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Comparing Augmented Reality, Video-Based, and Traditional Instruction for Enhancing Environmental Literacy in Indonesian Eco-Schools

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ABSTRACT

Purpose of the study: This study aimed to examine the effects of augmented reality–based instruction, video-based instruction, and traditional instruction on fourth-grade students' environmental literacy, encompassing environmental knowledge, environmental attitudes, and pro-environmental behavior, within an Adiwiyata-certified elementary eco-school.

Methodology: A quasi-experimental design was employed involving 81 fourth-grade students from an Adiwiyata-certified elementary eco-school in Semarang, Indonesia. Data were collected using a validated multiple-choice environmental knowledge test and Likert-scale questionnaires measuring environmental attitudes and pro-environmental behavior. Data were analyzed using multivariate analysis of covariance (MANCOVA) and analysis of covariance (ANCOVA) with IBM SPSS Statistics version 26.

Main Findings: The results revealed a significant multivariate effect of instructional method on overall environmental literacy. Augmented reality–based instruction produced the highest post-test scores in environmental knowledge and environmental attitudes, followed by video-based instruction and traditional instruction. Instructional method also exerted a statistically significant but smaller effect on pro-environmental behavior.

Novelty/Originality of this study: This study provides novel empirical evidence through a three-arm comparison of augmented reality, video-based, and traditional instruction within the Adiwiyata (eco school) framework. It advances environmental education research by demonstrating differentiated cognitive, affective, and behavioral effects of immersive and non-immersive instructional methods at the elementary school level.

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1. INTRODUCTION

Environmental degradation, biodiversity loss, and climate change have intensified global concern regarding the need to develop environmental literacy from the early stages of formal education. This study is theoretically grounded in the Model of Responsible Environmental Behavior [1], which remains a cornerstone in environmental education for explaining how cognitive and affective variables interact to produce action [2]. Within this framework, environmental literacy is conceptualized as a multidimensional construct comprising environmental knowledge, environmental attitudes, and pro-environmental behavior [3], [4]. Furthermore, to evaluate the efficacy of digital interventions, this research utilizes the Theory of Planned Behavior [5] to explain how immersive technologies like Augmented Reality influence students' perceived behavioral control and subsequent environmental intentions [6], [7]. Recent research highlights elementary education as a critical developmental period, during which students begin to consolidate the cognitive understanding and value orientations defined by these models [8]. Strengthening environmental literacy at this level through technology-integrated instruction is therefore increasingly viewed as a foundational strategy for achieving long-term sustainability goals and fostering responsible citizenship.

In Indonesia, environmental literacy development is institutionally supported through the Adiwiyata (eco school) Program, Indonesia's national eco-school program aligned with Education for Sustainable Development (ESD). This initiative is designed to integrate environmental education into school policies, instructional practices, and daily routines by cultivating environmental values and behaviors within school culture [9]-[11]. While Adiwiyata-certified eco-schools often demonstrate superior institutional environmental practices compared to non-certified schools [12], [13], significant challenges remain at the classroom level. Recent evidence suggests that instruction within Adiwiyata-certified eco-schools frequently remains highly teacher-centered and lecture-dominated, characterized by minimal student interactivity and a lack of pedagogical innovation [14]-[16]. Furthermore, the integration of instructional technologies is often uneven, with many educators struggling to move beyond traditional rote learning methods [17], [18]. This gap underscores the need to examine how instructional methods within Adiwiyata classrooms can be optimized, specifically through interactive digital tools, to more effectively support multidimensional environmental literacy outcomes.

Advances in educational technology have expanded the range of instructional approaches available for environmental education at the elementary level. The theoretical foundation for these approaches is rooted in the Cognitive Theory of Multimedia Learning [19] and Cognitive Load Theory [20], which suggest that instructional design must align with human cognitive architecture to be effective. When aligned with instructional objectives and learners' cognitive characteristics, digital-based instruction has been shown to improve engagement, conceptual understanding, and learning outcomes [21]-[23]. In environmental education, digital technologies are particularly valuable because they provide multimodal representations [24], [25] that can visualize abstract ecological processes and represent dynamic environmental systems [26]-[28]. By utilizing dual visual and auditory channels, these technologies reduce extraneous cognitive load and facilitate the construction of mental models for complex environmental phenomena [29]-[31]. Such affordances provide contextualized learning experiences that are difficult to achieve through traditional instruction alone [19], [32], [33], suggesting that instructional modality plays a critical role in shaping students' environmental learning outcomes.

Among commonly adopted technologies, instructional video presents a widely accessible form of digital-based learning. Research conducted during and after the COVID-19 period indicates that video-based learning supports conceptual understanding and motivation through audiovisual explanations and real-world representations, particularly for elementary learners [19], [22]. However, within the multidimensional construct of environmental literacy, video-based instruction often demonstrates significant limitations in fostering attitudinal and behavioral change [34]-[36]. Because learner engagement with video content is largely observational and passive [37], [38], it lacks the active exploration required to deeply internalize environmental values or simulate pro-environmental decision-making [39]-[41]. While effective for knowledge transmission, the linear nature of video may not sufficiently stimulate the "perceived behavioral control" [42], [43] or "personal responsibility" [44], [45] necessary to translate environmental awareness into sustained action [2], [8]. This gap suggests that while video is a valuable baseline technology, it may be less effective than more interactive modalities in driving the affective and behavioral components of environmental literacy.

Augmented reality (AR) offers a contrasting instructional approach by overlaying digital information onto the physical environment, enabling learners to interact with virtual content while remaining situated in real-world contexts. Meta-analytic and review studies consistently report that AR-based instruction enhances engagement, conceptual understanding, motivation, and situational interest by increasing interactivity and contextual relevance [46]-[48]. In environmental and sustainability education, AR has been shown to support learners' exploration of ecosystems and human–nature interactions, facilitating stronger learning outcomes and attitudinal development [49]-[51]. Despite these benefits, a scientific assessment of AR must account for significant implementation challenges, including the potential for high cognitive load if the interface is overly complex [52], [53], technical instability in outdoor environments [51], [55], and the novelty effect Mendoza-Ramírez et al. [55], Miguel-Alonso et al. [56], and Maduku & Mxinwa [57], where initial student engagement may stem from the excitement of the technology rather than pedagogical depth [33], [58]. Identifying these constraints is essential for determining the boundary conditions of AR effectiveness. Consequently, empirical evidence directly comparing AR-based instruction with more established media such as instructional video particularly at the elementary level and within policy-driven environmental programs remains necessary to validate its comparative pedagogical value.

Despite the growing body of research on digital learning, several critical gaps persist in the environmental education literature. First, many existing studies rely on binary comparisons, most commonly contrasting augmented reality (AR)–based instruction with conventional teaching methods. Such designs make it difficult to determine whether observed learning gains stem from the unique interactive affordances of AR or simply from its multimedia visualization features, which are also present in less complex technologies such as instructional video [59]-[61]. Second, prior research has predominantly emphasized cognitive outcomes, particularly environmental knowledge, while providing limited empirical evidence on how immersive or interactive technologies influence the affective and behavioral dimensions of environmental literacy, including value internalization and pro-environmental behavior [62]-[64]. Finally, few empirical investigations have been conducted within clearly defined national policy frameworks, such as Indonesia's Adiwiyata (eco school) Program, resulting in a lack of contextualized evidence needed to inform pedagogical decision-making and support system-level implementation of Education for Sustainable Development.

The novelty of this research lies in its rigorous comparative design, which addresses these limitations by distinguishing between passive visualization (video-based instruction), active interactive simulation (AR-based instruction), and conventional methods. Unlike previous studies that treat technology as a monolith, this research isolates the variable of "interactivity" to determine its specific contribution to the multidimensional constructs of the Model of Responsible Environmental Behavior. Furthermore, this study offers a distinct theoretical contribution by applying the Theory of Planned Behavior to explain how digital immersion influences the "perceived behavioral control" necessary for environmental action. Contextually, this is among the first studies to examine these variables specifically within Adiwiyata-certified eco-schools, providing unique, policy-relevant empirical data that bridges the gap between national sustainability mandates and classroom-level pedagogical realities.

Based on this gap analysis and theoretical framework, the present quasi-experimental study investigates the comparative effects of augmented reality–based instruction, video-based instruction, and traditional instruction on fourth-grade students' environmental literacy. Specifically, this study examines differences in students' overall environmental literacy as well as in each of its constituent dimensions after controlling for pre-test scores. The objectives of this study are as follows: (1) to determine whether instructional methods differ in their effects on students' overall environmental literacy; (2) to examine differences in environmental knowledge across instructional methods; (3) to examine differences in environmental attitudes across instructional methods; and (4) to examine differences in pro-environmental behavior across instructional methods within an ESD-oriented educational context.

2. RESEARCH METHOD

2.1. Type of Research and Research Design

This study employed a quantitative research approach using a quasi-experimental non-equivalent control group design with pre-test and post-test measures. This design was selected to balance methodological rigor with ecological validity, as random assignment of individual students was impractical due to established administrative classroom structures within the school setting [65], [66]. By utilizing intact classes, the study preserved the naturalistic instructional environment while enabling systematic comparison of instructional effects across different teaching modalities.

The research followed a structured pre-test–intervention–post-test sequence. Baseline measurements (pre-tests) were administered prior to the intervention, followed by the implementation of instructional treatments over a fixed instructional period, and concluded with outcome measurements (post-tests) using identical instruments. This design structure allowed for the assessment of changes attributable to the instructional interventions while maintaining consistency in measurement conditions.

Within this framework, the independent variable was the instructional method, operationalized across three levels: augmented reality–based instruction (experimental group 1), video-based instruction (experimental group 2), and traditional instruction (control group). The dependent variables comprised the multidimensional construct of environmental literacy, operationalized through environmental knowledge, environmental attitudes, and pro-environmental behavior. To mitigate threats to internal validity associated with non-random assignment, pre-test scores were incorporated as covariates in the statistical analyses. This approach enabled statistical control of baseline differences among groups, reduced error variance, and enhanced the precision of treatment effect estimation [67].

2.2. Population and Sample

The target population for this study consisted of fourth-grade students attending Adiwiyata-certified elementary eco-schools in Semarang, Central Java, Indonesia. To select the specific research site, a purposive sampling technique was employed based on two rigorous inclusion criteria: (1) the school's validated status as a nationally recognized Adiwiyata (eco-school) institution; and (2) the school's administrative readiness and infrastructure to implement technology-integrated instruction. From this population, the final research sample comprised 81 students (N = 81) aged approximately 9–10 years, enrolled during the 2024–2025 academic year. This age group was selected based on developmental appropriateness, as fourth-grade students possess the requisite cognitive maturity and reading proficiency to engage meaningfully with digital instructional materials and self-report assessment instruments.

Consistent with the study's quasi-experimental design, the sample was drawn from three intact classes to preserve the school's existing administrative structure. These classes were subjected to cluster random assignment, resulting in three homogeneous instructional conditions with equal group sizes: the augmented reality–based instruction group (n = 27), the video-based instruction group (n = 27), and the traditional instruction control group (n = 27). Data integrity was maintained throughout the instructional intervention, with all enrolled participants completing both the pre-test and post-test assessments, resulting in zero attrition.

Prior to data collection, strict ethical protocols were observed. Ethical approval was obtained from the relevant institutional authority, and formal permission was granted by the school administration. Written informed consent was secured from the parents or legal guardians of all participants, ensuring that student participation was strictly voluntary. Furthermore, measures were implemented to guarantee the anonymity and confidentiality of all participant data, which were utilized solely for research purposes. Accordingly, the findings should be interpreted with caution, as the use of a single Adiwiyata-certified elementary eco-school and a specific grade level limits the generalizability of the results to other educational contexts, regions, and age groups.

2.3. Data Collection Techniques

Data were collected using a pre-test–intervention–post-test procedure in accordance with the quasi-experimental research design. Prior to the instructional intervention, all participating students completed a pre-test to measure baseline levels of environmental knowledge, environmental attitudes, and environmental behavior. The pre-test was administered during regular class hours under standardized conditions by the classroom teacher, with guidance from the research team to ensure procedural consistency across groups.

Following the pre-test, students participated in an eight-week instructional intervention, during which each intact class received instruction according to its assigned instructional method. The augmented reality (AR) group engaged in technology-enhanced lessons utilizing AR-based learning materials designed to support interactive exploration of environmental concepts. The video-based instruction group received the same curricular content delivered through instructional videos incorporating visual and auditory explanations. The traditional instruction group was taught using conventional teacher-centered methods, including textbooks and verbal explanations, without the integration of digital media. To maintain internal validity, all groups covered identical environmental education topics aligned with the national curriculum and the Adiwiyata (eco-school) program objectives, and instruction was delivered for an equivalent duration and frequency across groups.

At the conclusion of the intervention period, a post-test was administered to all participants using the same instruments as the pre-test. The post-test was conducted under conditions identical to those of the pre-test to minimize testing bias. Throughout the data collection process, researchers monitored implementation fidelity to ensure that instructional procedures were followed as planned and that no additional interventions were introduced. All completed instruments were collected immediately after administration, coded anonymously, and securely stored for subsequent statistical analysis.

2.4. Research Instruments

Three standardized instruments were used to measure the multidimensional construct of environmental literacy: environmental knowledge, environmental attitudes, and pro-environmental behavior. All instruments were developed to be developmentally appropriate for fourth-grade students and were administered as both pre-tests and post-tests.

Table 1. Summary of Research Instruments

Instrument	Construct Measured	Number of Items	Response Format	Score Range	Reliability
Environmental Knowledge Test	Environmental Knowledge	20	Multiple-choice	0–20	KR-20 > 0.80
Environmental Attitude Scale	Environmental Attitudes	20	Likert (1–5)	20–100	$\alpha > 0.90$
Pro-Environmental Behavior Scale	Environmental Behavior	20	Likert (1–5)	20–100	$\alpha > 0.90$

2.4.1. Environmental Knowledge

Students' environmental knowledge was assessed using a standardized cognitive test consisting of 20 multiple-choice items, each with four response options and one correct answer. One point was awarded for each correct response, yielding total scores ranging from 0 to 20. The instrument measured students' understanding of core environmental concepts, including human–environment relationships, environmental issues, conservation practices, and sustainability principles aligned with the fourth-grade curriculum.

Content validity was established through alignment with national curriculum standards and expert review by educational researchers and experienced elementary teachers. Item analysis indicated acceptable levels of item difficulty and discrimination. Construct validity was examined using exploratory factor analysis (EFA), which demonstrated adequate sampling adequacy (KMO = 0.836) and a significant Bartlett's test of sphericity ($\chi^2(190) = 523.703$, $p < 0.001$), supporting the factorability of the data. The extracted factor solution accounted for 57.85% of the total variance, indicating a coherent underlying structure. Internal consistency reliability, assessed using the Kuder–Richardson Formula 20 (KR-20), exceeded 0.80 for both pre-test and post-test administrations, indicating strong reliability.

2.4.2. Environmental Attitudes

Environmental attitudes were measured using a 20-item Likert-type scale with five response options ranging from strongly disagree (1) to strongly agree (5). Total scores ranged from 20 to 100, with higher scores reflecting more positive environmental attitudes. The instrument assessed students' affective dispositions toward environmental protection, conservation, and sustainability.

Content validity was ensured through theoretical alignment with established environmental attitude frameworks and expert review by environmental education scholars. Construct validity was examined through EFA, which demonstrated excellent sampling adequacy (KMO = 0.935) and a significant Bartlett's test of sphericity ($\chi^2(190) = 1155.119$, $p < 0.001$). The extracted factor solution explained 61.92% of the total variance, indicating a strong and well-defined attitudinal structure. Internal consistency reliability, assessed using Cronbach's alpha, exceeded 0.90 for both administrations, reflecting excellent reliability.

2.4.3. Pro-Environmental Behavior

Students' pro-environmental behavior was assessed using a 20-item self-report scale rated on a five-point frequency scale ranging from never (1) to always (5), producing total scores from 20 to 100. The instrument measured the frequency of environmentally responsible behaviors related to waste management, energy conservation, sustainable consumption, and participation in environmental activities within students' daily contexts.

Content validity was established through expert evaluation by environmental education specialists. Construct validity was examined using EFA, which demonstrated excellent sampling adequacy (KMO = 0.938) and a significant Bartlett's test of sphericity ($\chi^2(190) = 1176.069$, $p < 0.001$). The extracted factor solution accounted for 63.45% of the total variance, indicating a strong and coherent behavioral construct. Internal consistency reliability, assessed using Cronbach's alpha, exceeded 0.90 for both pre-test and post-test administrations, indicating excellent reliability.

2.5. Data Analysis Techniques

All quantitative analyses were conducted using IBM SPSS Statistics (Version 26). Descriptive statistics, including means and standard deviations, were calculated to summarize students' pre-test and post-test scores in environmental knowledge, environmental attitudes, and environmental behavior across instructional groups. To examine the effects of instructional method while controlling for baseline differences, multivariate analysis of covariance (MANCOVA) and analysis of covariance (ANCOVA) were employed, consistent with recommended procedures for quasi-experimental educational research [67], [68]. In the multivariate analysis, instructional method served as the independent variable, post-test environmental knowledge, environmental attitudes, and environmental behavior were entered as dependent variables, and corresponding pre-test scores were included as covariates. When a significant multivariate effect was detected, follow-up univariate ANCOVA analyses were conducted to identify the specific outcome dimensions contributing to the overall effect.

Prior to inferential analyses, key assumptions of ANCOVA and MANCOVA were examined, including normality, linearity, homogeneity of variances, homogeneity of covariance matrices, homogeneity of regression slopes, absence of multicollinearity, and the presence of outliers. These assumptions were assessed using graphical inspections, skewness and kurtosis indices, Levene's test, and Box's M test [68], [69]. Where significant univariate effects were observed, Bonferroni-adjusted post-hoc pairwise comparisons based on estimated marginal means were performed to control for Type I error [65]. Effect sizes were reported using partial eta squared (η_p^2) to indicate the magnitude of instructional effects in covariance analyses, in line with conventions in educational research [66], with the level of statistical significance set at $\alpha = .05$ (two-tailed) for all analyses.

2.6. Research Procedures

The research procedures were implemented systematically following a structured sequence designed to ensure consistency, internal validity, and ethical compliance. Prior to data collection, ethical approval was obtained from the relevant institutional authority, and formal permission was secured from the school administration. Written informed consent was obtained from parents or legal guardians, and participants were informed that their participation was voluntary and that all data would be treated confidentially. Following these approvals, participants were selected based on the established inclusion criteria and assigned to instructional groups through cluster random assignment of intact classes, in accordance with the quasi-experimental research design.

The study followed a pre-test–intervention–post-test procedure. Initially, all participating students completed pre-test assessments measuring environmental knowledge, environmental attitudes, and pro-environmental behavior to establish baseline equivalence across groups. This was followed by an eight-week instructional intervention, during which each group received instruction according to its assigned instructional method—augmented reality–based instruction, video-based instruction, or traditional instruction. All groups were taught identical environmental education content aligned with the national curriculum and Adiwiyata (eco-school) program objectives, with equivalent instructional duration and learning activities to ensure comparability across conditions. Instructional implementation was monitored to maintain fidelity and prevent cross-contamination among groups. At the conclusion of the intervention period, post-test assessments were administered using the same instruments under standardized conditions to minimize testing bias. All data were subsequently collected, anonymized, coded, and analyzed using descriptive statistics, MANCOVA, and follow-up ANCOVA procedures as detailed in the data analysis section. To enhance clarity and replicability, the overall research process is summarized in Figure 1, which presents the procedural flow of the study.

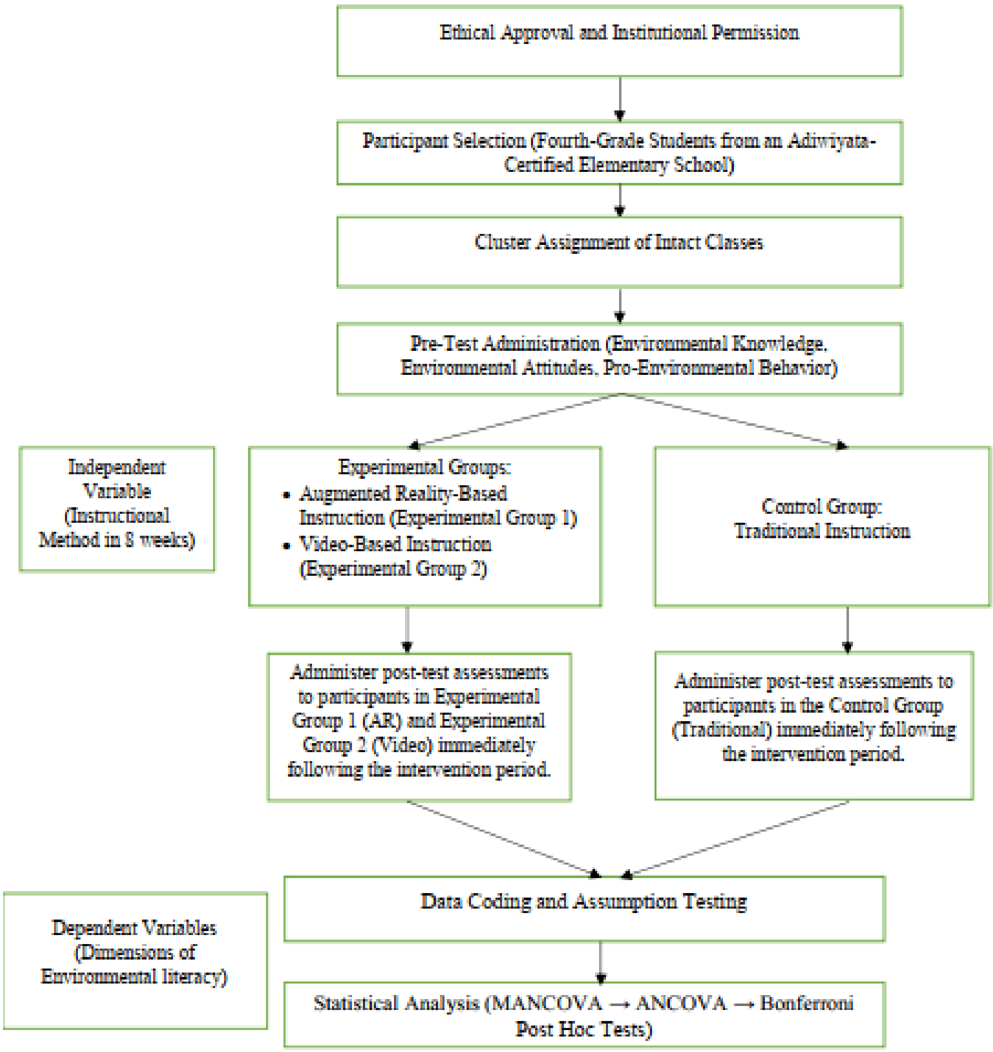

Figure 1. Research Proced

3. RESULTS AND DISCUSSION

3.1. Multivariate Effects of Instructional Methods on Environmental Literacy

As a preliminary step, descriptive statistics were examined to summarize students' post-test environmental literacy outcomes across the three instructional methods. Prior to conducting the Multivariate Analysis of Covariance (MANCOVA), statistical assumptions were rigorously evaluated. Multivariate normality was supported, with skewness and kurtosis values falling within acceptable ranges (|z| < 1.96). Homogeneity of covariance matrices was confirmed by a non-significant Box's M test ($p > 0.001$), and Levene's tests indicated equality of error variances across groups for all dependent variables ($p > 0.05$). Assumptions of linearity, absence of multicollinearity, and homogeneity of regression slopes were also satisfied, with all interaction terms between covariates and instructional method being non-significant ($p > 0.05$).

As shown in Table 2, descriptive results revealed a consistent hierarchical pattern across all dimensions of environmental literacy, with students in the augmented reality (AR) group attaining the highest post-test mean scores, followed by those in the video-based instruction group, and lastly those receiving traditional instruction. Although this pattern suggests a potential advantage for AR-based instruction, these descriptive differences alone do not establish instructional effectiveness and must be interpreted in conjunction with inferential analyses that control for baseline differences.

Table 2. Descriptive Statistics of Post-Test Environmental Literacy Outcomes by Instructional Method

Variable	Instructional Method	Mean	*SD*	*N*
Environmental Knowledge	Augmented Reality	14.37	4.124	27
	Video	12.00	4.377	27
	Traditional	10.81	4.591	27
Environmental Attitudes	Augmented Reality	77.04	17.361	27
	Video	66.89	20.260	27
	Traditional	61.30	18.332	27
Pro-Environmental Behavior	Augmented Reality	78.30	17.993	27
	Video	71.81	20.056	27
	Traditional	65.04	21.543	27

To examine whether these observed differences represented statistically significant instructional effects after controlling for baseline characteristics, a MANCOVA was conducted. Instructional method served as the independent variable, post-test environmental knowledge, attitudes, and pro-environmental behavior were entered as dependent variables, and corresponding pre-test scores were included as covariates. Results indicated a statistically significant multivariate effect of instructional method on students' combined environmental literacy outcomes, Wilks' Λ = 0.576, $F(6, 146) = 7.72$, $p < 0.001$, as presented in Table 3.

Table 3. Multivariate Analysis of Covariance (MANCOVA) Results for Instructional Method

Multivariate Test	Value	*F*	Hypothesis *df*	Error *df*	*p*	η_p^2
Wilks' Λ	0.576	7.720	6	146	< 0.001	0.241

The partial eta-squared value (η_p^2 = 0.241) indicates a substantial multivariate effect, suggesting that instructional method accounted for approximately 24.1% of the variance in students' combined environmental literacy outcomes after controlling for pre-test scores [66]. In applied educational research, this magnitude reflects a meaningful instructional influence rather than a trivial statistical artifact. Nevertheless, it is equally important to note that approximately 75% of the variance remained unexplained by instructional modality alone, underscoring the multifactorial nature of environmental literacy development.

From a theoretical perspective, these findings extend the application of the Cognitive Theory of Multimedia Learning (CTML) within environmental education contexts. The comparatively stronger adjusted outcomes observed for the AR group suggest that interactive and immersive learning environments may facilitate deeper generative processing by enabling learners to actively integrate visual, spatial, and contextual information, a core mechanism proposed within CTML and immersive learning frameworks [33], [50]. Unlike video-based instruction, which primarily supports observational learning, AR allows learners to engage directly with simulated environmental scenarios, thereby promoting active sense-making and potentially reducing extraneous cognitive load through spatially contiguous representations [19], [55]. However, these findings should not be interpreted as evidence of inherent or universal superiority of AR across all instructional settings; rather, they underscore the pedagogical value of interactivity when it is deliberately aligned with learning objectives and learners' cognitive capacities.

In relation to the Adiwiyata (eco school) framework, the results provide empirical support for the argument that institutional environmental culture alone may be insufficient to optimize students' environmental literacy. While prior research has emphasized school-wide policies and sustainability-oriented norms as key drivers of environmental learning [12], [71], the present findings suggest that instructional delivery functions as a critical mediating mechanism. Specifically, technology-enhanced pedagogical strategies appear to play an important role in translating institutional commitments into meaningful cognitive, attitudinal, and behavioral learning outcomes [13], [72]. While these findings underscore the potential of technology-mediated instruction within sustainability frameworks, a balanced assessment of the study's implications requires an acknowledgment of its inherent methodological constraints.

Despite these contributions, the findings should be interpreted with caution. The quasi-experimental design and relatively modest sample size limit the generalizability of the results beyond the studied context. In addition, the possibility of a novelty effect associated with AR-based instruction cannot be fully excluded, particularly given students' limited prior exposure to immersive technologies [56]. Environmental attitudes and pro-environmental behaviors were also assessed through self-report measures, which may be subject to social desirability bias [2]. Finally, external factors such as students' intrinsic motivation, family environmental practices, and community exposure to sustainability initiatives may have influenced outcomes independently of instructional method [48]. These methodological considerations necessitate a nuanced interpretation of the results, yet the robustness of the primary multivariate findings justifies further investigation into the specific dimensions contributing to the observed intervention effects.

Taken together, the significant multivariate effect underscores the importance of instructional design in shaping environmental literacy outcomes, while simultaneously highlighting the need for cautious interpretation and further research. To better understand the specific dimensions driving this overall effect (RQ1), follow-up univariate ANCOVA analyses were conducted and are reported in the subsequent section.

3.2. Effects of Instructional Methods on Environmental Knowledge

Following the significant multivariate effect observed for overall environmental literacy (RQ1), a univariate analysis of covariance (ANCOVA) was conducted to examine differences in students' environmental knowledge. Pre-test environmental knowledge was included as a covariate to control for baseline differences and isolate the effects of instructional method.

Table 4. ANCOVA Results for Post-Test Environmental Knowledge

Source	*df*	*F*	*p*	η_p^2
Instructional Method	2	11.17	< .001	0.230
Covariate (Pre_EK)	1	26.61	< .001	0.262
Error	75			

Note. Dependent variable: Post-test Environmental Knowledge.

The ANCOVA revealed a statistically significant main effect of instructional method on post-test environmental knowledge, $F(2, 75) = 11.17, p < 0.001$. The associated effect size was large ($\eta_p^2 = 0.230$), indicating that instructional modality accounted for approximately 23% of the variance in students' environmental knowledge after adjusting for pre-test scores. The covariate was also statistically significant ($p < 0.001$), confirming that prior knowledge was a strong predictor of post-test performance and supporting the use of ANCOVA to enhance statistical precision. Bonferroni-adjusted post-hoc comparisons were conducted to clarify group differences, as presented in Table 5.

Table 5. Bonferroni-Adjusted Pairwise Comparisons for Environmental Knowledge

Comparison	Mean Difference (*MD*)	*p*
AR – Video	3.139	0.004
AR – Traditional	4.381	< 0.001
Video – Traditional	1.241	0.575

Post-hoc results revealed a clear hierarchy of instructional effectiveness. Students in the augmented reality (AR) group achieved significantly higher adjusted mean scores than both the video-based instruction group (p = 0.004) and the traditional instruction group ($p < 0.001$). In contrast, no statistically significant difference was found between video-based and traditional instruction ($p = 0.575$).

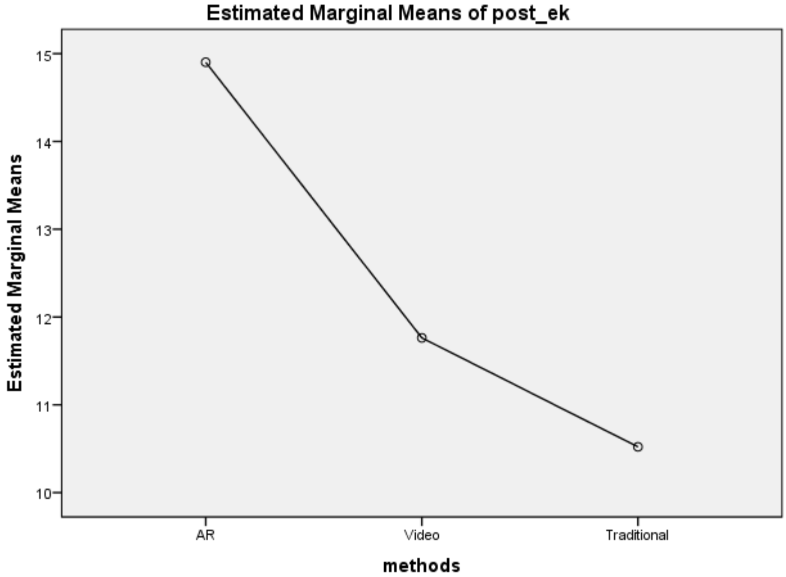

Figure 2. Estimated Marginal Means of Post-Test Environmental Knowledge

Figure 2 illustrates the estimated marginal means of post-test environmental knowledge across instructional methods after controlling for pre-test scores. Students receiving augmented reality–based instruction demonstrated the highest adjusted mean scores, followed by those receiving video-based instruction, while students in the traditional instruction group obtained the lowest adjusted scores.

From a theoretical standpoint, this study makes two explicit contributions. First, these findings extend CTML by suggesting that multimedia representation alone may be insufficient for substantial gains in environmental knowledge unless it elicits generative processing [33]. While both AR and video provide visualizations, AR uniquely allows learners to interact with spatially embedded content, which may promote deeper cognitive engagement and reduce extraneous processing demands compared with passive viewing [20], [47]. Consistent with this mechanism, only AR yielded significantly superior adjusted outcomes relative to video and traditional instruction in the present study. Beyond the cognitive mechanics of information processing, these findings also suggest that immersive and interactive modalities can shape learners' psychological engagement and learning-related motivation [48, [52].

Second, the results provide empirical support for the Cognitive Affective Model of Immersive Learning (CAMIL), which posits that immersion enhances learning primarily when it affords learners meaningful agency and action-based engagement [47]. In the present study, AR likely reduced extraneous cognitive load associated with mentally constructing abstract ecological systems by spatially aligning digital information with the physical environment. This spatial contiguity enabled learners to devote greater cognitive resources to generative processing, thereby facilitating deeper knowledge acquisition [72]. However, these advantages appear to be contingent upon the interactive nature of the medium, as evidenced by the notably different performance of non-interactive digital tools.

Equally important, the absence of a significant difference between video-based and traditional instruction carries important pedagogical implications. This finding challenges the common assumption that digital media is inherently more effective than conventional teaching. Although instructional video offers dynamic visual content, it often remains a predominantly passive learning experience when learners are positioned as observers rather than active participants [19], [37]. Without embedded interactivity or inquiry-oriented tasks, video-based instruction may not elicit higher levels of cognitive engagement than well-structured teacher-led lessons [22]. The parity observed between these two groups is therefore not an isolated finding, but aligns with established research highlighting the limitations of non-interactive multimedia for promoting deep learning.

This result aligns with recent meta-analytic evidence indicating that passive video instruction frequently produces learning outcomes comparable to traditional methods when learner interaction is minimal [19], [73]. Within the context of the Adiwiyata (eco school) program, this suggests that simply substituting textbooks with video content is unlikely to substantially improve students' environmental knowledge. Instead, meaningful gains appear to depend on instructional designs that promote active engagement with environmental concepts, whether through AR or other inquiry-based pedagogical strategies [51]. Collectively, these findings highlight that interactivity, rather than digitization alone, is the critical mechanism driving knowledge acquisition in environmental education.

3.3. Effects of Instructional Methods on Environmental Attitudes

Following the significant multivariate effect observed for overall environmental literacy, a univariate analysis of covariance (ANCOVA) was conducted to examine differences in students' environmental attitudes. Pre-test environmental attitudes were included as a covariate to control for baseline affective dispositions and isolate the effects of instructional method.

Table 6. ANCOVA Results for Post-Test Environmental Attitudes

Source	*df*	*F*	*p*	η_p^2
Instructional Method	2	9.47	< 0.001	0.202
Covariate (Pre_EA)	1	32.74	< 0.001	0.304
Error	75			

Note. Dependent variable: Post-test Environmental Attitudes.

The ANCOVA revealed a statistically significant main effect of instructional method on post-test environmental attitudes, $F(2, 75) = 9.47$, $p < 0.001$. The associated effect size was large ($\eta_p^2 = 0.202$), indicating that instructional modality accounted for approximately 20.2% of the variance in students' environmental attitudes after adjusting for pre-test scores. The covariate was also statistically significant ($p < 0.001$), confirming that students' initial attitudes strongly predicted post-intervention outcomes. Bonferroni-adjusted post-hoc comparisons based on estimated marginal means were conducted to clarify group-level differences, as presented in Table 7.

Table 7. Bonferroni-Adjusted Pairwise Comparisons for Environmental Attitudes

Comparison	Mean Difference (MD)	*p*
AR – Video	9.040	0.067
AR – Traditional	17.300	< 0.001
Video – Traditional	8.260	0.110

Post-hoc analyses revealed a refined pattern. Students receiving augmented reality (AR)–based instruction demonstrated significantly more positive environmental attitudes than those in the traditional instruction group ($p < 0.001$). However, differences between AR and video-based instruction ($p = 0.067$) and between video-based and traditional instruction ($p = 0.110$) did not reach statistical significance.

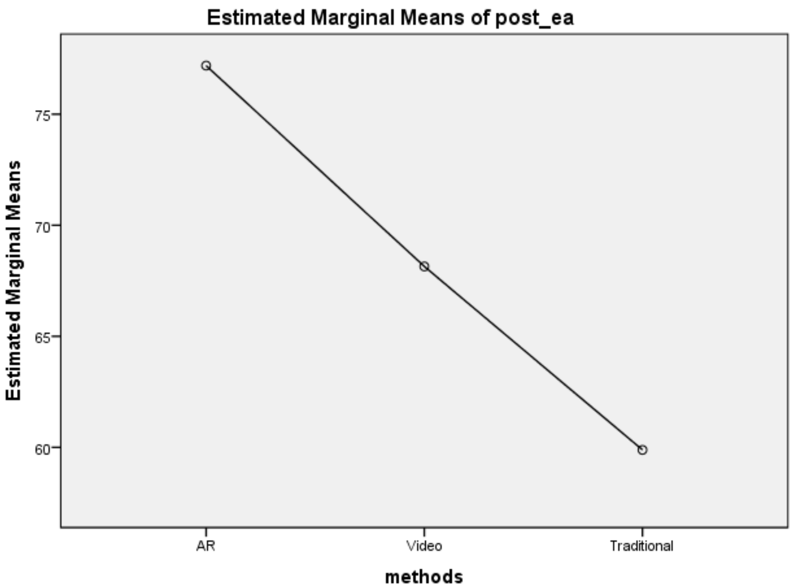

Figure 3. Estimated Marginal Means of Post-Test Environmental Attitudes

Figure 3 displays the estimated marginal means of post-test environmental attitudes across instructional methods after controlling for pre-test scores. Consistent with the ANCOVA and post-hoc results, augmented reality–based instruction yielded the highest adjusted attitude scores, followed by video-based instruction and traditional instruction.

From a theoretical perspective, these findings make an explicit contribution to the Cognitive Affective Model of Immersive Learning (CAMIL). Specifically, the significant advantage of AR over traditional instruction is consistent with CAMIL, which posits that affective learning benefits emerge when immersive technologies generate a strong sense of presence and learner agency, thereby enhancing intrinsic motivation and self-efficacy [47]. This study extends CAMIL by demonstrating that such affective gains are observable within elementary environmental education contexts, where learners are still forming foundational environmental values.

In environmental learning settings, AR does more than present information; it situates learners within simulated ecological scenarios and supports contextualized experiences of environmental consequences [41], [51]. This experiential relevance fosters situational interest, which has been identified as a critical precursor to enduring attitudinal change and value internalization [1], [50]. The present findings therefore suggest that interactive agency—rather than exposure to visual content alone—is a key mechanism through which environmental attitudes are shaped.

Equally important, the absence of a statistically significant difference between video-based and traditional instruction challenges the assumption that visual media automatically elicits empathy or pro-environmental concern [19], [34]. Although instructional video offers vivid imagery, it often positions learners as passive observers, and learning outcomes depend on whether video use is designed to prompt active cognitive engagement rather than simple viewing [19], [37]. Without interactive engagement, video-based instruction may fail to generate the emotional resonance necessary for meaningful attitudinal change, reinforcing broader evidence that passive multimedia alone is a limited tool for affective learning.

This interpretation aligns with recent systematic reviews indicating that while video-based instruction can support cognitive learning, its impact on affective outcomes tends to plateau in the absence of active pedagogical integration [73], [74]. For Adiwiyata-certified eco-schools seeking to cultivate environmental stewardship, these findings suggest that simply incorporating videos into instruction is unlikely to produce substantial attitudinal shifts. Instead, pedagogical approaches that promote learner interaction, contextualized decision-making, and experiential engagement appear essential for translating environmental knowledge into positive environmental attitudes [51], [72]. The pivotal role of this interactive agency is empirically illustrated when examining the specific comparative performance between the two digital modalities investigated in this study.

Notably, the marginal difference between AR and video-based instruction ($p = 0.067$) further underscores the importance of interactivity. While visualization may contribute to affective engagement, it appears insufficient on its own to reliably outperform traditional instruction. Rather, it is the combination of visualization and interaction characteristic of AR-based learning that approaches the threshold necessary for meaningful attitudinal change in environmental education.

3.4. Effects of instructional methods on pro-environmental behavior

Following the significant multivariate effect observed for overall environmental literacy, a univariate analysis of covariance (ANCOVA) was conducted to examine differences in students' pro-environmental behavior. Pre-test pro-environmental behavior was included as a covariate to control for baseline behavioral tendencies and isolate the effects of instructional method.

Table 8. ANCOVA Results for Post-Test Pro-Environmental Behavior

Source	*df*	*F*	*p*	η_p^2
Instructional Method	2	7.86	0.001	0.173
Covariate (Pre_PEB)	1	52.48	< 0.001	0.412
Error	75			

Note. Dependent variable: Post-test Pro-Environmental Behavior.

The ANCOVA revealed a statistically significant main effect of instructional method on post-test pro-environmental behavior, $F(2, 75) = 7.86$, $p = 0.001$. The associated effect size was moderate ($\eta_p^2 = 0.173$), indicating that instructional modality accounted for approximately 17.3% of the variance in students' reported pro-environmental behavior after adjusting for pre-test scores. The covariate demonstrated a strong effect ($\eta_p^2 = 0.412$, $p < 0.001$), underscoring that prior behavioral habits are a dominant predictor of subsequent behavior. Bonferroni-adjusted post-hoc pairwise comparisons were conducted to further examine specific group differences, as presented in Table 9.

Table 9. Bonferroni-Adjusted Pairwise Comparisons for Pro-Environmental Behavior

Comparison	Mean Difference (*MD*)	*p*
AR – Video	7.353	0.119
AR – Traditional	12.702	0.002
Video – Traditional	5.350	0.397

Post-hoc analyses indicated that students receiving augmented reality (AR)–based instruction reported significantly higher levels of pro-environmental behavior than those in the traditional instruction group ($p = 0.002$).

However, differences between AR and video-based instruction (p = 0.119), as well as between video-based and traditional instruction (p = 0.397), were not statistically significant.

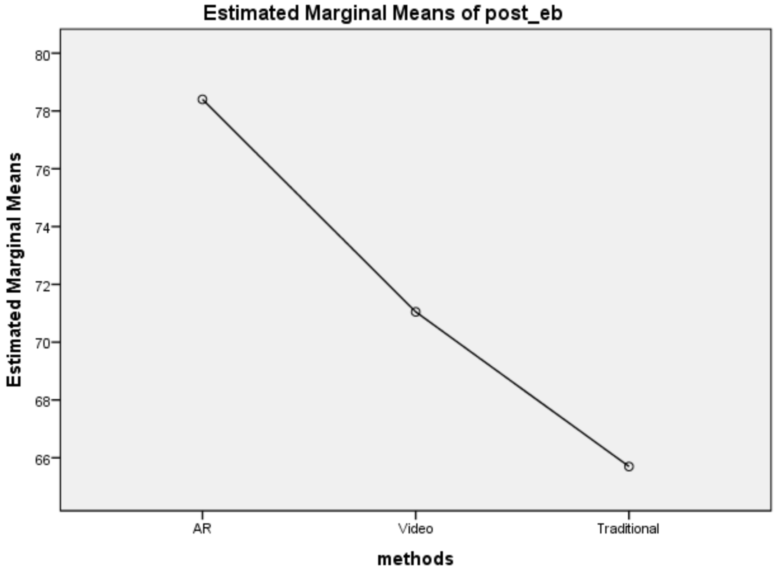

Figure 4. Estimated Marginal Means of Post-Test Pro-Environmental Behavior

Figure 4 illustrates the adjusted post-test pro-environmental behavior scores across instructional methods after controlling for pre-test scores. Although AR-based instruction yielded the highest adjusted mean, the separation among instructional methods was less pronounced than that observed for environmental knowledge and attitudes.

From a theoretical standpoint, these findings make an explicit contribution to both the Theory of Planned Behavior (TPB) and the Model of Responsible Environmental Behavior. Specifically, the superior performance of the AR group relative to traditional instruction provides empirical support for TPB's assertion that perceived behavioral control is a critical precursor to action [5]. By allowing students to virtually rehearse environmentally responsible actions such as waste sorting or ecosystem restoration AR appears to strengthen learners' confidence in their ability to perform such behaviors in real-world contexts [49]. This finding extends TPB by demonstrating that perceived behavioral control can be meaningfully enhanced through immersive, simulation-based pedagogy, even among elementary school learners who are still developing habitual patterns of behavior.

The absence of a statistically significant difference between video-based and traditional instruction has important pedagogical implications. This finding challenges the assumption that digital media alone is sufficient to promote behavioral change. Consistent with the well-documented knowledge–behavior gap, the mere provision of environmental information whether through textbooks or videos does not automatically translate into pro-environmental action [75]. Without opportunities for active decision-making or behavioral rehearsal, video-based instruction remains a largely spectator experience and therefore fails to foster behavioral adoption [54]. This suggests that replacing traditional materials with video content, without fundamentally redesigning instructional pedagogy, is unlikely to yield meaningful improvements in students' pro-environmental behavior.

A comparative interpretation of effect sizes further clarifies these findings. The effect size observed for pro-environmental behavior (η_p^2 = 0.173) was notably smaller than those identified for environmental knowledge and attitudes. This pattern reflects a well-established hierarchy of educational outcomes, wherein behavioral change is more resistant to short-term instructional interventions than cognitive or affective learning [76]-[78]. Accordingly, the moderate behavioral effect identified in this study highlights both the promise and the limitations of technology-enhanced instruction, underscoring the need for sustained reinforcement and contextual support to achieve durable behavioral transformation.

These results are broadly consistent with prior meta-analytic evidence demonstrating that AR-based instruction produces stronger learning outcomes than traditional approaches [48]. In line with earlier studies, AR in the present research promoted higher engagement and experiential understanding [72]. Importantly, however, this study adds nuance by showing that video-based instruction often positioned as a modern alternative did not significantly outperform traditional teaching methods in shaping pro-environmental behavior. This finding corroborates prior evidence indicating that passive multimedia consumption is insufficient for value internalization in the absence of interactive engagement [79]. Thus, the effectiveness of educational technology appears to depend less on its novelty and more on the degree to which it enables learners to actively practice and internalize targeted behaviors.

The primary novelty of this research lies in its rigorous three-arm comparison of augmented reality, video-based, and traditional instruction within the Adiwiyata (eco school) framework. Few existing studies have explicitly isolated the role of interactivity by directly comparing AR with video while simultaneously examining environmental knowledge, attitudes, and pro-environmental behavior. Moreover, this study is among the first to apply the Cognitive Affective Model of Immersive Learning (CAMIL) in an Indonesian primary education context, illustrating how immersive technology can function as a pedagogical amplifier within schools that already possess a strong environmental culture [47]. Together, these findings provide a robust theoretical and empirical foundation for re-evaluating how environmental education is designed and implemented in real-world classroom settings.

From an instructional design perspective, the findings suggest that Adiwiyata-certified eco-schools should favor interactive, experiential learning designs over passive media when targeting pro-environmental behavior. This aligns with sustainability education frameworks that emphasize action competence and practice-oriented learning rather than exposure-based approaches [3], [80]. AR may be particularly suitable because it can anchor representations in the learner's environment and support situated interaction, a pattern also reported in prior AR-for-environmental-education work [41], [51]. Consistent with broader evidence, effects are more likely when technology use is integrated with learner-centered, interactive design principles, rather than functioning as a direct substitute for conventional delivery [53], [81]. Thus, investments should include teacher professional development and instructional design support to enable effective implementation in green-school contexts.

Limitations should be considered when interpreting the results. AR benefits may partly reflect a novelty effect, producing short-term gains that may attenuate over time [56]. The eight-week duration may be insufficient to capture behavioral consolidation, which typically requires longer and more ecologically embedded interventions than those needed for knowledge or attitude change [76], [77]. Further, self-report outcomes can be influenced by social desirability in norm-salient contexts, and the attitude–behavior relationship is not straightforward [2]. Finally, the study's focus on a single cohort of fourth-grade students in Semarang limits generalizability to other contexts.

4. CONCLUSION

This study demonstrates that instructional method plays a significant role in shaping fourth-grade students' environmental literacy within an Adiwiyata-certified elementary eco-school. Multivariate analyses revealed a significant overall effect of instructional method on environmental knowledge, environmental attitudes, and pro-environmental behavior after controlling for pre-test scores, confirming that pedagogical design remains influential even in schools with established environmental orientations. At the univariate level, augmented reality (AR)–based instruction produced significantly stronger outcomes than traditional instruction across all dimensions of environmental literacy. These effects were most pronounced for environmental knowledge and environmental attitudes, indicating that immersive and interactive learning environments are particularly effective in enhancing cognitive understanding and affective engagement. In contrast, instructional effects on pro-environmental behavior were more modest, reflecting the greater complexity and resistance of behavioral change to short-term instructional interventions. Notably, video-based instruction did not significantly outperform traditional instruction in the affective or behavioral domains, suggesting that digital visualization alone is insufficient to drive deeper environmental value internalization or action. Collectively, these findings provide empirical support for multidimensional models of environmental literacy, which posit that knowledge and attitudes are more immediately responsive to pedagogical interventions, whereas behavioral development requires sustained reinforcement and opportunities for active participation.

From a theoretical perspective, the findings extend the Theory of Planned Behavior and the Model of Responsible Environmental Behavior by demonstrating that immersive, simulation-based instruction can strengthen perceived behavioral control, thereby supporting the intention-to-action pathway in environmental education. Practically, the results highlight the potential of integrating interactive technologies such as augmented reality into Adiwiyata (eco school) programs to enhance learning quality, while simultaneously underscoring that technology alone is insufficient to produce durable behavioral change. For long-term impact, technology-enhanced instruction should be embedded within consistent, school-wide sustainability practices that reinforce behavioral enactment beyond the classroom. Future research should therefore adopt longitudinal and mixed-method designs to examine how repeated exposure to interactive learning environments, in combination with institutional culture, translates cognitive and affective gains into enduring pro-environmental behavior.

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AUTHOR CONTRIBUTIONS

Conceptualization, M.S. and F.R.; Methodology, M.S. and F.R.; Software, M.S.; Validation, M.S., F.R., I.Z., and U.U.; Formal Analysis, M.S.; Investigation, M.S.; Resources, F.R., I.Z., and U.U.; Data Curation, M.S.; Writing – Original Draft Preparation, M.S.; Writing – Review & Editing, F.R., I.Z., and U.U.; Visualization, M.S.; Supervision, F.R., I.Z., and U.U.; Project Administration, F.R.; Funding Acquisition, I.Z.

INFORMED CONSENT STATEMENT

Informed consent was obtained from all participants involved in the study. Prior to participation, each participant received a detailed explanation of the study's objectives, procedures, potential risks, and benefits. Participation was voluntary, and all participants provided written informed consent..

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

USE OF ARTIFICIAL INTELLIGENCE (AI)-ASSISTED TECHNOLOGY

Not applicable.

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