvaniti (2020)	VR enhances positive attitudes, environmental awareness, appreciation for ecosystems, and motivation to learn about ecological issues.
Bhang & Huh (2023); Chen et al. (2024); Chen (2022); Simsek (2024)	AR increases awareness of air pollution, positive attitudes toward climate change, and environmental understanding with a high effect size (>0.9).
Suryati et al. (2025); Lo and Tsai (2022); Ho et al. (2024); Fokides & Chachlaki (2020)	VR increases climate change awareness (moderate→high), conservation motivation, and positive attitudes toward endangered species.
Roy T et al. (2025); Gestiada et al. (2025); Michel-Acosta et al. (2024)	Google Cardboard-based VR and 360° tours increase motivation, marine ecological awareness, and appreciation for natural phenomena.

The findings show that attitude changes through XR are driven by several affective mechanisms. VR's emotional presence allows students to directly experience environmental threats. Furthermore, phenomena like the overview effect and embodiment offer transformative perspectives, deepening the emotional connection to nature. Simultaneously, AR personalizes abstract threats by visualizing previously invisible environmental risks. These mechanisms demonstrate that XR is critical for activating the emotional dimension, which drives authentic ecological awareness and responsibility.

3.4.3 The Influence of XR on Pro-Environmental Behavior

The behavioral dimension is the culmination of a holistic environmental learning process, where knowledge and attitudes are expected to be transformed into concrete actions. Of the 24 studies analyzed, 12 studies showed that the use of XR successfully increased students' intentions and motivation to behave in an environmentally friendly manner.

Table 3. Summary of the impact of XR on the behavioral aspect

Source	Behavioral Focus
Adjanin & Brooks (2023); Xiong et al. (2024); Plechatá et al. (2022); Ho et al. (2024)	VR increases environmental protection behavioral intentions, pro-environmental food choices, and behavioral intentions toward plastic waste.
Tyski & Henderson (2024); Tan et al. (2024); Liu & Yeh (2022)	VR increases participation in climate mitigation and problem-solving intentions, but actions remain individual.
van Horen et al. (2024); Spangenberger et al. (2024)	The VR overview effect enhances pro-environmental behavior through nature connectedness.
Bhang & Huh (2023); Chen (2022)	AR/VR changes 10 types of behavioral attitudes (effect size >0.9): cleanliness, masks, environmental responsibility.
Manoharan, A. P. S. (2025).; Chiang (2021); Fokides & Chachlaki (2020)	VR games enhance actual behaviors related to nature protection and conservation actions.

Behavioral change mechanisms through Extended Reality (XR) are mediated by several psychological pathways. Interactive VR experiences foster perceived autonomy and self-efficacy, which are crucial for mediating the transition from pro-environmental intention to actual action. Additionally, VR simulations offer opportunities for behavioral modeling, allowing students to safely practice decision-making before real-world application.

DISCUSSION

As outlined, various global environmental issues necessitate the urgency of environmental education (EE). In this context, the findings of these 24 literature reviews reinforce the transformative potential of Extended Reality (XR), encompassing Virtual Reality (VR) and Augmented Reality (AR), as a key innovation in EE to enhance students' ecoliteracy across cognitive, affective, and behavioral aspects.

Cognitive Enhancement and Contextual Comparison

The results showing that XR enhances conceptual understanding and ecological knowledge through immersive visualization (Tabbu et al., 2024; Chen et al., 2024; Liao et al., 2025) align with and extend the views of constructivism and experiential learning. XR bridges abstract concepts with real-world phenomena, an aspect often difficult to achieve through traditional EE methods (pen-and-paper). The new insight is that this effectiveness lies in XR's ability to manipulate time and spatial scales, for instance, allowing students to witness the real-time effects of pollution or the lengthy process of the carbon cycle, which is impossible in conventional classroom settings.

Affective Development and Environmental Empathy

The strengthening of ecological empathy and sense of place through XR (Tyski & Henderson, 2024) reinforces the findings of contextual learning theories regarding the role of emotional involvement. Virtual exposure to environmental degradation elicits strong emotional responses, which are an essential prerequisite for forming authentic ecological concern. These findings complement non-XR research showing that digital storytelling strongly influences affect, but XR elevates this impact through richer visual and kinesthetic senses.

Behavioral Promotion and the Need for Further Study

The reported increase in intention and motivation to engage in pro-environmental actions (Plechatá et al., 2022; Xiong et al., 2024) indicates that XR successfully triggers action readiness. The key difference from other behavioral research is that XR effects are often short-term. While other studies focusing on community-based interventions show more stable behavioral change through social reinforcement and sustained programs, current XR results are limited to intent. This suggests that XR is highly effective as an initial catalyst for awareness and intent but needs to be integrated into broader EE programs and supported by social reinforcement to achieve sustained behavioral change.

Variations in Effectiveness and Design Considerations

The variation in effectiveness based on technology type (AR vs. VR) and student characteristics (Simsek, 2024; Tabbu et al., 2024; Gestiada et al., 2025) highlights the need for intelligent pedagogical design. These findings provide the insight that there is no one-size-fits-all XR solution. For example, AR excels in cognition for young learners due to lower cognitive load, compared to VR which is more suitable for complex simulations for adolescents. This underscores that XR effectiveness heavily depends on the alignment of the technology with the learning objective, the students' developmental level, and the complexity of the ecological content being delivered.

Implication for Practice

Governments and educational institutions, particularly in Indonesia, are encouraged to adopt XR as a powerful complementary tool in EE curricula, not as a replacement for outdoor experiences (Fokides & Chachlaki, 2020). Implementation should focus on: (1) Developing localized content to address specific Indonesian environmental issues; (2) Adequate teacher training in XR pedagogy; and (3) Innovative device procurement strategies to address infrastructural gaps and device availability.

Implication for Future Research

Future research must address the limitations of current studies by focusing on: (1) Longitudinal studies to measure the duration and sustainability of pro-environmental behavior change; (2) Using more objective quantitative methods (e.g., physiological measurements or real-life behavioral observation) rather than solely self-reports; and (3) Cost-effectiveness comparisons** among various types of XR in the context of schools in developing countries.

Limitations

Although promising, the existing evidence is limited by short intervention durations, small sample sizes, and reliance on self-report measures. Furthermore, the predominantly school-centered and geographically narrow research context hinders generalizability. The variation in findings between studiesfor instance, VR cognitive boost without behavioral impact versus AR behavioral change with modest cognitive gains (Bhang & Huh, 2023) also indicates the necessity for standardization of design and measurement in XR studies.

4. CONCLUSION

This review shows that Extended Reality (XR) meaningfully supports ecoliteracy by improving conceptual understanding, ecological empathy, and pro-environmental intentions, with VR offering the strongest immersive benefits and AR aiding younger learners through reduced cognitive load. Although promising, most evidence reflects short-term behavioral intentions, indicating the need for research on sustained impacts. Future work should explore long-term behavioral outcomes, cultural contexts such as Indonesia, and integration with pedagogical models, while educators are encouraged to use XR as a transformative tool for fostering environmental awareness and action.

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