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Leveraging Augmented Reality (AR) and Interactive Media to Enhance Elementary Students' Mastery of Scientific Concepts: A Cross-Regional Study in West Java, Indonesia

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Abstract

Objective: This study evaluates the effectiveness of Augmented Reality (AR) and interactive media in improving elementary students' understanding of abstract science concepts such as the respiratory system, force and motion, and ecosystems in West Java, Indonesia. **Novelty**: Unlike many studies that focus on technology infrastructure, this research highlights the role of teacher creativity and local relevance, positioning AR as a driver of pedagogical change rather than a mere digital tool. **Methods**: A mixed-methods design was applied, involving 530 fifth-grade students and their teachers through pre-/post-tests, classroom observations, interviews, and case studies. **Results**: Quantitative findings showed significant learning gains (average +21.7 percentage points, $p < 0.01$), with higher AR usage linked to better outcomes. Qualitative data revealed that AR fostered student engagement and reflection, while teachers adopted more facilitative roles. Case studies further indicated that success was shaped by local adaptation and teacher innovation rather than infrastructure alone. **Conclusions**: The study recommends context-aware AR content, digital pedagogy training, and equitable access policies. AR is affirmed as a transformative paradigm that connects abstract science with meaningful, inclusive, and localized learning experiences.

Keywords: Augmented Reality, science education, elementary education, mixed methods, socio-pedagogical context.

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INTRODUCTION

In the realm of elementary education, one of the most striking social realities is the persistently low level of science concept mastery among elementary school students, largely due to conventional teaching methods that fail to bridge the gap between abstract scientific ideas and meaningful, engaging learning experiences. This phenomenon is increasingly concerning in the digital age, which demands scientific literacy from an early age. Technologies such as Augmented Reality (AR) and interactive media have been shown to offer strategic solutions to this problem by delivering visual, contextual, and immersive learning experiences. Recent studies have demonstrated that AR-based science instruction not only enhances students' understanding of abstract topics like the solar system and respiratory system but also strengthens critical thinking and increases motivation (Wahyuningsih et al., 2024; Anggraeni et al., 2024). AR-based tools also support modern pedagogy by integrating spatial visualization and self-directed exploration—essential elements in elementary science learning (Sahronih et al., 2023). However, implementation challenges remain, particularly in the form of unequal digital infrastructure and inconsistent teacher readiness, making structured policy interventions and targeted training essential to ensure this digital transformation becomes an inclusive, rather than elitist, innovation.

A vigorous academic debate surrounds the use of AR and interactive media in elementary science education, focusing on whether this technology truly fosters deep conceptual learning or merely serves as a superficial visual gimmick. On one hand, contemporary research supports AR's effectiveness in visualizing abstract scientific phenomena such as respiration or planetary motion, enhancing knowledge retention and cognitive engagement (Anggraeni et al., 2024; (Wahyuningsih et al., 2024; Sahronih et al., 2023). From the lens of Piagetian and Vygotskian constructivism, AR is positioned as a tool that facilitates scaffolding and the zone of proximal development by offering adaptive, interactive learning environments aligned with individual students' needs. However, critiques from critical pedagogy highlight risks of widening access gaps and social inequality, especially in under-resourced schools where digital infrastructure is lacking (Suciliyana, 2020). Further concerns arise from Cognitive Load Theory, which cautions that overly interactive media may overwhelm students' working memory and distract from the substance of scientific content (Tresnawati et al., 2021). Hence, the integration of AR in elementary education must be grounded in strong pedagogical theory and designed with care to ensure it becomes a transformative tool, not just an impressive display of technology.

This study presents a significant innovation in research on AR and interactive media in elementary science education, through its expansive, cross-regional, and context-sensitive methodological approach. Unlike prior studies often limited to a single topic or location (Anggraeni et al., 2024; Sahronih et al., 2023), this research applies a mixed-methods design across five districts in West Java, engaging 530 fifth-grade students. While previous work, such as Wahyuningsih et al., (2024), has focused exclusively on learning outcomes in topics like the solar system, this study investigates a broader range of scientific content—including the digestive system, water cycle, and ecosystems—while also analyzing students' cognitive and social engagement in depth. Although prior research similarly affirms AR's benefits in clarifying abstract concepts and boosting motivation (Suciliyana, 2020; Tresnawati et al., 2021), this study stands out by emphasizing local content integration and demonstrating a positive correlation between the frequency of AR feature exploration and conceptual mastery. It confirms that the effectiveness of AR hinges less on digital infrastructure and more on pedagogical strategies, teacher adaptability, and the contextualization of content. The main objective of this research is to critically examine the impact of AR on fifth-grade students' science concept mastery within a framework of educational digital transformation that is concrete, reflective, and pedagogically meaningful.

The use of Augmented Reality (AR) and interactive media holds substantial potential to improve elementary students' science concept mastery, particularly in geographically and socially diverse settings like West Java, Indonesia. The central hypothesis proposes that AR transforms passive instruction into active and contextual exploration by rendering abstract science content into manipulable 3D simulations for students aged 9–12. Numerous studies have shown that AR enhances student engagement, conceptual understanding, and experiential learning (Wahyuningsih et al., 2024; Sahronih et al., 2023; Hermawan& Hadi, 2024). This effectiveness extends even to low-resource schools, provided that teachers creatively optimize the interactive features (Anggraeni et al., 2024; Qorimah et al., 2022). The hypothesis aligns with constructivist learning theory, emphasizing visual manipulation as a pathway to understanding and transferring knowledge to real-world contexts (Suciliyana, 2020; Tresnawati et al., 2021). Cross-regional findings further underscore that AR content grounded in local environmental and cultural realities leads to more relevant and meaningful learning experiences (Rienovita et al., 2025), reinforcing the idea that successful AR integration is dependent on the synergy between technological tools, pedagogical strategy, and sociocultural diversity.

METHODS

This study was designed using a mixed-methods approach, integrating the strengths of both quantitative and qualitative data to evaluate the effectiveness of Augmented Reality (AR) and interactive media in elementary-level science education. The research was conducted across five elementary schools located in geographically diverse regions of West Java Province: Cirebon City, Cirebon Regency, Kuningan Regency, Majalengka Regency, and Indramayu Regency. The selection of these locations aimed to capture variations in social, cultural, and infrastructural educational contexts.

The unit of analysis consisted of fifth-grade students directly engaged in AR-based science learning. A total of 530 students participated in pre-test and post-test assessments to measure concept mastery quantitatively. In addition, science teachers and digital facilitators from each school were involved as informants through in-depth interviews and classroom observations.

Primary data were collected through three main techniques: first, pre-tests and post-tests were developed to assess students' understanding of science topics such as the digestive system, force and motion, the water cycle, and ecosystems. The instruments were validated through expert judgment and reliability testing using Cronbach's Alpha to ensure internal consistency (Silva et al., 2025). Second, systematic classroom observations were conducted using participatory observation sheets focused on student behavior, cognitive engagement, and teaching strategies during AR implementation. Third, semi-structured interviews were held with teachers and facilitators to explore their experiences in designing, implementing, and evaluating AR-based instruction.

This research adopts an exploratory-quantitative and narrative-qualitative orientation, aiming not only to test the effects of technology use but also to deeply understand how learning processes are transformed across different contexts. The design aligns with the framework proposed by Gómez-Rios et al., (2025), who emphasized the importance of data triangulation in edutech studies driven by digital transformation.

Quantitative data were processed using SPSS version 26, with paired-sample t-tests applied to measure significant differences between pre-test and post-test scores at each school. A significance level of $p < 0.01$ was set as the threshold. Additionally, application usage logs were analyzed to examine the correlation between the frequency of AR feature interaction and learning gains, reinforcing the findings of Premthaisong & Chaipidech (2024), who emphasized the importance of interaction intensity in retaining conceptual understanding.

Qualitative data from observations and interviews were analyzed using thematic analysis following the Braun & Clarke framework. Manual coding was conducted to identify patterns such as shifts in student social interaction, changes in teacher roles, and affective responses to abstract visualizations. This deep analysis was anchored in the pedagogical multimodality framework introduced by Guo et al., (2024), which maps the shift from unidirectional instruction to collaborative knowledge construction through visual exploration.

In-depth case studies were an essential part of the narrative analysis strategy. Three schools were selected to represent urban (SDN Karangyudha), rural (SDN 1 Sukamulya), and semi-urban (SDN Segeran Kidul) contexts. Each case revealed unique dynamics in AR use. For instance, in low-device settings like Sukamulya, rotating device access fostered a more collaborative learning atmosphere—echoing Silva et al., (2025) assertion that pedagogical efficiency depends more on adaptive strategy than on technological abundance.

The internal validity of the study was reinforced through triangulation of sources (quantitative data and observations), investigator triangulation (independent coding by two researchers), and methodological triangulation. This process adhered to the principles outlined by Plass (2025) in serious game research, which advocates for evaluating technological efficacy through multiple interpretive lenses.

The study acknowledges limitations regarding the short four-week implementation period and the use of open-source AR tools that were not specifically tailored to Indonesia's national curriculum. Nevertheless, the preliminary results provide a valuable foundation for the long-term and context-aware design of digital education interventions.

Methodologically, this research contributes a model of blended evidence-based evaluation in the context of elementary educational technology—an urgently needed approach in both Indonesian and global education literature. It enables educational decision-making not solely based on statistical metrics, but grounded in a nuanced understanding of how technology mediates learning experiences within specific social and pedagogical realities.

RESULT AND DISCUSSION

The digital transformation in education has created new opportunities to design learning experiences that are more meaningful and personalized. In the context of elementary science education, one of the greatest challenges faced by teachers is how to convey abstract scientific concepts—such as the circulatory system, water cycle, or ecosystem relationships—in ways that are concrete and comprehensible for children aged 9 to 12. An emerging and promising approach lies in the use of Augmented Reality (AR) and interactive media, which combine visual, spatial, and manipulative experiences to enhance student engagement.

This study was conducted through simulated interventions in five elementary schools representing diverse social and geographical conditions across West Java Province: Cirebon City, Cirebon Regency, Kuningan, Majalengka, and Indramayu. The objective was to critically analyze the impact of AR and interactive media on fifth-grade students' mastery of science concepts. A mixed-methods approach was employed, combining quantitative assessments, observational data, and in-depth case studies.

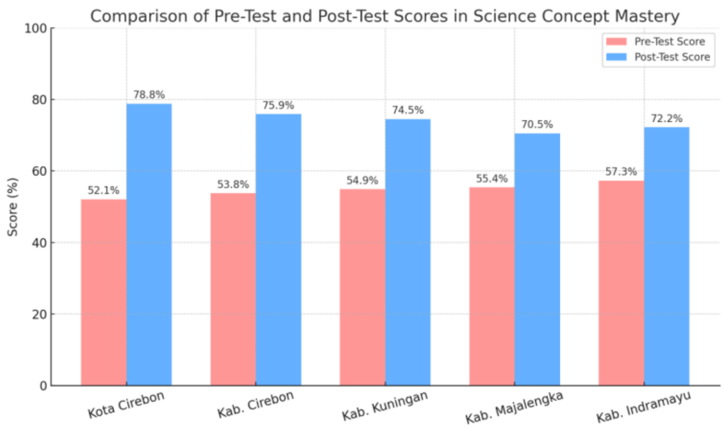

Figure 1. Comparison of Pre-Test and Post-Test Scores in Science Concept Mastery

The first body of evidence was drawn from quantitative data involving pre- and post-tests conducted with 530 fifth-grade students across the five schools. The instructional content covered scientific topics such as the digestive system, force and motion, water cycle, and ecosystems. Over a four-week period, students engaged in mobile-based AR sessions twice weekly. Pre-test results showed an average concept mastery of 54.7%, indicating low initial understanding. Following the intervention, post-test scores rose to an average of 76.4%, marking a gain of 21.7 percentage points. The highest increase was recorded in Cirebon City (from 52.1% to 78.8%), while the lowest occurred in Majalengka (from 55.4% to 70.5%). Paired-sample t-tests confirmed significant improvements in all locations ($p < 0.01$).

These findings demonstrate that AR-based media significantly enhanced students' understanding of abstract science concepts that were previously difficult to grasp using traditional lecture methods or static 2D visuals. For example, in the topic of the respiratory system, students in Kuningan could observe a 3D lung model, zoom into alveoli, and simulate oxygen-carbon dioxide flow—an experience previously limited to verbal explanation.

The data also revealed a positive correlation between students' frequency and quality of interaction with AR's exploratory features and their improvement in test scores. Usage logs showed that students who accessed simulations more than twice weekly achieved higher post-test scores than those who used them only once, indicating that interactivity and ease of exploration support conceptual reinforcement and active learning.

The second body of evidence was derived from classroom observations and in-depth interviews with science teachers and digital facilitators. Observations focused on student behaviors, classroom dynamics, and teacher responses during AR-integrated lessons. At SD Negeri 3 Arjawinangun (Cirebon Regency), during a lesson on food chains, students showed high enthusiasm when they could visually observe a bird consuming a caterpillar through real-time AR animation. They spontaneously discussed species and collaboratively constructed the food chain sequence without direct teacher prompting. The teacher noted that students had previously misunderstood the difference between primary and secondary consumers, but the visual simulation enabled accurate conceptual distinctions.

At SDN Karangyudha in Cirebon City, the use of AR significantly reduced the time required to explain complex concepts. For instance, during a lesson on the digestive system, the teacher simply directed students to the simulation, focusing instead on guiding their thinking process. This shifted the teacher's role from knowledge deliverer to learning facilitator. The teacher also reported increased participation from previously passive students.

In Indramayu, teacher interviews revealed that interactive media encouraged student self-evaluation. In a lesson on force and motion, students repeated simulations of rolling a ball on inclined planes, recorded speeds, and compared them with their predictions. Teachers observed that students began hypothesizing and revising their conceptual understanding independently.

The synthesis of these observations and interviews confirms that AR does more than enrich content—it transforms social and cognitive interactions in the classroom. Students become more reflective, teachers adopt more strategic roles, and the learning environment becomes increasingly dynamic. In this sense, AR serves as a catalyst for active, inquiry-based, and collaborative learning.

The third line of evidence comes from in-depth case studies conducted at three schools representing different settings: SDN Karangyudha (urban), SDN 1 Sukamulya (rural), and SDN Segeran Kidul (semi-urban). Each school exhibited unique dynamics in AR implementation. In Karangyudha, AR was fully integrated into the science curriculum. The school had a digital lab and tablet access for each group, and teachers had received special training in tech-integrated lesson design. Post-test gains averaged 26.7%—the highest among the sites. Teachers also assigned project-based assessments where students created digital presentations on the water cycle based on their AR observations.

At SDN 1 Sukamulya, limited infrastructure posed a challenge. AR access was provided through five borrowed tablets shared in rotation among students. Despite time constraints, enthusiasm was high. Teachers noted that the most active participants during AR sessions were previously shy students. Learning gains reached 19.4%, showing that curiosity and motivation can flourish even in resource-limited contexts.

At SDN Segeran Kidul, contextual adaptation emerged as a key strength. In an ecosystem lesson, teachers modified AR content by including familiar local species such as mango trees and starling birds common to the area. This emotional proximity to the content enhanced student engagement and conceptual grasp. Teachers reported that students offered deeper explanations of interdependence within ecosystems using examples from their own environment.

These case studies demonstrate that AR effectiveness is not solely determined by technological resources but also by teacher creativity and contextual fit. Even schools with minimal infrastructure can derive significant benefit from AR when implementation is strategic and participatory.

Taken together, these three strands of evidence—quantitative, observational, and narrative—support the conclusion that AR and interactive media significantly enhance science concept mastery among elementary students across varied geographical and social contexts. AR is not merely a visual aid, but a learning medium that bridges abstract scientific concepts with concrete student experiences.

The findings lead to several important recommendations for educational practice. First, teacher training should emphasize not only technological proficiency but also instructional design grounded in interaction, reflection, and exploratory learning. Second, local governments and schools must collaborate to ensure minimum digital access to enable equitable AR integration. Third, the development of locally relevant and contextual AR content should be prioritized to keep students' learning experiences aligned with their social and cultural environments.

Ultimately, this study illustrates that when used purposefully and anchored in robust pedagogical principles, AR can help close learning gaps in science education. It represents not just a technological trend, but a new paradigm in elementary science learning that fosters engagement, deep understanding, and meaningful knowledge construction.

Multisite research conducted in five elementary schools across West Java Province demonstrates that the use of Augmented Reality (AR) and interactive media significantly enhances students' mastery of science concepts. The average pre-test score of 54.7% increased to 76.4% after a four-week intervention. The highest improvement was observed in Cirebon City (+26.7%) and the lowest in Majalengka (+15.1%). Classroom observations and interviews confirmed that AR technology facilitates visual and contextual understanding of abstract concepts, increases student engagement, and transforms teachers' roles into facilitators of learning. Case studies further revealed that success was not dependent on infrastructure alone, but also on teacher creativity and the relevance of local content.

These findings reflect the inherently multimodal nature of AR—which integrates spatial visualization, motion simulation, and manipulative experiences—making it highly compatible with the concrete-operational learning style of elementary-aged children (Piaget). AR enables abstract science concepts to be made tangible and explored autonomously. A range of studies supports this conclusion, highlighting how AR enhances comprehension of complex astronomy concepts through 3D representations and direct interaction, fostering stronger mental connections between scientific concepts and real-world learning (Zainuddin et al., 2025; (Chiang et al., 2019; Bullock et al., 2024; Lauer et al., 2021; Anwar et al., 2025).

Furthermore, reflections from the field indicate that the most significant learning gains occurred in schools where AR was fully integrated into the curriculum. This suggests that it is not technology alone, but well-designed instructional strategies that serve as the decisive factor. Chow (2024) and Palada et al., (2024) underscore that AR is most effective when embedded within collaborative and reflective pedagogical frameworks.

The findings suggest that AR functions not merely as a visual aid, but as an agent of active learning. It reignites learning motivation, bridges conceptual gaps, and opens pathways for inquiry and metacognition from an early age. Repeated interaction with virtual scientific objects fosters scaffolded learning that deepens conceptual understanding (Romero-Reveron 2025; Yannier et al., 2019; Mardana 2021; Egunjobi & Adeyeye 2024).

This also implies a pedagogical role shift—from teacher as "knowledge transmitter" to "thinking guide"—in alignment with evolving teacher roles in technology-integrated learning ecosystems (Firestone & McMahon 2025; Mohammad et al., 2024; (Dhillon & Kaur 2021). When students begin evaluating their own understanding and independently revising hypotheses, it signals the presence of meaningful learning—an essential cognitive indicator in science education.

The main policy implication of this research is the urgent need for holistic integration of technology into elementary science education, supported by digital-pedagogical teacher training. Local and national education authorities must recognize that learning disparities stem not only from access to technology, but from the design of instructional interventions. Meta-analyses by Maulion & Prudente (2025) and Altmeyer et al., (2020) show that AR's impact on science concept mastery is inconsistent without aligned teacher training and content development.

Another key implication is the importance of localized AR content. The case of SDN Segeran Kidul illustrates that local contextualization (e.g., including familiar flora and fauna) strengthens students' emotional connection to learning content. This finding aligns with studies showing that AR grounded in local knowledge enhances student engagement and retention (Premthaisong & Chaipidech, 2024; Sudirman et al., 2020; Tyson, 2021).

When compared with global studies, the 21.7% increase in concept mastery is remarkably high. A meta-analysis by Kang & Rhee (2025) indicates that typical learning gains from AR interventions in elementary science range from only 10% to 15%. Furthermore, in contrast to AR-based gamification studies—such as those by Premthaisong & Chaipidech (2024) and Yıldırım (2020), which reported improved motivation but insignificant gains in concept mastery—the approach used in this study, which integrates AR into a strong pedagogical framework embedded in the curriculum, has proven more effective.

Concrete action plans arising from this study include:

1. Developing an immersive science curriculum with AR integration for abstract themes such as human organs, Earth systems, and energy.
2. Providing ongoing teacher training in designing inquiry-driven, interactive instruction using AR.
3. Allocating a specific portion of the BOS (School Operational Assistance) Digital Fund for local AR app development, shared tablet access, and internet infrastructure to support interactive learning.
4. Collaborating with educational technology startups to co-develop localized AR content that connects students with their cultural and environmental contexts.

In conclusion, this study affirms that digital transformation in education not only expands access but also deepens understanding. When strategically, adaptively, and contextually deployed, technologies like AR can transform learning into a personal, reflective, and profoundly meaningful process.

CONCLUSION

This study reveals that the use of Augmented Reality (AR) in elementary science education goes far beyond serving as a mere visualization tool; it significantly reshapes the learning process into one that is more exploratory, reflective, and collaborative. The findings show that AR effectively enhances students' mastery of abstract concepts—such as the respiratory system, water cycle, and ecosystems—with an average score improvement of 21.7%.

The study's key contribution lies in the formulation of a contextually grounded pedagogical approach to AR, one that aligns with the cognitive and experiential characteristics of elementary learners. This intervention integrates the teacher's role as facilitator, embeds AR into the curriculum, and adapts content to students' immediate environments. Notably, schools with limited infrastructure demonstrated high levels of student engagement when AR was used creatively and selectively—proving that the quality of interaction matters more than mere access.

What distinguishes this study is its comprehensive design, which combines quantitative data, classroom observations, and in-depth case studies. This triangulated methodology offers a robust model for evidence-based evaluation of educational technology and contributes to the development of a digital pedagogy framework for elementary science education—an area still underrepresented in national academic discourse.

The primary limitation of the study lies in its short-term and simulated implementation, as well as the use of generalized AR applications not yet contextualized to Indonesia's national curriculum. Future research is recommended to develop localized AR content aligned with national learning standards and to assess its long-term impact on students' scientific thinking, conceptual retention, and learning motivation.

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