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Implementation of Augmented Reality-Based Pop-Up Books to Enhance Elementary Students' Understanding of Ecosystem Concepts

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Abstract

This study aims to implement and examine the effectiveness of an Augmented Reality (AR) based Pop-Up Book in enhancing elementary students' understanding of ecosystem concepts. The research employed a One Group Pretest-Posttest Design, involving 139 fifth-grade students from five elementary schools in Surabaya City, Indonesia. The research instruments consisted of a concept comprehension test, observation sheets, and a student response questionnaire. Data were analyzed using a paired-sample t-test and the Normalized Gain (N-Gain) calculation. The findings revealed a significant improvement in students' learning outcomes, with an average pretest score of 62 and posttest score of 89, resulting in an N-Gain of 0.70, which falls within the high category. Moreover, the classical mastery level reached 100%, and the student response rate toward the media was 98%, categorized as very positive. The AR-based Pop-Up Book proved to be effective in helping students comprehend ecosystem concepts, as it enables them to visualize interrelationships among organisms, energy flow, and biotic–abiotic components in a concrete, engaging, and interactive manner. Furthermore, this medium enhanced students' motivation, participation, and engagement throughout the learning process. Hence, the AR-based Pop-Up Book can serve as an innovative, contextual, and effective science learning medium aligned with the characteristics of 21st century learners.

How to Cite

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INTRODUCTION

Science education in elementary schools is expected to build a strong foundation of scientific literacy by developing students' ability to observe, reason, and interpret natural phenomena. However, learning activities in this context often remain focused on factual recall rather than meaningful conceptual understanding. This issue becomes more evident in the implementation of the Merdeka Curriculum, which combines Natural and Social Sciences (IPAS) and emphasizes ecosystem topics that require students to comprehend abstract and interconnected concepts. Despite curricular expectations, previous studies consistently show that many elementary students struggle to understand food chains, interactions between biotic and abiotic components, and energy flow within ecosystems (Narulita et al., 2024). These difficulties highlight an urgent need for instructional innovations that can concretize abstract ecological processes and support deeper cognitive engagement.

The persistent learning challenges are closely associated with the dominant use of conventional media, such as textbooks and static images, which are limited in presenting dynamic ecological relationships. Traditional resources tend to encourage rote memorization rather than active exploration and reasoning (Zaelani et al., 2025). Meanwhile, digital transformation in education demands learning media that are not only informative but also interactive and able to support 21st-century learning skills (Huang et al., 2022). Although technology integration in elementary science learning has progressed, many existing interventions still focus on either digital media alone or physical manipulatives, leaving a gap in multimodal, immersive solutions that combine physical engagement and digital interactivity.

Augmented Reality (AR) has recently emerged as a promising tool for visualizing complex scientific phenomena. AR allows students to interact with three-dimensional digital objects embedded into their real environment, making it easier to understand ecological concepts that are otherwise difficult to grasp through static materials (Darmawan et al., 2024). On the other hand, pop-up books provide tactile, hands-on experiences that support concrete operational learning processes aligned with constructivist principles (Piaget, 1970; Vygotsky, 1978). Although both media have shown potential in enhancing conceptual understanding, studies combining AR with pop-up books especially in the context of elementary ecosystem learning remain limited. This insufficient integration represents a clear research gap, particularly concerning how hybrid physical–digital media can promote conceptual clarity and student engagement simultaneously.

The integration of AR with pop-up books offers a novel instructional approach that unites tangible, three-dimensional interactions with dynamic digital simulations. Such multimodal learning is supported by Dual Coding Theory, which emphasizes the importance of combining verbal and visual systems for stronger cognitive processing (Paivio, 1991), and Experiential Learning Theory, which promotes learning through concrete experiences and reflection (Kolb, 1984). Although several studies have explored AR in science learning, empirical research examining AR-based pop-up books specifically for ecosystem concepts in Indonesian elementary schools is still scarce. Thus, potential of this hybrid medium to address conceptual difficulties in ecology education has not been fully investigated.

Preliminary observations in five elementary schools in Surabaya SD Negeri Gayungan 2, SD Negeri Karah 1, SD Negeri Karah 3, SD Negeri Wiyung 1, and MI Plus Darul Hikmah reveal that ecosystem learning is still dominated by lectures and textbook-based explanations. Teachers noted that students had difficulty visualizing ecological relationships and understanding the roles of various ecosystem components. These findings underscore the need for an innovative learning medium that can simultaneously offer visual clarity, digital interactivity, and physical engagement.

Responding to this educational need and research gap, this study examines the implementation of an Augmented Reality-Based Pop-Up Book designed to enhance elementary students' understanding of ecosystem concepts. This medium is expected to provide a more concrete, engaging, and scientifically meaningful learning experience by presenting ecological interactions through both physical 3D structures and interactive AR features. The study aims not only to evaluate its effectiveness but also to contribute empirical evidence to the development of multimodal, technology-enhanced learning models in elementary science education.

METHOD

Research Design

This study employed an experimental approach using One Group Pretest–Posttest Design to examine the effectiveness of Augmented Rea-

lity-Based Pop-Up Book in improving elementary students' understanding of ecosystem concepts.

Research Participants

The research was conducted in five elementary schools in Surabaya City SD Negeri Gayungan 2, SD Negeri Karah 1, SD Negeri Karah 3, SD Negeri Wiyung 1, and MI Plus Darul Hikmah with a total of 139 fifth-grade students selected purposively based on curriculum relevance to implement digital learning media.

Implementation Augmented Reality based Pop-Up Book

Prior to classroom implementation, the development of the AR-Based Pop-Up Book followed four systematic stages that included needs analysis, design, production, and expert validation. The needs analysis stage focused on identifying learning difficulties, media limitations, and teacher requirements related to ecosystem concepts. The design stage involved developing the book layout, three-dimensional pop-up structures, AR markers, and digital animation scenarios. Once the design was completed, the production process included creating the physical book, integrating AR components, and aligning them with the instructional objectives. The final stage consisted of expert validation by material specialists, media design experts, and elementary school teachers, followed by revisions to ensure content accuracy, usability, and feasibility.

The implementation of the learning intervention was carried out in three interconnected phases. The orientation phase introduced students to the use of the AR application, where the teacher demonstrated how to scan markers embedded in the pop-up book pages. During the exploration phase, students interacted directly with the media by observing the AR animations, examining three-dimensional structures, and engaging in group discussions as they interpreted ecosystem interactions such as food chains, energy flow, and relationships between biotic and abiotic components. This was followed by the reflection phase, in which students summarized their observations, formulated conclusions, and discussed how the visualizations enhanced their understanding of ecological concepts. All learning activities were monitored using observation sheets to capture the depth of engagement and behavioral responses toward the media.

Data Collection

Data collection was conducted using three instruments: a multiple-choice test assessing conceptual understanding, observation sheets documenting students' engagement and behavioral responses, and a Likert-scale questionnaire evaluating students' perceptions of the media. The test was administered before and after the intervention to measure cognitive improvement, while the questionnaire gathered information on the media's usability, clarity, interactivity, and visual appeal. Observation data provided contextual insights into how students interacted with the media and how the media influenced learning behaviors. These combined data sources enabled triangulation for a more comprehensive understanding of the media's effectiveness.

Data Analysis

Data analysis involved both quantitative and qualitative techniques. The comparison between pretest and posttest scores was examined using a paired-sample t-test to determine statistically significant differences in students' conceptual understanding before and after using the AR-Based Pop-Up Book. Additionally, the magnitude of improvement was analyzed using the Normalized Gain (N-Gain) formula.

$$<\text{N-gain}> = \frac{Spost - Spre}{Smax - Spre}$$

Explanation:

N-gain	:	Conceptual understanding values
S_{pre}	:	Pre-test Score
S_{post}	:	Post-test Score
S_{max}	:	Maximum Score

The level of conceptual understanding in Table 3.

Table 1. Level of Conceptual Understanding

Score	Criteria
$0.7 \leq g \leq 1$	High
0.3 g 0.7	Medium
0< g 0.3	Low

Questionnaire responses were averaged and interpreted using established criteria presented in Table 2.

Table 2. Criteria of student questionnaire responses

Score	Criteria
4.21–5.00	Excellent
3.41–4.20	Good
2.61–3.40	Adequate
1.81–2.60	Poor
1.00–1.80	Very Poor

Qualitative data from observations and open-ended responses were analyzed descriptively to support the interpretation of quantitative findings. The interpretation of the research results was conducted by integrating improvements in students' test scores, patterns of classroom engagement, and the consistency of positive student responses. Cognitive improvement was evaluated through pretest–posttest comparisons and N-Gain values, while affective and behavioral dimensions were interpreted based on observation notes and questionnaire patterns. This triangulated interpretation allowed the study to comprehensively assess how the AR-Based Pop-Up Book influenced students' conceptual understanding, motivation, and engagement, thereby providing robust empirical evidence of the medium's effectiveness as a technology-enhanced instructional tool for elementary science learning.

RESULT AND DISCUSSION

The implementation of the Augmented Reality (AR)-Based Pop-Up Book media was conducted through three learning stages: orientation, exploration, and reflection. At the orientation stage, the teacher introduced the AR media and guided students in operating the application. Students showed great enthusiasm upon seeing that the physical pop-up book could generate three-dimensional objects through a tablet or smartphone. The teacher demonstrated how to scan the AR markers on each page, which then displayed interactive animations related to ecosystems, such as interactions among plants (producers), animals (consumers), and microorganisms (decomposers).

The exploration stage served as the core learning activity, where students worked in groups to observe simulations of organism interactions using AR features. For instance, on the page illustrating food chains, students could visualize feeding relationships, energy transfer, and interactions between living organisms and their environments dynamically. These activities stimulated students' scientific thinking through observation, questioning, and reasoning. The teacher acted as a facilitator, guiding students in connecting their observations with theoretical ecological concepts. During the reflection stage, students discussed their observations and concluded how ecosystem balance is maintained. They demonstrated the ability to explain the relationships between biotic and abiotic components coherently, indicating a significant improvement in conceptual understanding.

Pretests and posttests were administered to measure students' conceptual understanding of ecosystems before and after using the AR-Based Pop-Up Book. The results revealed a significant improvement across all participating schools. The average pretest scores ranged from 56 to 70, while the posttest averages increased to 87–91, indicating that the AR-based learning media effectively enhanced conceptual comprehension. The data show a substantial increase in students' performance from pretest to posttest across all schools. Overall, average pretest scores (56–70) rose to posttest averages (87–91), confirming that the instructional model effectively enhanced students' conceptual understanding.

Additionally, individual progress was evident, as the lowest pretest scores (24–40) improved significantly to 80–96 in posttests, suggesting that even lower-achieving students benefited from the intervention. The number of students achieving the Minimum Mastery (score ≥ 75) in SD Negeri Gayungan 1, mastery increased from 50% (pretest) to 85% (posttest). Similar trends were observed in all schools, with posttest mastery levels ranging between 85% and 88%, demonstrating the model's effectiveness in promoting comprehensive student achievement.

A normality test was conducted to determine whether the pretest and posttest data followed a normal distribution for students across the five participating schools: SD Negeri Gayungan 1, SD Negeri Karah 3, SD Negeri Karah 1, MI Plus Darul Hikmah, and SD Negeri Wiyung 1. Since the total sample exceeded 139 students, the Kolmogorov-Smirnov test in SPSS version 26 was used, as shown in Table 3.

Table 3. Results of Normality Test

Class	Tests of Normality					
	Kolmogorov-Smirnova			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
Pretest	.128	139	.200	.958	139	.268
Posttest	.204	139	.160	.964	139	.391

a. Lilliefors Significance Correction

The normality test results indicated that the pretest significance value was 0.200 and the posttest value was 0.160. According to the Kolmogorov–Smirnov criterion, data are considered normally distributed when Sig. > 0.05. Therefore, both the pretest (0.200 > 0.05) and posttest (0.160 > 0.05) data were normally distributed. The pretest and posttest data from all five schools were normally distributed, allowing further analysis

using parametric statistical tests, such as the paired-sample t-test, to determine the significance of learning improvement.

After confirming normal distribution, a paired-sample t-test was performed using SPSS 26 to determine whether there was a significant difference between pretest and posttest scores. The results are presented in Table 4. The analysis showed a Sig. (2-tailed) value of 0.000. According to the paired t-test criterion, if Sig. < 0.05, there is a significant difference between the two measurement conditions. Therefore, the results indicate a significant difference between pretest and posttest scores. These findings confirm that the use of the AR-Based Pop-Up Book significantly improved students' learning outcomes. The intervention effectively enhanced students' conceptual understanding of ecosystems.

To measure proportional learning improvement after the implementation of the AR-Based Pop-Up Book, the Normalized Gain (N-Gain) formula was applied. N-Gain assesses the extent of students' learning progress relative to the maximum achievable score, offering a proportional measure of instructional effectiveness. Based on the results presented in Table 5, all schools involved as research subjects demonstrated a significant improvement in students' understanding of ecosystem concepts following the implementation of the Augmented Reality (AR)-Based Pop-Up Book. The average pretest score of 62.0 increased to 89.0 in the posttest, reflecting an average gain of 27 points. This improvement is also supported by the mean N-Gain score of 0.70, which falls under the "high" category according to Hake's (1999) classification, indicating that the media enhanced students' understanding by 70% of the maximum potential improvement.

Furthermore, the classical completeness rate reached 100% across all schools, signifying that all students successfully met the Minimum Mastery Criteria (≥ 75). This finding confirms that the AR-Based Pop-Up Book is not only effective for students with high academic ability but also inclusive, as it assists students with moderate and lower abilities in achieving optimal conceptual understanding. The success of this learning media demonstrates its tangible positive impact on improving learning outcomes, particularly in the topic of ecosystems. The combination of physical three-dimensional visuals and AR-based digital animations allows students to visualize abstract concepts such as food chains, energy flow, and the interaction between biotic and abiotic components in a realistic and engaging manner. What was once a textual and static learning experience has been transformed into an interactive, contextual, and exploratory one. Direct visualization of organism interactions helps students grasp the role of each living creature in maintaining ecological balance. This medium has also proven to enhance students' motivation and curiosity by providing an engaging and novel learning experience. Students are not only exposed to static images but can also observe dynamic simulations of animals and plants in lifelike three-dimensional motion. Teachers reported that lessons using this media were more effective, capturing students' attention, reducing boredom, and accelerating conceptual comprehension.

Table 4. Paired Sample t-Test Results

Paired Samples Test

		Paired Differences					t	Df	Sig. (2-tailed)
		Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference				
					Lower	Upper			
Pair 1	Pretest – Posttest	-25.32374	14.63083	1.24097	-27.77752	-22.86997	-20.406	138	.000

Table 5. N-Gain Calculation Results for Elementary Students' Ecosystem Concept Understanding

No	School	Average Pretest	Average Posttest	N-Gain	Category	Classical Mastery (%)	Effectiveness Category
1	SD Negeri Gayungan 2	56.6	87.2	0.71	High	100	Effective
2	SD Negeri Karah 1	65.0	90.0	0.71	High	100	Effective
3	SD Negeri Karah 3	61.0	89.0	0.71	High	100	Effective
4	SD Negeri Wiyung 1	63.0	90.0	0.71	High	100	Effective
5	MI Plus Darul Hikmah	66.0	90.0	0.69	Medium–High	100	Effective
Overall Average		62.0	89.0	0.70	High	100	Effective

The study findings reveal that the implementation of the Augmented Reality (AR)-Based Pop-Up Book significantly improved elementary students' conceptual understanding of ecosystems. A comparison between pretest and posttest results showed an increase in average score from 62.0 to 89.0, reflecting a 27-point improvement. This difference confirms a notable enhancement in students' ability to comprehend ecosystem concepts after introduction of innovative media. The calculation of the Normalized Gain (N-Gain) yielded an average of 0.70, categorized as "high" according to Hake's (1999) criteria, indicating that the use of this media increased students' understanding by up to 70% of the maximum potential gain. Moreover, the classical completeness rate reached 100%, meaning that all students exceeded Minimum Mastery Criteria (≥ 75). These findings affirm that AR-Based Pop-Up Book is both effective and inclusive, helping students with diverse academic abilities develop a comprehensive understanding of ecosystem concepts.

The significant improvement in comprehension is closely related to the media's ability to visualize interactions among biotic and abiotic components within an ecosystem. The integration of three-dimensional physical book elements with AR-based interactive animations enables students to observe natural processes such as food chains, energy flow, and the ecological roles of living organisms in maintaining balance. Such visualization assists students in grasping abstract concepts that were previously conveyed only through text, making the information more accessible and easier to retain. Beyond the cognitive domain, the use of this medium also enhances student engagement and motivation. Students actively observed, analyzed, and drew conclusions about organismal interactions, showing high enthusiasm during class discussions. This confirms that the AR-Based Pop-Up Book not only improves learning outcomes quantitatively but also strengthens emotional and cognitive engagement. Therefore, this medium proves highly effective in improving conceptual understanding of ecosystems by integrating visual, interactive, and conceptual elements into a concrete, engaging, and meaningful learning experience.

During the implementation of the AR-Based Pop-Up Book in ecosystem learning, students demonstrated active engagement and high enthusiasm. The learning process was interactive and enjoyable, marked by increased student participation in questioning, discussing, and presenting their observations of ecosystem simulations displayed through the media. When teachers introduced how to use media, students showed great excitement upon viewing the pop-up book pages that projected three-dimensional objects on a tablet or smartphone screen. The animations depicting food chain processes, animal movements, and interactions among biotic and abiotic components made the concept of ecosystems more tangible and easier to understand. Learning that was previously abstract and text-based transformed into a concrete and immersive visual experience. Direct interaction between students and the media fostered curiosity, increased learning motivation, and strengthened comprehension of inter-organism relationships within ecosystems.

To measure students' acceptance of the learning media, a response questionnaire was administered, consisting of ten statements rated using a five-point Likert scale (1–5). The assessed aspects included interest, ease of use, conceptual understanding, interactivity, and the overall usefulness of the media in supporting learning process. The questionnaire data were analyzed to determine average score and percentage of positive student responses to the AR-Based Pop-Up Book. The results of the questionnaire in Table 6 show that 98% of students gave a very positive response to the use of the AR-Based Pop-Up Book in ecosystem learning. The average score of 4.88 out of a maximum of 5.00 indicates that almost all students found the medium engaging, easy to use, and helpful in understanding concepts that were previously difficult. The aspect that obtained the highest score was "the learning experience feels real and enjoyable," with a value of 5.00 or 100%, indicating that the immersive element of the AR media was highly appreciated by students. In addition, almost all students stated that the three-dimensional visualization in the media helped them understand how living organisms interact within an ecosystem, in accordance with the intended learning objectives.

Teachers who accompanied the learning process also provided feedback consistent with the students' questionnaire results. According to the teachers, the use of the AR-Based Pop-Up Book greatly assisted in explaining abstract concepts in a concrete and easily understandable way. Teachers observed that students were more active in asking questions, showed high curiosity, and seemed to enjoy the learning process. With the presence of visual and animated elements, students did not merely memorize the material but were also able to explain the relationships among organisms and ecosystem processes in their own words. Based on these results, it can be concluded that the implementation of the AR-Based

Pop-Up Book is not only effective in improving conceptual understanding but also enriches students' affective and psychomotor learning experiences, creating a more engaging, participatory, and meaningful learning atmosphere.

Table 6. Student Response Questionnaire Results on the AR-Based Pop-Up Book

No.	Evaluated Aspect	Statement Indicator	Mean Score	(%)	Category
1	Interest	The media is engaging and enjoyable to use	4.9	98	Excellent
2	Ease of Use	The book and AR application are easy to use	4.8	96	Excellent
3	Concept Understanding	The media helps in understanding ecosystem concepts	4.9	98	Excellent
4	Visualization	The 3D animation makes it easier to imagine ecosystem interactions	4.9	98	Excellent
5	Interactivity	Students can directly interact with the media	4.8	96	Excellent
6	Learning Motivation	The media makes me more enthusiastic about learning	4.9	98	Excellent
7	Engagement	I am more active and focused during learning	4.8	96	Excellent
8	Visual Appeal	The images and colors are very attractive	4.9	98	Excellent
9	Overall Benefit	The media helps me understand relationships among living organisms	4.8	96	Excellent
10	Learning Experience	Learning feels real and enjoyable	5.0	100	Excellent
Average			4.88	98	Excellent

The results of this study demonstrate that the implementation of the Augmented Reality (AR)-Based Pop-Up Book is effective in enhancing elementary school students' understanding of ecosystem concepts. This is reflected in the increase of the average pretest score from 62.0 to 89.0 on the posttest, with an N-Gain value of 0.70 categorized as high, and a classical completeness rate reaching 100% across all schools. In addition, students' responses to the media were highly positive (98%), indicating that the integration of three-dimensional visuals and digital interactivity creates a more engaging, meaningful, and easily comprehensible learning experience. These findings align with Paivio's (1991) Dual Coding Theory, which posits that the combination of verbal and visual representations enhances information retention by engaging two distinct cognitive processing systems, allowing words and images to mutually reinforce conceptual understanding (Gayathri & Vijayalakshmi, 2025).

This finding is supported by studies conducted by Novika (2025) and Puti (2023), which state that the use of Augmented Reality in science education significantly increases students' motivation and conceptual understanding. AR technology assists students in visualizing abstract concepts, thereby facilitating the process of knowledge construction. Similarly, Singh et al. (2024) found that AR-based instructional media strengthen student engagement and enhance critical thinking skills, as learners actively explore three-dimensional objects. In the same context, Ho et al. (2023) reported that the integration of AR with printed media such as pop-up books creates multimodal learning experiences that stimulate students' visual, auditory, and kinesthetic abilities simultaneously.

From the perspective of constructivist theory (Piaget, 1970; Vygotsky, 1978), learning becomes more meaningful when students actively construct knowledge through interaction with their environment and direct experience. The use of the AR-Based Pop-Up Book supports this principle, as it allows students to observe, reason, and independently discover ecosystem concepts through visual exploration. This finding is consistent with Aulia et al. (2022), who noted that pop-up books stimulate students' visual-spatial intelligence and enhance emotional engagement

in science learning. By adding the digital AR element, the medium extends learning experiences from mere physical observation to dynamic virtual interaction.

Furthermore, based on Kolb's (1984) Experiential Learning Theory, effective learning occurs when students directly experience the phenomena being studied through four stages: concrete experience, reflection, abstract conceptualization, and active experimentation. The orientation, exploration, and reflection stages applied in this study effectively represent this cycle. Students not only read and listen to explanations but also interact with ecosystem animations, reflect on their observations, and draw conclusions independently (Stomme & Mork, 2021). This is also supported by Yani (2025), who found that the application of AR in thematic learning at the elementary level improves students' scientific thinking skills through observation and visual-based discussion.

Research by Aulia et al. (2025) and Saputri & Ulia (2024) reinforces these findings, emphasizing that elementary science learning remains predominantly abstract and requires innovative media to concretize ecosystem concepts. The AR-Based Pop-Up Book addresses this challenge by presenting natural phenomena virtually yet contextually. Students not only understand theoretical relationships among organisms but also see the interactions and energy flows through AR visualizations. Thus, the medium effectively integrates cognitive (conceptual understanding), affective (interest and motivation), and psychomotor (interaction and exploration) dimensions.

These findings are also consistent with Dewi et al. (2024), who demonstrated that AR-based media improved elementary students' science learning outcomes by 75% compared to conventional methods. Similarly, Hasnawiyah and Maslena (2024) found that the use of interactive visual media enhances analytical skills and concept retention in basic science learning. In the context of physical media, Daswananda and Fathoni (2024) reported that educationally designed pop-up books strengthen students' spatial representation and promote effective visual learning. When both approaches interactive print media and AR are combined, as in this study, the result becomes synergistic in improving instructional effectiveness (Fan et al, 2020).

Beyond cognitive aspects, this study also highlights the positive impact on students' affective domains. Based on the questionnaire results, 98% of students provided highly positive responses to the media, with the highest score found in the statement "learning feels real and enjoyable." This aligns with Lestari (2025) and Cotu (2025), who found that AR-based learning increases students' intrinsic motivation by combining elements of surprise, exploration, and visualization that spark curiosity. From the teachers' perspective, this medium was considered practical and effective in facilitating the explanation of complex material, consistent with Blyznyuk and Kachak (2024), who stated that the integration of interactive media reduces instructional time while increasing students' attention and focus.

This research also supports Mayer's (2001) Cognitive Theory of Multimedia Learning, which asserts that learning becomes more effective when information is presented through complementary combinations of text, images, and animation. In this context, the AR-Based Pop-Up Book functions as a multimodal medium that integrates narrative text, three-dimensional visuals, and dynamic animation processed simultaneously by the brain. Such a learning experience promotes deep learning and strengthens long-term memory retention.

The results of this study are consistent with findings published in Frontiers in Psychology (Lawson & Mayer, 2024), which revealed that Augmented Reality-based children's books enhance cognitive, affective, and social engagement by providing interactive and immersive reading experiences. Similarly, Damayanti (2023) found that the use of AR in teaching the "Natural Environment" theme in elementary schools increases student activeness.

Overall, the findings of this study provide strong empirical evidence that combining physical media (pop-up books) with digital technology (Augmented Reality) is a highly effective innovation in the context of elementary education. This medium not only improves learning outcomes quantitatively but also provides a more holistic and meaningful learning experience. Students learn not merely through text and images but through exploration, observation, and active reflection a learning approach consistent with the student-centered learning paradigm (Koehler & Meech, 2022). Therefore, this study makes an important contribution to the development of innovative, technology-based learning models that teachers can adapt to enhance the quality of science education in elementary schools.

CONCLUSION

The implementation of the Augmented Reality (AR)-based Pop-Up Book proved to be very effective in improving elementary school

students' understanding of ecosystem concepts. Based on the analysis results, the average pretest score of 62 increased to 89 in the posttest with an N-Gain value of 0.70 (high category), and the classical completeness reached 100%, meaning that all students achieved the minimum mastery criteria. The t-test results showed a significant difference between learning outcomes before and after using the media, indicating a real effect on the improvement of students' conceptual understanding. This medium combines the advantages of three-dimensional physical visualization from the pop-up book with the digital interactivity of AR, thus bridging the gap between abstract concepts and concrete experiences. Students can observe relationships among organisms, energy flow, and ecosystem balance in a more real, interesting, and meaningful way. Student responses to the media were also very positive (98%), showing increased motivation, engagement, and curiosity. Therefore, the integration of pop-up books and AR not only improves cognitive learning outcomes but also strengthens affective and psychomotor aspects.

This study recommends the use of innovative digital technology-based media like this to enrich science learning in elementary schools. PBL Plus class achieving a higher post-test score of 81.03 while the regular PBL class achieved an average post-test score of 62.31. The N-Gain value for the regular PBL class was 0.22, while the N-Gain value for the PBL Plus class was 0.58, which was categorized as high. T-test (two tails) value is $0.00 < 0.05$. Thus, it can be concluded that the PBL Plus learning model is effective in improving students' conceptual understanding of mirror material and that there is a difference in student learning engagement between the PBL Plus class and the regular PBL class, where PBL Plus, based on 4 indicators of student learning engagement, shows that the category of active students is higher than in the regular PBL class.

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