

AUGMENTED REALITY FOR ENVIRONMENTAL EDUCATION: THE EFFECTIVENESS OF AN EXPERIENTIAL AND PLACE-BASED HYBRID MODULE IN IMPROVING ELEMENTARY SCHOOL STUDENTS' ECOLOGICAL AWARENESS

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ABSTRACT

Increasingly complex environmental degradation in Indonesia demands a shift in ecological awareness from an early age, yet environmental education at the elementary school level remains dominated by conventional, decontextualized instruction, while the use of augmented reality (AR) in Indonesian environmental education remains very limited. This study aims to describe the implementation process of a hybrid AR-based learning module integrating Experiential Learning Theory and Place-Based Education, while also examining its effectiveness on elementary students' ecological awareness. This study employed a Quasi-Experimental Design using a Nonequivalent Pretest-Posttest Control Group Design, involving 67 fourth-grade students (34 experimental, 33 control) in Sukabumi Regency. The experimental group followed the hybrid AR module for eight weeks (16 sessions), while the control group received conventional instruction. Results showed excellent implementation fidelity (90.3%). The experimental group achieved moderate-category improvement in environmental knowledge (N-Gain 0.50; large effect size 1.87), pro-environmental attitude (N-Gain 0.53), and environmental concern/intention (N-Gain 0.49), substantially higher than the control group, which only reached the low category across all three dimensions (N-Gain 0.17–0.18). It is concluded that the hybrid AR module was well implemented and effectively enhances elementary students' ecological awareness holistically across the cognitive, affective, and conative dimensions, with potential for broader adaptation in environmental education in Indonesia.

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INTRODUCTION

The global environmental crisis has become an urgent challenge that demands immediate responses from various sectors, including education. Indonesia faces serious environmental pressures, including the high national waste generation mostly plastic waste that has not yet been managed through an adequate circular economy system, potentially polluting the environment while wasting its economic potential (Rifal et al., 2024). A similar problem occurs in water pollution, as seen in the Citarum River, once named the most polluted river in the world, yet still serving as a source of livelihood for approximately 9 million residents despite being heavily contaminated by waste from around 2,000 factories along its course (Marsingga, 2020). This environmental degradation is further exacerbated by Indonesia's high rate of primary forest loss, which, according to Margono, Potapov, Turubanova, Stolle, and Hansen (2014), placed Indonesia among the countries with the highest primary forest loss rates in the world in the early 21st century, contributing to biodiversity loss and increased risk of ecological disasters. These conditions underscore the importance of transforming how humans understand and interact with the environment, a transformation that should begin from an early age through effective environmental education. Such a transformation cannot rely solely on regulatory or technological interventions; it requires cultivating environmentally conscious citizens from childhood, since the values, knowledge, and habits formed during this period tend to shape long-term environmental behavior.

Early childhood is a critical period in the development of environmental literacy, and children's positive experiences with nature have been shown to be closely related to the emergence of environmental concern and participation in pro-environmental behavior in adulthood (Ardoin & Bowers, 2020). However, conventional learning has often failed to provide meaningful direct experiences for understanding complex and abstract environmental issues (Guevara-Herrero et al., 2024). In this context, augmented reality (AR) technology offers an innovative approach to strengthen environmental education, as it enables the integration of digital content with the real world through immersive and contextual learning experiences. Several studies indicate that AR has great potential in helping visualize complex ecological processes while enhancing students' emotional engagement (Ladykova et al., 2024 ; Simon et al., 2025). Similar findings have emerged in the Indonesian context, where locally grounded AR has been shown to improve elementary students' learning outcomes (Wijayati, 2024).

Although AR has proven effective in environmental education in various countries, its application in Indonesia particularly at the elementary school level remains far behind. This gap is twofold: on one hand, existing AR research for elementary schools in Indonesia has not specifically targeted environmental education (Husniah et al., 2020; MZ et al., 2022; Rusli et al., 2022) on the other hand, existing environmental education research in Indonesia has not yet adopted AR as a learning medium (Sukma et al., 2020; Prayogo et al., 2024). This double gap has only recently begun to be addressed. Shobirin, M. et al., (2026) compared the effectiveness of AR-based, video-based, and conventional instruction on the environmental literacy of fourth-grade students at an Adiwiyata school in Semarang. However, their study did not explicitly integrate Experiential Learning Theory and Place-Based Education into its AR design, nor did it package these elements into a single hybrid learning model combining printed modules, AR, and interactive simulation.

This gap becomes even more critical from a conceptual standpoint. Most environmental education studies measure students' knowledge, attitudes, and intentions separately, without integrating them into a single, holistic construct of ecological awareness, which makes the comprehensive measurement of intervention effectiveness difficult (van de Wetering et al., 2022; Ardoin et al., 2020). Unlike previous AR research in Indonesia that developed IPAS or ecoliteracy learning media without integrating both theoretical frameworks with Place-Based Education itself emphasizing the importance of connecting the learning process to students' local context, culture, and environment (Yemini et al., 2025; Taufik Afandi & Umi Mahmudah, 2024; Narulita et al., 2024) this study offers a distinct novelty: an AR-based hybrid learning module that explicitly integrates Experiential Learning Theory and Place-Based Education while measuring ecological awareness holistically across three dimensions cognitive, affective, and conative within a single coherent construct.

Based on these gaps, this study aims to describe the implementation process of an Augmented Reality-based hybrid learning module that integrates Experiential Learning Theory and Place-Based Education for elementary school students, while also testing its effectiveness in improving environmental knowledge, environmental care attitudes, and environmental action intentions regarding local Indonesian environmental issues. This study is expected to provide theoretical benefits in the form of empirical evidence on the integration of AR with experiential and contextual pedagogical approaches, as well as practical benefits in the form of a replicable learning model for elementary school teachers to foster students' ecological awareness of environmental issues in their surroundings.

METHOD

This study employs a quantitative approach with an experimental method to examine the effectiveness of an Augmented Reality (AR)-based hybrid module on the ecological awareness of elementary school students. The research consists of a preliminary (development) phase to produce a valid and feasible AR module, and a main (effectiveness testing) phase as the primary focus of the study. The AR module was developed using the ADDIE model (Analysis, Design, Development, Implementation, Evaluation).

The research design employs a Quasi-Experimental Design with a Nonequivalent Pretest-Posttest Control Group Design. The experimental group received instruction using the AR hybrid module for eight weeks (sixteen sessions, twice a week), while the control group used conventional textbook-based instruction; both groups were measured through pretests and posttests. The independent variable was the type of learning media, the dependent variable was ecological awareness encompassing cognitive, affective, and conative dimensions, while control variables included students' age, teaching staff, learning duration, and learning materials, which were equated between both groups from the research design stage. The initial equivalence of both groups prior to treatment was examined through a pretest homogeneity test, which indicated statistical equivalence at baseline not that all control variables were fully controlled throughout the course of the study.

The study was conducted at an elementary school in Sukabumi Regency during July–August. The school was selected using purposive sampling based on criteria of A accreditation, availability of digital facilities, and teacher commitment to collaboration. The research population consisted of all fourth-grade students at the school, divided into four class groups. From these four groups, two classes were selected using an intact group technique as the experimental and control groups. The role of each selected class (experimental or control) was then determined through a manual lottery: two slips of paper labeled "experimental" and "control" were prepared, and a representative from each class drew one slip to determine its assigned group. The total research sample comprised 67 students, consisting of 34 students in the experimental group and 33 students in the control group.

Data were collected through instruments that had undergone expert review, including empirical testing for the knowledge instrument. The instrument package comprises an environmental knowledge test for the cognitive domain consisting of ten multiple-choice questions and five essay items spanning Bloom's Taxonomy levels C1 to C6; an environmental attitude scale and an action intention scale for the affective and conative domains, respectively, each containing fifteen dichotomous (Yes/No) items; a learning observation sheet formatted as a 4-point rubric to assess implementation fidelity and student engagement; and a student response questionnaire to measure the practicality and usability of the AR module. A dichotomous scale (Yes/No) was chosen for the attitude and intention instruments considering that the study participants were fourth-grade elementary students in the concrete-operational stage of cognitive development. Consequently, a simple, unambiguous response scale was deemed more easily comprehended and effective in minimizing response bias compared to a multi-point Likert scale, which demands a more abstract capacity for fine-grained discrimination of agreement levels. Similar considerations are widely adopted in environmental education research instruments tailored for primary school-aged children. The validity of all instruments was tested through expert judgment (content, construct, and language), with revisions made accordingly, and further reinforced through empirical validity testing using item-total correlation—point-biserial for the dichotomous items (multiple-choice, attitude, and intention scales) and product-moment for the essay items. Reliability was calculated using matching techniques: KR-20 for the dichotomous instruments (multiple-choice test, attitude scale, and intention scale) and Cronbach's Alpha for the polytomous essay items. Both validity and reliability coefficients were interpreted using the same classification, with instruments considered reliable if they fell within the High or Very High category.

Data analysis differed according to each dimension's characteristics. For the cognitive dimension, data were analyzed using parametric statistics through normality and homogeneity prerequisite tests, followed by an Independent Samples T-Test; if data were normally distributed but not homogeneous, testing was shifted to Welch's T-Test, while non-normally distributed data were analyzed using the non-parametric Mann-Whitney U Test. For the affective and conative dimensions, questionnaire data were analyzed descriptively through mean scores based on categorical intervals (Very Good, Good, Fair, Poor), percentages of Yes/No responses, and an N-Gain Score test to measure the magnitude of score improvement within each group. It should be acknowledged that the analysis of these two dimensions did not include between-group inferential testing (such as a t-test or Mann-Whitney U test); therefore, differences in outcomes between the experimental and control groups on the affective and conative dimensions cannot yet be considered statistically

significant and remain limited to descriptive trends. This methodological limitation is an important consideration when interpreting the study's findings.

RESULT AND DISCUSSION

Feasibility of the AR Hybrid Module and Research Instruments

The Augmented Reality-based hybrid module "EcoLearn AR" was developed using the ADDIE model and validated by media experts and content experts prior to use in the effectiveness testing phase. The media expert validation yielded a feasibility percentage of 91.7% (Very Good category), with six of the seven aspects falling into the Very Good category and only the layout/typography aspect falling into the Good category (75.0%); feedback from the validator included adjusting the module size, improving layout and typography consistency, enlarging the QR code or marker size, and improving image print quality. The content expert validation yielded a percentage of 88.3% (Very Good category), with the highest score achieved in ecological awareness content (100%) and the lowest in language readability (75.0%); feedback provided included strengthening reflection questions at each stage of experiential learning, updating environmental data source references, and simplifying several sentences to be more communicative for elementary school-aged readers. The three research instruments the environmental knowledge test, the environmental care attitude scale, and the action care/intention scale were also declared valid, with an overall average feasibility of 96.7%. Thus, it can be concluded that the module and instruments used in the effectiveness testing phase met adequate feasibility standards as a prerequisite for testing the learning impact.

To provide a visual overview of the developed module, Figures 1 to 4 present the module's cover design, content layout, AR visualization output, and instructional video display.

Figure 1. Cover Display of the "EcoLearn AR" Module



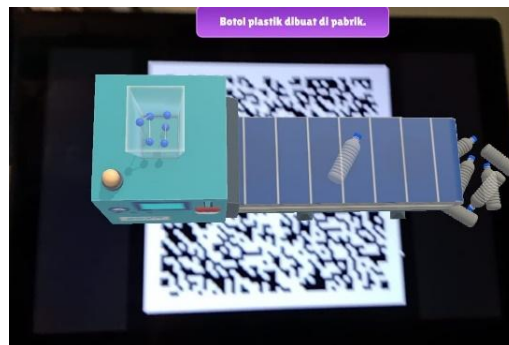
Source: Researcher's Documentation, 2026

Figure 2. Content Display of the Module



Source: Researcher's Documentation, 2026

Figure 3. Augmented Reality (AR) Visualization



Source: Researcher's Documentation, 2026

Figure 4. Instructional Video Display



Source: Researcher's Documentation, 2026

Learning Process in the Experimental and Control Groups

Learning in the experimental group began with a pretest to measure students' baseline ecological awareness, followed by the implementation of the AR-based hybrid module for eight weeks (16 sessions, twice a week), covering four main topics: Waste Management, Biodiversity, Water Pollution, and Climate Change. Each topic was delivered over four meetings that consistently followed the module structure: introduction and concept orientation, in-depth material through AR/video visualization, game activities as formative evaluation, the experiential activity "Let's Try It" involving direct observation or experimentation in the school environment, and real action and reflection in the form of environmental conservation practices. For example, in Topic 1, students observed the impact of waste through the AR visualization "The Journey of a Plastic Bottle," conducted the field observation "School Waste Detective," and then practiced composting; a similar pattern was applied in subsequent topics with adjusted experiential activities, such as "Hunting for Living Creatures at School" in Topic 2, "Water Quality Detective" in Topic 3, and "Calculating Carbon Footprint" in Topic 4. The learning series concluded with a posttest in the 16th session. This structure consistently aligned with the integration of Experiential Learning Theory and Place-Based Education, so that students not only gained knowledge (cognitive) but also experienced the continuous formation of attitudes (affective) and the drive to act (conative). To provide a visual illustration of the implementation process, Figures 5 to 7 present the delivery of learning materials, students' use of the AR feature, and hands-on field practice activities during the experimental group's learning sessions.

Figure 5. Delivery of Learning Materials to Students



Source: Researcher's Documentation, 2026

Figure 6. Students' Use of the Augmented Reality (AR) Feature



Source: Researcher's Documentation, 2026

Figure 7. Hands-on Field Practice Activity



Source: Researcher's Documentation, 2026

Learning in the control group also began with a pretest and ended with a posttest in the 16th session, covering the same material (four topics identical to the experimental group) and the same duration (eight weeks, 16 sessions), but without using the AR hybrid module, interactive visualization, or place-based experiential activities. Learning was conducted through lecture methods, question-and-answer sessions, group discussions, and completion of student worksheets based on the thematic textbook. In Topic 1, for example, students only learned about types of waste and the 3R principle through readings and discussion, then completed written assignments without direct observation in the school environment. The same pattern was repeated in other topics: flora-fauna identification based only on textbook images (Topic 2), practice questions on water characteristics without direct water quality testing (Topic 3), and written assignments on climate change mitigation without real action such as calculating carbon footprints or planting trees (Topic 4). Overall, the learning process in the control group was oriented toward text-based information delivery and exercises, without interactive visualization, environmental observation, or real environmental conservation action. To provide a visual illustration of this process, Figure 8 presents the implementation of conventional textbook-based learning in the control group.

Figure 8. Implementation of Conventional Learning in the Control Group



Source: Researcher's Documentation, 2026

Learning Implementation Fidelity

The implementation of learning in the experimental group was observed over 16 meetings covering four ecology-themed modules: Waste Management, Biodiversity, Water Pollution, and Climate Change. Observations used a structured observation sheet consisting of 18 indicators across six components: (A) Introduction and Orientation, (B) AR Hybrid Module Implementation, (C) Experiential Learning, (D) Place-Based Learning, (E) Student Response and Ecological

Awareness, and (F) Closing and End-of-Session Reflection. Each module had a maximum score of 72 points. A recapitulation of the learning implementation results for each module is presented in Table 1.

Table 1. Recapitulation of Learning Implementation per Module

Module	Score	Percentage	Category
Module 1 – Waste Management	56/72	77.8%	Good
Module 2 – Biodiversity	66/72	91.7%	Very Good
Module 3 – Water Pollution	66/72	91.7%	Very Good
Module 4 – Climate Change	72/72	100.0%	Very Good
Average	65/72	90.3%	Very Good

Source: Processed by Researcher, 2026

Based on Table 1, the implementation of the AR hybrid module achieved an average implementation rate of 90.3%, categorized as Very Good. Learning implementation showed a consistent increase from one module to the next. Module 1 achieved a percentage of 77.8% (Good), then increased to 91.7% in Modules 2 and 3, and reached 100% in Module 4. Although Modules 2 and 3 recorded the same overall percentage, component-level analysis revealed a different pattern between the two: the AR hybrid module implementation component (Component B) actually declined from 87.5% to 75.0% in Module 3 due to technical issues including device crashes while loading 3D animations and inaccessible AR links but this decline was offset by increases in the Experiential Learning (Component C) and Place-Based Learning (Component D) components, both of which rose from 91.7% to 100% in the same module, resulting in an unchanged overall score. This indicates that the equal total percentage between Modules 2 and 3 masks an underlying fluctuation at the component level: technical constraints on the AR feature temporarily hindered implementation, yet the strength of experiential and location-based activities was maintained and even improved, preventing an overall decline in learning quality. This increasing pattern indicates that the implementation process became increasingly optimal as teachers and students adapted to the use of the Augmented Reality-based hybrid module.

Effectiveness on Environmental Knowledge (Cognitive)

The effectiveness of the Augmented Reality (AR)-based hybrid module on environmental knowledge was analyzed through descriptive statistics, prerequisite tests, hypothesis testing, and effect size. Descriptive analysis aimed to describe changes in learning outcomes before and after treatment in the experimental and control groups.

The results in Table 2 show that both groups experienced an increase in environmental knowledge after learning. However, the increase in the experimental group was higher than in the control group. The average score of the experimental group increased by 18.923 points, while the control group increased by only 7.173 points. In addition, the decrease in standard deviation in the experimental group indicates that students' concept mastery became more evenly distributed after learning.

Table 2. Descriptive Statistics Results for Environmental Knowledge

Group	Stage	N	Mean	SD	Minimum	Maximum
Experimental	Pretest	34	64.021	15.7582	30.0	86.7
	Posttest	34	82.944	10.2069	66.7	100.0
Control	Pretest	33	60.412	4.6903	50.0	70.0
	Posttest	33	67.585	5.5502	53.3	76.7

Source: Processed by Researcher, 2026

To determine the magnitude of the increase in learning outcomes, an N-Gain analysis was conducted, as presented in Table 3.

Table 3. N-Gain Analysis Results for Environmental Knowledge

Group	N	Mean N-Gain	Category
Experimental	34	0.5029 (50.29%)	Moderate
Control	33	0.1838 (18.38%)	Low

Source: Processed by Researcher, 2026

Based on Table 3, the experimental group obtained an N-Gain value of 0.5029, classified as moderate, while the control group obtained a value of 0.1838, classified as low. These results indicate that the increase in environmental knowledge in the group using the AR-based hybrid module was higher than that of conventional learning. Before hypothesis testing, the data were first tested using normality and homogeneity tests as analysis prerequisites.

Table 4. Normality and Homogeneity Test Results

Test	Group	Sig.	Description
Shapiro-Wilk (Pretest)	Experimental	0.112	Normal
	Control	0.087	Normal
Shapiro-Wilk (Posttest)	Experimental	0.064	Normal
	Control	0.091	Normal
Levene's Test (Pretest)	–	0.000	Not homogeneous
Levene's Test (Posttest)	–	0.001	Not homogeneous

Source: Processed by Researcher, 2026

The normality test results using Shapiro-Wilk show that all pretest and posttest data in both the experimental and control groups had significance values greater than 0.05, indicating a normal distribution. Meanwhile, the homogeneity test results using Levene's Test show that the variances of the two groups were not homogeneous for both the pretest and posttest (Sig. < 0.05). Therefore, hypothesis testing was conducted using the Independent Samples t-Test with the Equal Variances Not Assumed assumption (Welch's t-test).

Table 5. Independent Samples t-Test Results

Stage	t	Sig.	Description
Pretest	1.278	0.209	No difference in initial ability
Posttest	7.682	0.000	Significant difference present

Source: Processed by Researcher, 2026

The t-test results show that there was no difference in initial ability between the experimental and control groups (Sig. = 0.209 > 0.05). In contrast, the posttest yielded a significance value of 0.000 (< 0.05), indicating a significant difference in environmental knowledge after treatment. The average posttest score of the experimental group (82.944) was higher than that of the control group (67.585), indicating that the AR-based hybrid module was proven more effective in improving students' environmental knowledge compared to conventional learning.

To determine the magnitude of the treatment effect in practical terms, an effect size analysis was conducted using Cohen's d.

Table 6. Effect Size Results (Cohen's d)

Stage	Cohen's d	Category
Pretest	0.31	Small
Posttest	1.87	Large

Source: Processed by Researcher, 2026

A Cohen's d value of 0.31 at pretest indicates that the initial ability of both groups was relatively equivalent. Meanwhile, a Cohen's d value of 1.87 at posttest falls into the large effect category, indicating that the AR-based hybrid module had a strong influence on improving students' environmental knowledge. This finding reinforces the hypothesis test results that the AR-based hybrid module was not only statistically significant but also had a high practical impact on improving students' cognitive dimension.

Effectiveness on Environmental Care Attitudes (Affective)

Environmental care attitude is an affective dimension describing students' tendency to show concern for the environment. This dimension includes three indicators: appreciation for the environment, sensitivity toward the environment, and motivation and intention to act in preserving the environment. Data were obtained using a dichotomous scale instrument (Yes/No) consisting of 15 statement items. The effectiveness of the AR-based hybrid module on environmental care attitude was analyzed through descriptive statistics and N-Gain Score in the experimental and control groups. To obtain a general picture of changes in environmental care attitude before and after learning, descriptive statistical analysis was conducted.

Table 7. Descriptive Statistics Results for Environmental Care Attitude

Group	Stage	N	Mean	SD	Minimum	Maximum
Experimental	Pretest	34	71.765	20.5027	26.67	100.00
	Posttest	34	90.588	10.6512	60.00	100.00
Control	Pretest	33	63.636	13.6515	33.33	86.67
	Posttest	33	69.899	10.1545	46.67	86.67

Source: Processed by Researcher, 2026

Table 7 shows that both groups experienced an increase in environmental care attitude after learning. However, the increase in the experimental group was greater than in the control group. The average score of the experimental group increased by 18.824 points, while the control group increased by only 6.263 points. The decrease in standard deviation in both groups also indicates that students' environmental care attitude became more evenly distributed after learning.

To determine the magnitude of the normalized increase in learning outcomes, an N-Gain Score analysis was conducted.

Table 8. N-Gain Analysis Results for Environmental Care Attitude

Group	N	Mean N-Gain	Category
Experimental	34	0.5260 (52.60%)	Moderate
Control	33	0.1669 (16.69%)	Low

Source: Processed by Researcher, 2026

Based on Table 8, the experimental group obtained an N-Gain value of 0.5260, classified as moderate, while the control group obtained a value of 0.1669, classified as low. These results indicate that the increase in environmental care attitude in the group using the Augmented Reality-based hybrid module was higher than that of conventional learning.

Overall, the experimental group showed a higher increase in environmental care attitude compared to the control group, as seen from both the increase in average scores and N-Gain values. This finding indicates that the Augmented Reality-based hybrid module was more effective in improving students' affective dimension compared to conventional learning.

Effectiveness on Action Care/Intention (Conative)

Action care/intention is a conative dimension measuring students' intentions and tendencies to demonstrate pro-environmental behavior. This dimension includes four indicators: waste sorting and management, use of environmentally friendly products and habits, energy and water conservation, and pro-environmental social engagement. Data were obtained using a dichotomous scale instrument (Yes/No) consisting of 15 statement items. The effectiveness of the AR-based hybrid module on pro-environmental action care/intention was analyzed through descriptive statistics and N-Gain Score in the experimental and control groups.

To obtain a picture of changes in action care/intention before and after learning, descriptive statistical analysis was conducted.

Table 9. Descriptive Statistics Results for Action Care/Intention

Group	Stage	N	Mean	SD	Minimum	Maximum
Experimental	Pretest	34	73.137	17.7134	40.00	100.00
	Posttest	34	89.608	10.5334	66.67	100.00
Control	Pretest	33	68.687	9.2022	46.67	86.67
	Posttest	33	73.333	8.6602	53.33	93.33

Source: Processed by Researcher, 2026

Table 9 shows that both groups experienced an increase in action care/intention after learning. However, the increase in the experimental group was greater than in the control group. The average score of the experimental group increased by 16.471 points, while the control group increased by only 4.646 points. The decrease in standard deviation in both groups also indicates that students' action care/intention became more evenly distributed after learning. To determine the magnitude of the normalized increase, an N-Gain Score analysis was conducted.

Table 10. N-Gain Analysis Results for Action Care/Intention

Group	N	Mean N-Gain	Category
Experimental	34	0.4932 (49.32%)	Moderate
Control	33	0.1678 (16.78%)	Low

Source: Processed by Researcher, 2026

Based on Table 10, the experimental group obtained an N-Gain value of 0.4932, classified as moderate, while the control group obtained a value of 0.1678, classified as low. These results indicate that the increase in action care/intention in the group using the Augmented Reality-based hybrid module was higher than that of conventional learning.

Overall, the experimental group showed a higher increase in action care/intention compared to the control group, as seen from both the increase in average scores and N-Gain values. This finding indicates that the Augmented Reality-based hybrid module was more effective in improving students' conative dimension compared to conventional learning.

Practicality and User Response

Student responses to the module showed an average of 93.2% (Very Good), with eight of the ten statement items falling into the very good category. The highest-rated aspects were the convenience of carrying the module, enjoyment in participating in learning activities, enjoyment of playing educational games, and the desire to reuse the module (each reaching 100%), while relatively lower aspects though still in the good category were text/image readability (79.4%) and ease of using the AR application (82.4%), consistent with the media expert validator's notes on the layout and typography aspects. Open-ended questionnaire data reinforced these quantitative findings: 73.5% of students enjoyed hands-on practical activities (composting, planting, making water filters), 50% of students did not experience significant difficulties during learning, and all students were able to identify new knowledge from the four module themes and expressed intentions to apply environmentally friendly behaviors daily.

The teacher practicality questionnaire yielded a perfect score of 100% across all aspects, with teachers rating the module as easy to use, able to attract attention and motivate students, supportive of outdoor learning activities, and explicitly recommending this AR hybrid module for wider implementation at the elementary school level. This consistency between student and teacher responses indicates that the module's advantages were not only felt from the learners' side but also from the facilitators directly interacting with the implementation process.

DISCUSSION

The findings show that the AR-based hybrid module integrating Experiential Learning Theory and Place-Based Education improved students' ecological awareness across all three dimensions, with the experimental group consistently outperforming the control group. This consistency matters: the module's advantage was not confined to a single dimension but fostered ecological awareness holistically, addressing the conceptual gap in previous meta-analytic and systematic reviews, which found that intervention effectiveness is difficult to compare comprehensively when knowledge, attitudes, and behavior are measured separately (Ardoin et al., 2020 ; van de Wetering et al., 2022).

It should be noted, however, that the gains fell within the moderate category (N-Gain 0.49–0.53) rather than high ($g \geq 0.70$), warranting a proportionate interpretation. Three factors may explain this: the eight-week intervention was relatively short for shaping a complex, multidimensional construct; the dichotomous (Yes/No) scale used for the affective and conative instruments, while developmentally appropriate, has more limited sensitivity than a graded scale in capturing gradual attitudinal shifts; and some students had already scored near the upper bound at baseline, constraining further gains through a ceiling effect. The moderate N-Gain can still be considered practically meaningful given the substantially larger gains relative to the control group, but should not be read as evidence of maximal effectiveness generalizable across durations and contexts.

The pronounced cognitive effect suggests AR visualization played a distinct role: by rendering hard-to-observe ecological processes waste decomposition, water pollution layers, the greenhouse effect more concrete, AR closed an instructional gap conventional textbook explanation cannot. This aligns with reviews confirming AR's potential to visualize complex ecological processes while enhancing emotional engagement Ladykova et al., (2024) ; Simon et al., (2025), and with AR-based models showing positive impacts on environmental education outcomes (Safitri et al., 2025).

In the affective and conative dimensions, the experimental group's stronger gains reinforce Guevara-Herrero et al., (2024) argument that conventional environmental education often fails to provide meaningful direct experience. This suggests context-based experiential activities such as the "Let's Try It" activities in this module may function as a necessary bridge between conceptual knowledge and the formation of attitudes and intentions, one textual transfer alone cannot provide. These findings align with Shobirin et al. (2026) study, which similarly found AR-based instruction outperforming video-based and conventional instruction among Indonesian elementary students.

This study also offers new contributions relative to prior AR research in Indonesia. Unlike Taufik Afandi & Umi Mahmudah (2024) and Narulita et al. (2024), who developed AR media without a hybrid framework, and Shobirin et al. (2026), who compared AR with video and conventional instruction without integrating Experiential Learning Theory and Place-Based Education, this study combines all three elements printed module, AR, and interactive simulation while foregrounding local environmental issues in Sukabumi Regency. This suggests AR's instructional value may be maximized not by the technology alone, but by embedding it within a pedagogical structure connecting visualization to lived, local experience.

High implementation fidelity and positive student and teacher responses lend further support to internal validity, suggesting the observed improvement can plausibly be attributed to implementation as designed rather than a Hawthorne effect or novelty alone. At the same time, the technical constraints that briefly reduced fidelity in Module 3 point to a

practical implication: AR-based learning's effectiveness depends on schools' digital infrastructure readiness, meaning wider adoption would likely require parallel investment in devices and connectivity, not curriculum design alone.

This study has several limitations: it was conducted at only one school with a limited sample, so broader generalization warrants caution; the measurement period covered only the implementation phase without long-term retention data, leaving open whether gains are sustained a gap that matters given Ardoin & Bowers (2020) emphasis on childhood environmental education's long-term impact on adult behavior; technical constraints related to devices and connectivity may have affected some sessions, though without significantly disrupting overall effectiveness; and the absence of a non-AR digital control condition means the specific contribution of the AR feature, relative to the experiential and place-based components, cannot be precisely isolated.

CONCLUSION

The AR-based hybrid module integrating Experiential Learning Theory and Place-Based Education was successfully implemented with very good fidelity (90.3%), following a consistent four-stage structure applied to each topic: concept introduction, AR-based material deepening, experiential exploration in the real environment, and real action/reflection. This structure enabled students to experience the learning cycle directly, from concrete observation to real conservation action grounded in local issues, with engagement increasing consistently throughout implementation despite temporary technical constraints in the AR features.

This well-implemented process, in turn, produced a meaningful impact on students' ecological awareness. The experimental group showed a moderate improvement in environmental knowledge (N-Gain 0.50; large effect size of 1.87), environmental care attitude (N-Gain 0.53), and action care/intention (N-Gain 0.49), substantially exceeding the control group, which only achieved a low category across all three dimensions (N-Gain 0.17–0.18). These findings suggest that the gap between the potential of AR technology and its application in environmental education in Indonesia can be bridged through instructional design that deliberately combines experiential and contextual pedagogical approaches. These conclusions should nonetheless be read within the study's scope: the single-school sample, the absence of long-term retention measurement, and the lack of a non-AR digital control condition mean that broader generalization warrants caution.

Based on these conclusions, it is recommended that elementary school teachers consider using the AR-based hybrid module as an alternative environmental learning medium, particularly for material that is abstract and difficult to visualize conventionally, while ensuring the readiness of school digital infrastructure to minimize technical constraints during implementation. For education policymakers, these findings point to two concrete priorities: developing AR-based training programs to strengthen teachers' technical and pedagogical readiness, and ensuring elementary schools have access to a minimum set of AR-compatible devices and stable internet connectivity, both of which this study identified as prerequisites for consistent implementation. For theoretical development, future research is recommended to examine the long-term retention of students' ecological awareness post-intervention, expand the sample scope to several schools with diverse characteristics, and compare the specific contribution of the AR component with other experiential and place-based components through a research design involving an additional control group.

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