PEDAGOGIK JURNAL PENDIDIKAN
P-ISSN : 2528-5793
E-ISSN : 2354-7960

CONTEXTUALIZED AUGMENTED REALITY FLASHCARDS BASED ON MANGROVE ECOSYSTEM DATA TO ENHANCE STUDENTS' SCIENTIFIC LITERACY

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Received: May 2026	**Accepted:** September 2026	**Published:** September 2026
DOI: https://doi.org/10.33650.pjp.v13i2.15323		

Abstract : *This study aimed to develop and evaluate contextually integrated Augmented Reality (AR) flashcards about mangrove ecosystems to enhance scientific literacy in biology education, addressing the critical gap between abstract classroom instruction and complex field ecology. Using a Research and Development design with the ADDIE framework and a quasi-experimental study with a control group (94 experimental students, 100 control students) in five coastal high schools. Expert validation resulted in a rating of "Very Feasible" (overall 90.00%), and user feedback was "Very Good" (overall 4.55). The quasi-experimental results showed that AR flashcards produced significantly higher learning gains than conventional instruction, with a very large between-group effect size (Cohen's *d* = 1.85) and 43% of post-test variance explained by treatment after controlling for pre-test scores (partial $\eta^2 = 0.43$, $p < 0.001$). The very large within-group effect size for the experimental group (Cohen's d = 3.98) was attributed to low baseline knowledge, AR novelty effects, high contextual relevance, and the systematic application of cognitive load and multimedia learning theory. Qualitative findings revealed increased engagement, conceptual understanding, and intrinsic motivation for environmental exploration.*

Keywords : *Augmented Reality; Scientific Literacy; Mangrove Ecosystem.*

Abstrak : *Studi ini bertujuan mengembangkan dan mengevaluasi kartu flash Augmented Reality (AR) yang terintegrasi secara kontekstual tentang ekosistem mangrove untuk meningkatkan literasi sains dalam pendidikan biologi, dengan mengatasi kesenjangan kritis antara pembelajaran kelas yang abstrak dan kompleksitas ekologi lapangan. Menggunakan desain penelitian dan pengembangan dengan kerangka ADDIE serta studi kuasi-eksperimental dengan kelompok kontrol (94 siswa eksperimen, 100 siswa kontrol) di lima sekolah menengah. Validasi ahli menghasilkan penilaian "Sangat Layak" (total 90,00%), dan umpan balik pengguna adalah "Sangat Baik" (total 4,55). Hasil kuasi-eksperimental menunjukkan bahwa kartu flash AR menghasilkan peningkatan pembelajaran yang secara signifikan lebih tinggi dibandingkan pembelajaran konvensional, dengan ukuran efek antar-kelompok yang sangat besar (Cohen's *d* = 1,85) dan 43% varians pasca-tes dijelaskan oleh perlakuan setelah mengendalikan skor pra-tes (partial $\eta^2 = 0{,}43$, $p < 0{,}001$). Ukuran efek dalam-kelompok yang sangat besar untuk kelompok eksperimen (Cohen's d = 3,98) dikaitkan dengan rendahnya pengetahuan awal, efek kebaruan AR, relevansi kontekstual yang tinggi, serta penerapan sistematis teori beban kognitif dan pembelajaran multimedia. Temuan kualitatif mengungkapkan peningkatan keterlibatan, pemahaman konseptual, dan motivasi intrinsik untuk eksplorasi lingkungan.*

Kata Kunci : *Augmented Reality; Literasi Sains; Ekosistem Mangrove.*

INTRODUCTION

Scientific literacy has become a critical competency in the 21st century, yet its achievement remains a significant challenge in Indonesian education. Recent data from the Programme for International Student Assessment (PISA) 2022 revealed that Indonesian students scored an average of 383 in science, far below the OECD average of 485, placing Indonesia in the bottom 10 among 81 participating countries (OECD, 2023). Similarly, the National Assessment (Asesmen Nasional) conducted by the Indonesian Ministry of Education reported that only 34.2% of high school students achieved the minimum competency in scientific literacy, with particularly low performance in ecology and environmental science domains (Kemendikbudristek, 2023). These findings indicate a persistent crisis in science education that requires urgent pedagogical intervention.

The low scientific literacy among Indonesian students can be attributed to multiple interconnected factors. First, traditional teaching methods in biology education heavily rely on textbooks and two-dimensional images, which inadequately represent the complexity of three-dimensional biological structures and ecological interactions (Kurniahtunnisa & Wowor, 2023; Onowugbeda et al., 2024). Second, the curriculum often presents abstract concepts without meaningful connection to students' local environments, creating a disconnect between theoretical knowledge and real-world applications (Sari et al., 2024; Gannar & Kilani, 2025). Third, the lack of interactive and engaging learning media fails to accommodate the learning preferences of digital-native students, resulting in low motivation and superficial understanding (Ramaila & Molwele, 2022; Van Laar et al., 2018). Fourth, most biology instruction emphasizes memorization of factual knowledge rather than developing higher-order thinking skills such as scientific reasoning and evidence-based decision-making (Afriana et al., 2016; Valladares, 2021). These factors collectively hinder students' ability to form accurate mental models of complex ecological systems, limiting their capacity to apply scientific knowledge to real-world environmental challenges, such as understanding the critical role of mangrove forests in coastal protection and climate change mitigation (Pati et al., 2023; Budiarti et al., 2023).

These limitations in conventional biology instruction indicate that simply adding more digital content is unlikely to resolve the representational and contextual problems identified above. What is needed is a learning medium that can make complex ecological structures visible and interactive while also connecting scientific concepts with students' immediate environment. Augmented Reality (AR) is particularly relevant to this need because it overlays digital three-dimensional objects onto the real-world environment, allowing abstract scientific concepts to be represented in a more concrete and interactive form (Siregar et al., 2025; Ghosh et al., 2025). Previous studies have shown that AR-based tools, including AR flashcards, can improve student engagement, conceptual understanding, and motivation in biology learning (Balcha et al., 2025; Izzati & Kamaludin, 2024). AR flashcards have also been reported as feasible and well received in topics such as animal classification and ecology (Listiani & Paramartha, 2025; Siregar et al., 2025). Thus, AR provides a pedagogically relevant response to the limitations of static and decontextualized learning media, rather than functioning only as a technological innovation.

Nevertheless, the existing literature leaves an important research gap. First, many AR-based educational studies emphasize the technological presentation of three-dimensional objects rather than the scientific and contextual quality of the content. Consequently, generic biological models are often presented without authentic, site-specific ecological data. Although field studies have documented mangrove zonation, species diversity, and environmental characteristics such as salinity (Budiarti et al., 2023; Trialfhianty et al., 2022), these data have rarely been systematically translated into interactive AR learning resources. Second, previous AR studies have seldom incorporated rigorous field inventory data from students' own environments, limiting the connection between digital learning content and ecological conditions that students can directly observe. Third, many studies emphasize cognitive test outcomes while giving less attention to affective dimensions relevant to scientific literacy, including environmental awareness, intrinsic motivation, and exploration interest (Alonso et al., 2023; Arici, 2024). Fourth, methodological limitations, including small samples, the absence of control groups, and insufficient control of baseline differences, remain evident in parts of the literature (Garzón et al., 2019). These gaps indicate the need for AR learning media that is simultaneously scientifically grounded, locally contextualized, affectively engaging, and evaluated through a rigorous comparative design.

The present study responds to this gap through a contextually grounded AR flashcard model based on authentic mangrove ecosystem data from the Pangkal Babu mangrove forest. Its novelty is defined by four connected contributions. First, authentic field inventory data on local mangrove species composition and distribution are directly incorporated into the AR content, strengthening scientific validity and contextual relevance. Second, the media design is informed by Cognitive Load Theory (Sweller, 1988), Multimedia Learning principles (Mayer, 2009), and embodied cognition to support visual processing, interaction, and knowledge construction. Third, accessible low-code platforms (Assembler

Edu, Canva, and Meshy AI) are used to provide a development approach that can be replicated by educators without advanced programming skills. Fourth, the product is evaluated through a quasi-experimental design with a control group and complementary quantitative analyses, including paired t-tests, independent t-tests, ANCOVA, effect sizes, and N-Gain, together with qualitative student feedback. By combining authentic ecological evidence, contextualized AR design, and rigorous evaluation, the study seeks to connect classroom biology learning with the ecological realities of students' local environment.

Accordingly, this study aims to develop and evaluate Contextually Integrated Augmented Reality Flashcards based on Mangrove Ecosystem Data to enhance students' scientific literacy in biology education. Specifically, the study aims to: (1) analyze teachers' and students' needs for innovative learning media on mangrove ecosystem materials; (2) design and develop an AR flashcard prototype that visualizes key mangrove species, zonation patterns, and ecological interactions using authentic field inventory data from the Pangkal Babu mangrove forest; (3) assess the feasibility of the prototype in terms of content, media design, and technical aspects using Aiken's V coefficient; (4) evaluate the practicality of the developed AR media through teacher and student responses using a 1–5 Likert-scale questionnaire; and (5) examine the initial effectiveness of the AR flashcards in improving students' conceptual understanding and fostering environmental awareness and exploration interest through a quasi-experimental comparison of experimental and control groups.

METHOD

This study employed a Research and Development (R&D) design utilizing the ADDIE (Analysis, Design, Development, Implementation, Evaluation) framework (Mudjisusatyo et al., 2024; Ramly et al., 2022; Spatioti et al., 2022). This model was chosen because of its systematic and iterative structure, enabling a replicable and high-quality product development process. To evaluate the effectiveness of the developed Augmented Reality (AR) flashcards in improving students' scientific literacy, a quasi-experimental design with a non-equivalent control group pretest-posttest was used . This design was chosen because random assignment of students to groups was not possible due to the existing class structure. The research design is illustrated in Table 1.

Table 1: Quasi-Experimental Research Design

Group	Pre-test	Treatment	Post-test
Experimental (E)	O_1	X (AR Flash Card)	O_2
Control (C)	O_3	Y (Conventional Learning)	O_4

Both groups underwent a pre-test to measure the students' initial level of conceptual understanding, designated as O_1 for the experimental group and O_3 for the control group. Subsequently, the experimental group received an intervention involving instruction with AR Flash Cards focused on mangrove plants (X), while the control group underwent conventional instruction utilizing textbooks, lectures, and two-dimensional images (Y). Following the instructional period, both groups took a post-test to assess changes in the students' conceptual understanding, designated as O_2 for the experimental group and O_4 for the control group. A comparison of the pre-test and post-test results between the two groups was used to analyze the impact of using AR Flash Cards on improving students' conceptual understanding of mangrove plants.

This study was conducted in five high schools in West Tanjung Jabung Regency, Jambi Province, Indonesia: SMA 1, SMA 2, SMA 8, MAN 1, and MAN 2 Tanjung Jabung Barat. These locations were purposefully selected due to their geographical proximity to the mangrove ecosystem, ensuring high contextual relevance for students. The study population consisted of all science students from these schools, totaling 375 students. The sample size was determined using the Slovin formula with a 5% margin of error (*e*), resulting in a target sample of 194 students (Nurkholis et al., 2024; Sasmita Saputra et al., 2024). A purposive sampling technique was used to select participants based on their enrollment in biology courses covering coastal ecosystems. The distribution of participants across schools is presented in Table 2.

Table 2: Distribution of Research Participants

School	Experimental Group	Control Group	Total
West Tanjung Jabung 1 High School	24	26	50
West Tanjung Jabung 2 High School	18	20	38
West Tanjung Jabung 8 High School	10	12	22
MAN 1 West Tanjung Jabung	22	24	46
MAN 2 West Tanjung Jabung	20	18	38
Total	94	100	194

Additionally, 10 biology teachers (two from each school) participated in the needs analysis and expert validation phase. All participants were informed of the study's purpose and provided written consent prior to data collection, in accordance with research ethics standards.

This research was operationalized through the five phases of the ADDIE model, with particular emphasis on the Implementation and Evaluation phases for the quasi-experiment.

Scientific literacy was assessed using a 12-item multiple-choice test developed according to the OECD scientific literacy framework (OECD, 2023). The instrument measured three dimensions: 1) explaining scientific phenomena, 2) evaluating and designing scientific investigations, and 3) interpreting scientific evidence and data. All items were contextualized within mangrove ecosystem issues to ensure authenticity and environmental relevance.

The content validity of the instrument was assessed using Aiken's V coefficient. The average coefficient obtained was 0.87, indicating high content validity. Construct validity was examined through Exploratory Factor Analysis (EFA). The Kaiser–Meyer–Olkin value of 0.81 and significant Bartlett's Test of Sphericity confirmed the suitability of the data for factor analysis (Hair et al., 2019). Reliability was evaluated through Cronbach's alpha, yielding a coefficient of 0.82, which exceeded the recommended threshold of 0.70 and indicated satisfactory internal consistency (Taber, 2018). To ensure the quality of the research instruments, rigorous validity and reliability testing has been conducted. The content validity of the conceptual understanding test was evaluated by two biology education experts using Aiken's V coefficient. The experts rated each item based on relevance, clarity, and alignment with learning objectives using a rating scale of 1–4. The analysis yielded an average Aiken's V coefficient of 0.87 (ranging from 0.82 to 0.92 across all items), indicating high content validity (Aiken, 1985). Items with coefficients below 0.75 were revised based on expert feedback before the final test.

Construct validity was assessed through exploratory factor analysis (EFA) using principal component extraction with varimax rotation. The Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy was 0.81, exceeding the recommended threshold of 0.60, and Bartlett's sphericity test was significant ($\chi^2 = 456.32$, $df = 66$, $p < 0.001$), indicating that the data were suitable for factor analysis. The analysis confirmed a three-factor structure corresponding to the three assessment aspects (mangrove diversity, adaptation, and zoning), with factor loadings ranging from 0.52 to 0.78, all exceeding the minimum acceptable threshold of 0.50 (Hair et al., 2019).

The reliability of the conceptual understanding test was established through a pilot study involving 30 students from a non-participating school with similar characteristics. Cronbach's alpha was calculated to assess internal consistency: 1) Overall test results: $\alpha = 0.82$ (good reliability), 2) Mangrove Diversity Subscale: $\alpha = 0.79$ (acceptable), 3) Mangrove Adaptation Subscale: $\alpha = 0.81$ (good), and 4) Mangrove Zoning Subscale: $\alpha = 0.78$ (acceptable). This coefficient exceeds the minimum acceptable threshold of 0.70 (Taber, 2018), indicating that the test has good internal consistency and reliably measures students' conceptual understanding of the mangrove ecosystem.

Data were analyzed using IBM SPSS Statistics version 26 with a significance level of $\alpha = 0.05$. The normality and homogeneity assumptions were examined before conducting inferential analyses. Differences in conceptual understanding scores within each group were analyzed using a paired-samples t-test for normally distributed data, while the Wilcoxon Signed Rank Test was applied for non-normally distributed data. Differences in post-test scores between the experimental and control groups were examined using an independent-samples t-test or Welch's t-test when the homogeneity assumption was violated. To control for initial differences in students' conceptual understanding, a one-way Analysis of Covariance (ANCOVA) was conducted with pre-test scores as the covariate and post-test scores as the dependent variable. The ANCOVA assumptions, including linearity, homogeneity of regression slopes, and normality of residuals, were tested prior to analysis.

The magnitude of the treatment effect was determined using effect size analysis. Cohen's d was calculated for t-test comparisons and interpreted as small (0.00–0.20), moderate (0.21–0.50), large (0.51–0.80), and very large (>0.80) effects (Cohen, 1988). For ANCOVA, partial eta squared (ηp^2) was calculated to estimate the proportion of variance in post-test scores explained by the intervention. Furthermore, students' improvement in conceptual understanding was assessed using the normalized gain (N-Gain) score, categorized as high ($g \geq 0.70$), medium ($0.30 \leq g < 0.70$), and low ($g < 0.30$) (Hake, 1998). Effect size calculations were verified using G*Power version 3.1.

RESULT AND DISCUSSION

1. Results

This section presents the empirical findings from the needs analysis, mangrove field inventory, AR media development and validation, user responses, and quasi-experimental effectiveness testing. The results are organized according to the research objectives. Tables and figures are introduced with concise statements of the main observed patterns, while theoretical interpretation, comparison with previous studies, and broader implications are presented in the Discussion section.

a) Media Needs and Feasibility Analysis Foundation

An initial needs analysis was conducted to identify learning challenges and assess the feasibility of developing AR media. The results, summarized in Table 3, provide a strong empirical foundation for the development of the media.

Table 3: Results of Needs Analysis for Learning Media

Aspects Analyzed	Teachers (n=10)	Students (n=100)	Key Findings
The Need for Innovative Media	Agree 100%	94.3% agree	High demand for interactive visual media.
The Difficulty of Understanding Mangrove Forests	Reporting difficulty 100%	85.7% experienced difficulties	The concept of zoning and adaptation is the most challenging.
Access to Smartphones	-	97.1% have	Technical feasibility supported.
Interest in AR Media	100% Support	91.4% very interested	High acceptance rate

Table 10 shows that 100% of participating teachers and 94.3% of students agreed on the need for innovative learning media. In addition, 85.7% of students reported difficulties understanding mangrove ecosystem concepts, while 97.1% had access to smartphones and 91.4% expressed very high interest in AR media. These findings establish the practical need and technological feasibility for developing a smartphone-based AR learning medium.

To ensure the contextual authenticity of the media content, a field inventory was conducted in the Pangkal Babu mangrove forest. Using a strip sampling method on a 100×100 m transect divided into three sections, 10 mangrove species were identified and quantified, as shown in Table 4.

Table 4: Results of Mangrove Plant Inventory per Transect

No	Local Name	Scientific Name	Transect 1	Transect 2	Transect 3	Total
1	Nipah	*Nypa fruticans*	15	12	18	45
2	Black Flames	*Avicennia alba*	22	25	20	67
3	Piai Lasa	*Acrostichum aureum*	8	10	7	25
4	Sea Fern	*Acrostichum speciosum*	5	6	4	15
5	Black Jeuruju	*Acanthus ebracteatus*	12	15	10	37
6	Fastener	*Sonneratia alba*	18	16	22	56
7	Oil Mangrove	*Rhizophora apiculata*	28	32	30	90
8	White Flames	*Marina Avicennia*	20	18	24	62
9	Mangrove Ringworm	*Rhizophora mucronata*	25	28	26	79
10	Speech	*Sonneratia caseolaris*	10	8	12	30
	TOTAL		**163**	**170**	**173**	**506**

The inventory identified 506 individual mangrove plants across the sampled 1-hectare area. Rhizophora apiculata was the most abundant species (90 individuals), followed by Rhizophora mucronata (79 individuals). The resulting species-composition and distribution data were subsequently used as the empirical basis for the AR content, particularly the representation of mangrove species and zonation.

Figure 1: Mangrove Vegetation Inventory, Species Identification, and Transect Measurement Activities Conducted at the Study Area

The field inventory data were incorporated into the AR content by using the identified species and their observed distribution as references for the three-dimensional models and learning information.

b) Media Design, Development, and Expert Validation

Based on the needs analysis, an AR flashcard prototype was designed and developed. The technical specifications and tools used are summarized in Table 5.

Table 5: Technical Specifications of Augmented Reality Flash Cards

Component	Specification	Implementation
Development Platform	Assembler Edu	The ultimate platform for building AR experiences without complex coding.
Flash Card Design	Canva	Creating a visual card design (8.5 cm × 5.4 cm) with a transparent marker
3D Model Creation	AI Mesh	Rapid 3D mangrove plant model creation using artificial intelligence.
Markers & Barcodes	Assembler Edu	Creation and management of unique barcodes as tracking targets for each card.

The development process produced three-dimensional models and flashcards representing selected local mangrove species. Canva was used for card design, Meshy AI for 3D model creation, and Assembler Edu for AR implementation and marker tracking. The resulting application was designed for operation on students' smartphones.

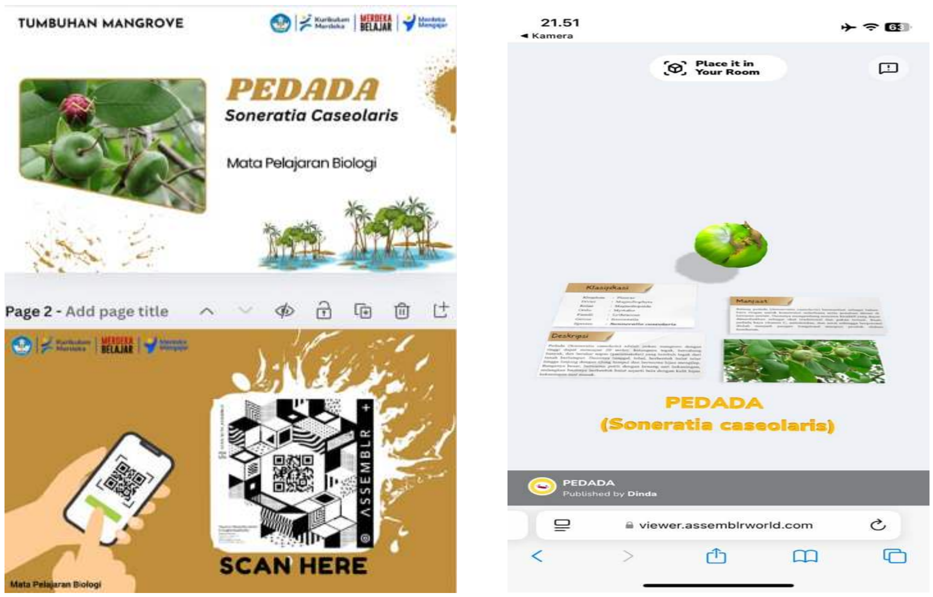

Figure 2: AR Flashcard App Screenshot

The developed prototype was then evaluated by experts for content, media design, and technical feasibility. Figure 3 summarizes the percentage scores obtained for each validation aspect.

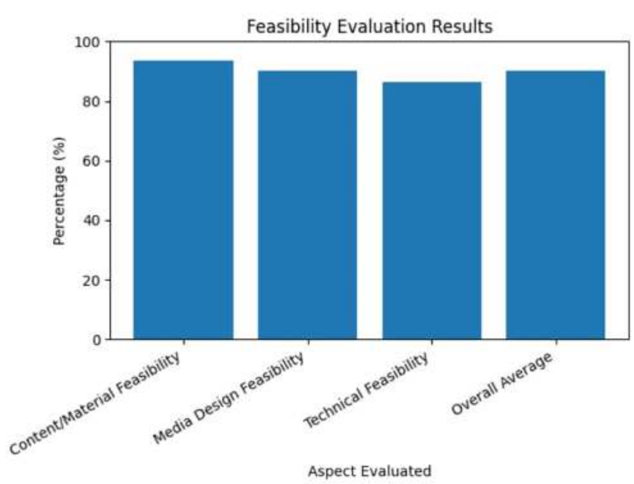

Figure 3: Results of Media Feasibility Validation

Figure 3 shows that the prototype obtained high feasibility scores across all assessed aspects: 93.75% for content, 90.00% for media design, and 86.25% for technical feasibility. The overall average was 90.00%, indicating that the prototype met the predetermined feasibility criteria for implementation.

c) User Response and Learning Effectiveness

To gain deeper insights into student experiences, qualitative feedback was collected through Focus Group Discussions (FGDs) with 30 students (six students per group from the pilot sample). A thematic analysis of their responses is summarized in Table 6.

Table 6: Summary of Qualitative Feedback from Student Focus Group Discussions

Theme	Student Representative Quotes	Interpretation / Implications
Engagement & Recency	*"Studying feels like playing a game; the 3D plants that suddenly appear are cool." "It's very different from just reading a book; I don't get bored."*	AR media provides a novel and game-like experience that maintains attention and reduces learning boredom, in line with the high "Media Appeal" score.
Increased Understanding	*"Finally, I could see what the 'aerial roots' actually looked like in 3D, not just a flat image." "Rotating the model helped me understand the differences in leaf shape between species."*	3D visualization and interactivity concretize abstract morphological concepts, directly addressing the cognitive load challenges identified in the needs analysis.
Ease of Use & Accessibility	*"The instructions on the card were clear; I just pointed my phone camera at it and it worked." "It was easy to use, just like opening a regular app."*	Intuitive design and simple operation lower the technical barrier to entry, supporting high "Ease of Use" scores and confirming the platform's viability.
Motivation for Exploration	*"After trying this, I wanted to find out more about the mangrove crabs mentioned in the information pop-up window." "I showed it to my brother at home; it made me curious about the mangrove forests near our house."*	The media stimulates extrinsic curiosity and intrinsic connection to the local environment, demonstrating the "Exploratory Interest" it fosters outside the classroom.
Suggestions for Improvement	*"Can we have more interactive features, like quizzes or mini-games within AR?" "It would be great if this app could work without having to print physical cards."*	Feedback indicated a desire for richer interactivity and greater accessibility, pointing to potential future directions for the medium's development and scalability.

The FGD results identified four main positive response themes: engagement and novelty, improved understanding through three-dimensional visualization, ease of use, and motivation to explore the local environment. Students also suggested additional interactive features, including quizzes or mini-games, and the possibility of accessing the AR content without printed cards. These responses were used to complement the quantitative user-response data. A limited implementation trial was conducted with an experimental group (n=94) to gather data on practicality and initial effectiveness. User feedback, detailed in the Graph , was largely positive.

Table 7: Results of User Response Analysis (Experimental Group)

Assessment Aspects	Average Item Score	Average Aspect Score	Category
Ease of Use	4.52	4.52	Very good
Media Attraction	4.65	4.65	Very good
Interest in Exploration	4.48	4.48	Very good
Overall Average	4.55	4.55	Very good

The quantitative response results were consistent across the three assessed aspects. Students gave average scores of 4.52 for ease of use, 4.65 for media attraction, and 4.48 for interest in exploration, producing an overall average of 4.55, categorized as Very Good. The qualitative responses provided additional evidence about students' experiences with these features.

d) Comparative Effectiveness: Experimental Group vs. Control Group

To rigorously evaluate the effectiveness of AR flashcards, a quasi-experimental design was used comparing an experimental group (AR flashcards, n=94) with a control group (conventional instruction, n=100). Prior to hypothesis testing, assumption checks were conducted to determine the appropriate statistical test.

Table 8: Results of Normality and Homogeneity Tests

Statistical Test	Variables	Group	Shapiro-Wilk (p-value)	Information	Levene's test (p-value)	Information
Normality Test	Pre-test	Experimental	0.071	Normal ($p > 0.05$)	–	–
		Control	0.083	Normal ($p > 0.05$)	–	–
	Post-test	Experimental	0.134	Normal ($p > 0.05$)	–	–
		Control	0.091	Normal ($p > 0.05$)	–	–
Homogeneity Test	Pre-test	Both Groups	–	–	0.215	Homogeneous ($p > 0.05$)
	Post-test	Both Groups	–	–	0.192	Homogeneous ($p > 0.05$)

Table 8 shows that all Shapiro–Wilk p-values for the pre-test and post-test scores were greater than 0.05, indicating no evidence of non-normality. Levene's test also produced p-values greater than 0.05 for both pre-test and post-test scores, indicating homogeneous variances between groups. These results supported the use of parametric analyses for subsequent comparisons.

Table 9: Descriptive Statistics of Pre-test and Post-test Scores by Group

Group	N	Pre-test (Mean ± SD)	Post-test (Mean ± SD)	Average Difference
Experimental (AR Flash Card)	94	45.21 ± 9.14	79.86 ± 8.57	34.65
Control (Conventional)	100	44.87 ± 9.32	62.34 ± 10.21	17.47

Table 9 shows similar pre-test means for the experimental group (45.21) and control group (44.87). After four weeks, the experimental group obtained a post-test mean of 79.86, whereas the control group obtained 62.34. The corresponding mean improvements were 34.65 points and 17.47 points, respectively.

Table 10: Results of Comparison Within Groups (Paired Samples t-Test)

Group	Average Difference	t value	df	p-value	Effect Size (Cohen's d)	Category
Experimental	34.65	24,718	93	0,000*	3.98	Very large
Control	17.47	12,845	99	0,000*	1.82	Very large

Table 10 shows statistically significant within-group improvements for both the experimental and control groups ($p < 0.001$). The experimental group improved by 34.65 points with Cohen's d = 3.98, while the control group improved by 17.47 points with Cohen's d = 1.82.

Table 11: Results of Comparison Between Groups (Independent Samples t-Test)

Comparison	Average Difference	t value	df	p-value	Effect Size (Cohen's d)	Category
Post-test: Experimental vs. Control	17.52	12,847	192	0,000*	1.85	Very large

Table 11 shows a statistically significant difference in post-test scores between the experimental and control groups, $t(192) = 12.847$, $p < 0.001$. The mean difference was 17.52 points, and the between-group effect size was Cohen's d = 1.85.

Table 12: Results of ANCOVA Analysis

Source	Type III Sum of Squares	df	Mean Square	F	p-value	Partial Eta Squared ($\eta^2 p$)
Corrected Model	18,456.78	2	9,228.39	98.45	0,000*	0.51
Intercept	5,234.67	1	5,234.67	55.84	0,000*	0.23
Pre-test (Covariate)	4,567.89	1	4,567.89	48.73	0,000*	0.20
Group (Treatment)	13,567.89	1	13,567.89	144.73	0,000*	0.43
Error	17,891.34	191	93.67			
Total	1,023,456.78	194				
Corrected Amount	36,348.12	193				

Table 12 shows a significant treatment effect after controlling for pre-test scores, $F(1,191) = 144.73$, $p < 0.001$, with partial $\eta^2 = 0.43$. The model explained 51% of the variance in post-test scores ($R^2 = 0.51$; adjusted $R^2 = 0.50$). The post-test comparison and ANCOVA results consistently showed higher achievement for students in the experimental group than for those in the control group. The experimental group also demonstrated a larger within-group improvement and a higher N-Gain score, as reported in Tables 17–20. The within-group and between-group effect-size estimates were larger for the experimental group than for the control group. These statistical results are reported descriptively here; possible explanations for the magnitude of the effects are considered in the Discussion section.

Table 13: Normalized Gain (N-Gain) Analysis

Group	N-Gain Score (g)	Category
Experimental (AR Flash Card)	0.61	Currently
Control (Conventional)	0.32	Currently

Table 13 shows an N-Gain score of 0.61 for the experimental group and 0.32 for the control group. Both scores fall within the moderate category according to the criteria used in this study. The experimental group therefore showed a higher normalized learning gain than the control group.

2. Discussion

The central finding is that contextually integrated AR flashcards can provide a meaningful learning advantage over conventional instruction when the digital content is grounded in authentic local ecological data. The advantage is evident not only in the higher post-test performance of the experimental group, but also in the consistently positive user responses and qualitative evidence of engagement and exploration. Taken together, these findings suggest that the educational value of AR in this study was associated with the combination of interactive representation, local contextualization, and structured learning use rather than with the presence of AR technology alone. This interpretation is consistent with Putri and Asrizal (2023), who emphasized the importance of needs analysis in developing learning media that addresses 21st-century learning demands.

The high level of smartphone access and strong interest in AR indicate that the intervention was technically and motivationally compatible with the participating students. The difficulty reported in understanding mangrove zonation and adaptation also provides a plausible explanation for why an interactive visual medium was useful in this context: these concepts require students to relate structural and ecological information that is difficult to represent through static images alone. This interpretation is consistent with Cognitive Load Theory (Sweller, 1988), because integrated visual representations can reduce the need to construct complex mental representations from text and two-dimensional images. The finding also extends Budiarti et al. (2026), who reported improved conceptual understanding through AR flashcards in mangrove learning, by combining similar contextual content with a control-group comparison and qualitative evidence.

A second important contribution concerns the role of authentic ecological data in the design of the learning medium. The 506 individual mangrove plants documented in the Pangkal Babu area, including 90 Rhizophora apiculata and 79 Rhizophora mucronata, provided a concrete empirical basis for the AR representations. This matters because contextual learning is strongest when learners encounter scientific concepts through phenomena that are recognizable within their own environment. The high content-feasibility score further indicates that experts judged the integration of local ecological information positively. In this respect, the study extends previous AR research that demonstrated feasibility but did not place the same emphasis on systematic field inventory data as the foundation for content development (Siregar et al., 2025; Balcha et al., 2025).

The effectiveness results indicate a substantial difference in learning outcomes between the two instructional conditions. Students who used the AR flashcards achieved higher post-test performance than students receiving conventional instruction, and the between-group effect size was very large. The finding is stronger than a simple pre-test/post-test comparison because the ANCOVA analysis also showed a significant treatment effect after controlling for baseline performance. The N-Gain results provide a more conservative interpretation: the experimental group reached the moderate category rather than the high category. Therefore, the evidence supports a meaningful improvement associated with the AR intervention, but it does not justify claiming that the intervention alone produced mastery of the learning content.

The very large within-group effect size in the experimental group should therefore be interpreted cautiously. One plausible factor is the relatively low baseline performance, which left considerable room for improvement. Kraft (2020) similarly noted that effect sizes can be larger when learners begin with limited prior knowledge and the intervention addresses foundational concepts. In addition, the four-week intervention may have combined novelty, contextual relevance, and intensive exposure to a new visual learning format. These factors provide reasonable explanations for the magnitude of the observed change, but the present design cannot isolate the independent contribution of each factor.

The qualitative evidence supports the interpretation that novelty and engagement were part of the learning experience. Students described the AR activity as game-like and reported that it was less boring than conventional reading. Such responses suggest that the interactive format helped sustain attention. However, because the study did not include a separate novelty-control condition, the novelty effect cannot be distinguished statistically from the effects of contextual content or three-dimensional visualization.

Contextual relevance provides a second plausible mechanism. The AR flashcards represented species and ecological information from the students' local mangrove environment, making the learning material directly connected to observable surroundings. This interpretation is consistent with Contextual Teaching and Learning principles and with findings that locally contextualized materials can support environmental literacy (Mahardhika et al., 2025; Sianturi et al., 2024). The local context may therefore have increased the meaningfulness of the content, although further comparative studies are required to determine whether the effect is larger than that of equally well-designed generic AR materials.

The third mechanism concerns the integration of learning theories into the media design. Cognitive Load Theory, Multimedia Learning, and embodied cognition provide complementary explanations for why manipulating three-dimensional objects may support understanding of biological structures. Student comments about rotating models and observing differences in leaf shape are consistent with this interpretation. Nevertheless, these mechanisms should be viewed as theoretically informed explanations rather than directly tested causal mediators, because the present study did not measure cognitive load, embodied interaction, or multimedia-processing variables independently.

The ANCOVA result indicates that the treatment accounted for a substantial proportion of post-test variance after baseline adjustment, while the N-Gain result indicates moderate normalized improvement. Together, these findings suggest that AR flashcards were effective in the present learning context but that the intervention still has room for improvement. Adding formative assessment, adaptive feedback, or richer interactive activities may be appropriate next steps, particularly because students themselves requested quizzes, mini-games, and cardless access. These suggestions are therefore directly grounded in both the quantitative outcome and the users' qualitative feedback.

The findings can be understood through three complementary mechanisms. First, AR provided integrated visual and textual representations that may have made complex ecological structures easier to process. Second, three-dimensional interaction enabled students to observe and manipulate biological forms rather than relying solely on static images. Third, the use of authentic local species increased the contextual relevance of the learning material. Together, these mechanisms offer a plausible explanation for the observed improvement in conceptual understanding and the reported interest in environmental exploration, while recognizing that the mechanisms were not independently tested in the present study.

The findings are broadly consistent with previous AR research but also extend it in important ways. Siregar et al. (2025) reported high feasibility for AR flashcards in animal classification, which is comparable to the feasibility observed here. Balcha et al. (2025) likewise reported positive responses to AR in ecology, consistent with the present user-response findings. The main difference is methodological and contextual: the present study combines authentic field inventory data from a local mangrove ecosystem with a quasi-experimental control group, ANCOVA, effect-size analysis, N-Gain, and qualitative feedback. Thus, the contribution is not simply another demonstration that AR is feasible, but evidence that a locally grounded AR design can be evaluated through multiple forms of evidence.

The study contributes to the literature in three main respects. First, it offers a replicable content-development approach in which field ecological data are translated into AR learning resources, thereby strengthening the connection between scientific evidence and classroom representation. Second, the quasi-experimental design provides comparative evidence that is stronger than feasibility or perception studies alone. Third, the qualitative findings show that the cognitive outcomes were accompanied by reported motivation to explore the local environment. These contributions help clarify how AR can be connected to meaningful scientific content rather than being treated primarily as a technological novelty.

The practical implication is that biology teachers, particularly in coastal areas, can use locally available ecological data as the starting point for developing contextual AR resources. The low-code development process also suggests that sophisticated programming expertise is not necessarily required for this type of instructional innovation. Theoretically, the findings support the value of combining contextual data with established learning principles when designing AR media. The study also demonstrates the usefulness of integrating quantitative effectiveness evidence with qualitative accounts of learner experience, because the statistical results show whether learning changed while the qualitative findings help explain how students experienced the intervention.

Several limitations qualify the interpretation of the findings. First, the four-week intervention was sufficient to examine immediate learning outcomes but not long-term retention; therefore, the persistence of the observed gains remains uncertain. Second, participants were drawn from coastal schools in West Tanjung Jabung where mangrove ecosystems are highly relevant, so the findings should not be generalized automatically to inland schools or regions with different ecological conditions. Third, the assessment emphasized conceptual understanding and affective responses and did not directly measure higher-order scientific literacy skills such as argumentation, evidence-based reasoning, or environmental decision-making. Finally, the very large within-group effect size should be replicated with larger and more diverse samples because the present design cannot determine how much of the effect was attributable to baseline performance, novelty, contextual relevance, or other concurrent factors.

The qualitative findings further indicate that the AR experience supported motivation for environmental exploration. Students reported seeking additional information about mangrove organisms and sharing their experiences outside the classroom. These responses suggest that the media extended attention beyond the immediate instructional task and helped connect classroom learning with local environmental experience. This interpretation is consistent with Alonso et al. (2023) and Arici (2024), who emphasized the affective dimension of scientific literacy, and with Kardianawati et al. (2025), who reported positive motivational responses to interactive AR flashcards. However, these qualitative findings represent students' reported experiences and should not be interpreted as evidence of long-term behavioral change.

The limitations identified above lead to specific directions for future research. A longitudinal design with follow-up assessments at approximately 3–6 months should be used to determine whether the observed learning gains are retained over time. Multi-site studies should include inland schools and regions with different ecological contexts to test the generalizability of the contextual AR approach. Future studies should also expand the outcome measures to include scientific argumentation, evidence-based reasoning, and environmental decision-making. Finally, larger samples and comparative conditions that separate AR novelty, contextual content, and three-dimensional interaction would help identify which components contribute most strongly to learning outcomes.

For educational practice, the findings support a practical development sequence: collect or obtain reliable local ecological data, translate the data into curriculum-aligned visual content, build the AR representations using accessible platforms, and implement the media as a structured supplement to classroom instruction. This sequence is particularly relevant for teachers working in contexts where local ecological resources are available but are not yet incorporated into digital learning materials.

The broader implication is that contextual AR should be adapted to the characteristics of the learning environment rather than transferred unchanged across settings. Coastal teachers may use mangrove data, whereas other regions may use locally relevant ecosystems such as coral reefs, tropical forests, or agricultural environments. Such adaptation preserves the central contribution of the present study—the integration of authentic scientific data with interactive representation—while allowing the learning resource to remain meaningful in different contexts.

Future studies should therefore prioritize four concrete directions: (1) longitudinal measurement of retention; (2) multi-site replication across contrasting geographic and ecological settings; (3) experimental comparison of smartphone-based AR, richer interactive AR, and conventional media; and (4) development of quizzes, mini-games, and cardless access followed by testing of their effects on engagement and learning. These directions directly respond to the limitations and user feedback identified in the present study and would provide stronger evidence regarding the scalability and sustainability of contextual AR learning.

CONCLUSION

This study developed and evaluated contextually integrated Augmented Reality flashcards based on authentic mangrove ecosystem data from Pangkal Babu. The findings indicate that the developed media was feasible, positively received by users, and more effective than conventional instruction for improving students' learning outcomes in the present context. The main contribution of the study is the integration of authentic local ecological inventory data with an accessible AR format, allowing students to engage with biological concepts through representations grounded in their own environment. The study also shows that combining quantitative effectiveness testing with qualitative learner feedback provides a more complete understanding of the value of contextual AR media. However, the four-week intervention limits conclusions about long-term retention, the coastal school setting limits generalizability to other ecological and educational contexts, and the assessment did not fully address higher-order scientific literacy skills. Future research should therefore examine retention through longitudinal follow-up, replicate the intervention across contrasting sites and larger samples, and test higher-order outcomes and additional interactive features such as quizzes, mini-games, and cardless access. Within these boundaries, contextual AR flashcards can be considered a promising and locally adaptable learning medium for biology education rather than a universally established or transformative solution.

ACKNOWLEDGMENT

The authors would like to express their sincere gratitude to all parties who contributed and supported the completion of this research, including supervisors, institutions, and respondents involved in the study.

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