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Augmented Reality in the TPACK Framework: A Qualitative Analysis of Environmental Science Learning in Elementary Schools

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ABSTRACT

This study examines the implementation of Augmented Reality (AR) in elementary environmental science learning through the Technological, Pedagogical, and Content Knowledge (TPACK) framework. Using qualitative data from interviews and classroom observations, the research identifies how teachers progressively integrate AR, moving from a technological orientation toward comprehensive pedagogical and conceptual alignment. Findings indicate that AR enhances students' engagement, conceptual understanding, and ability to connect digital simulations with real environmental phenomena. Teachers demonstrate reflective adaptation by refining instructional strategies, guiding analytical discussions, and integrating ecological values into science instruction. The study further reveals a sustainable integration model characterized by three stages: technological familiarization, conceptual reinforcement, and reflective contextualization. Successful implementation depends not only on technological accessibility but also on teachers' evaluative competence and institutional support. AR functions as an epistemic tool that facilitates experiential learning rather than merely providing visual enhancement. The TPACK framework is effective for conceptualizing the dynamic interplay among technology, pedagogy, and scientific content in environmental education. The research highlights the strategic importance of professional development and policy support to ensure the long-term sustainability of AR-based science learning innovations.

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1. INTRODUCTION

The rapid development of immersive technologies has transformed science learning at the elementary school level, particularly through the use of Augmented Reality (AR) to present abstract concepts in more contextual, visual forms. However, integrating AR into classroom practice is not merely a technical matter; it requires pedagogical readiness and strong content mastery to ensure meaningful learning. In many cases, the use of technology in elementary science classrooms remains predominantly demonstrative rather than conceptual, limiting its potential to foster deep understanding and ecological awareness. This condition indicates a gap between technological availability and its pedagogically meaningful implementation [1], [2].

The Technological Pedagogical Content Knowledge (TPACK) framework provides a theoretical foundation for understanding how technology, pedagogy, and content interact in instructional practice. TPACK emphasizes that effective technology integration occurs when these three domains are interconnected rather than applied separately. Previous studies have shown that teachers' TPACK competence remains a critical issue in responding to global educational challenges and promoting sustainable learning practices [1], [2]. Therefore, the integration of AR must be analyzed not only as a technological innovation but also as a pedagogical and conceptual process.

Several studies have explored the role of AR in strengthening TPACK competence, particularly in teacher education contexts. Karpudewan [3] found that AR enhances TPACK in sustainable chemistry learning, while Belda-Medina and Calvo-Ferrer [4] demonstrated improvements in digital competence and professional attitudes through AR integration. In the context of elementary education, Ga et al. [5] and Cha et al. [6] highlighted the importance of lesson planning and reflective practices in using AR and VR technologies. However, these studies primarily focus on preservice teacher training and instructional model development rather than examining actual classroom implementation.

Further research also emphasizes the importance of teacher training and technology acceptance in supporting AR integration. Küng and Brovelli [7] revealed that structured training improves teachers' ability to evaluate AR applications, while Park et al. [8] showed that technology acceptance influences sustainable integration through a TAM–TPACK perspective. Despite these contributions, existing studies have not specifically addressed the integration of AR in environmental science learning at the elementary level, particularly in real classroom contexts.

Environmental science learning in elementary schools requires contextual, visual, and interactive approaches to support students' ecological literacy. AR has been shown to enhance learning effectiveness when combined with innovative instructional models such as the flipped classroom [9]. In addition, Tan et al. [10] highlighted that AR supports the development of multimodal literacy through TPACK configurations. However, previous studies have not deeply explored how AR is implemented within environmental themes or how it shapes pedagogical interactions and students' ecological understanding.

Conceptual studies also suggest that AR integration can be applied across disciplines to enhance engagement and comprehension. Deviyanti and Hidayat [11] demonstrated the potential of AR in history education within a TPACK framework. Nevertheless, such studies remain largely theoretical and lack empirical investigation in elementary science classrooms. Bibliometric analyses further confirm that research on TPACK in primary education continues to grow, yet gaps remain in exploring immersive technologies within science subjects and their classroom implementation dynamics [2].

Based on this review, a clear research gap emerges: previous studies have focused on teacher competence, training models, or quantitative outcomes, while limited research has qualitatively examined how AR is implemented within the TPACK framework in real elementary science classrooms, particularly in environmental learning contexts. This study addresses this gap by analyzing the interaction between technology, pedagogy, and content in authentic learning settings.

This study aims to analyze the implementation of Augmented Reality within the TPACK framework in elementary school environmental science learning. Specifically, it seeks to (1) identify the configuration of TPACK in AR-based instruction, (2) examine pedagogical dynamics and student responses, and (3) develop a sustainable integration model based on classroom practices.

The expected contribution of this research is both theoretical and practical. Theoretically, it strengthens the elaboration of TPACK as an analytical framework for integrating immersive technologies in science education. Practically, it provides insights for teachers, schools, and policymakers in designing pedagogically meaningful and sustainable AR-based learning. Ultimately, this study offers a model of technology integration that is not only innovative but also contextually relevant and supportive of the development of environmental literacy in elementary education.

2. METHOD

This study employed a qualitative case study design to analyze the implementation of Augmented Reality (AR) within the TPACK framework in environmental science learning at the elementary school level. The case study design was selected to enable an in-depth exploration of instructional practices, pedagogical interactions, and the construction of students' ecological understanding within authentic classroom contexts. This approach enables a comprehensive interpretation of the dynamic interplay among technology, pedagogy, and content in real educational settings.

The study was conducted at SD Negeri Cisaat Gadis and SD Negeri Sukamanah 2, located in Cisaat District, Sukabumi Regency, West Java, Indonesia. These schools were purposively selected based on their demonstrated readiness to integrate digital learning media, particularly Augmented Reality, into classroom instruction. Such contextual selection was essential to ensure that the phenomenon under investigation could be observed in a setting where AR integration was actively implemented.

The research participants were five students and three elementary science teachers, selected through purposive sampling. The relatively small sample size is consistent with qualitative case study principles, which prioritize depth of analysis over generalization. The selected participants were directly involved in AR-based learning activities, enabling the researcher to capture rich, detailed, and context-specific data regarding instructional processes and learning experiences.

Table 1. Distribution of Respondents Based on Participant Category and Interview Identification Code

Initial Code	Status	Gender	Grade/Role	School
S-AR	Student	M	Grade V	SD Negeri Cisaat Gadis
S-NL	Student	F	Grade V	SD Negeri Cisaat Gadis
S-FK	Student	M	Grade IV	SD Negeri Sukamanah 2
S-DP	Student	F	Grade IV	SD Negeri Sukamanah 2
S-RM	Student	M	Grade V	SD Negeri Sukamanah 2
G-IA	Science Teacher	F	Grade V Teacher	SD Negeri Cisaat Gadis
G-HT	Science Teacher	M	Grade IV Teacher	SD Negeri Sukamanah 2
G-SM	Science Teacher	F	Science Subject Teacher	SD Negeri Sukamanah 2

Data were collected through in-depth semi-structured interviews, classroom observations, and documentation of instructional materials integrating Augmented Reality. The interviews were guided by a protocol developed based on the TPACK framework, covering technological knowledge (TK), pedagogical knowledge (PK), content knowledge (CK), and their intersections (TPK, PCK, and TPACK). Each interview lasted approximately 30–45 minutes and was conducted flexibly to allow participants to elaborate on their experiences.

Classroom observations were conducted over a period of four weeks, with a total of six observation sessions (each lasting 60–90 minutes) across the two schools. The observations focused on teacher instructional strategies, student engagement, interaction patterns, and the integration of AR within learning activities. Field notes and observation sheets were used to document classroom dynamics during each session systematically.

Data analysis followed an interactive model consisting of data reduction, data display, and conclusion drawing. The analysis process was conducted through several stages. First, all interview transcripts and observation notes were transcribed and organized. Second, open coding was performed to identify initial themes related to TPACK dimensions and AR implementation. Third, axial coding was applied to categorize and connect emerging themes, particularly in relation to technological, pedagogical, and content integration. Finally, selective coding was conducted to develop overarching patterns and construct a coherent interpretation of the implementation model.

To ensure the findings' trustworthiness, several validation strategies were applied. Source triangulation was conducted by comparing data from teachers and students, as well as across interviews, observations, and documentation. Member checking was carried out by confirming key findings with selected participants to ensure interpretive accuracy. Additionally, an audit trail was maintained throughout the research process to document analytical decisions and ensure transparency and consistency in data interpretation.

3. RESULTS AND DISCUSSION

3.1 RESULTS

Configuration of TPACK in AR Implementation

The findings indicate that the implementation of Augmented Reality (AR) in environmental science learning reflects an integrated configuration of technological, pedagogical, and content knowledge. Teachers did not use AR as a standalone tool; instead, they embedded it within problem-based instructional strategies. AR applications were used to visualize ecosystem cycles, pollution processes, and food chains through interactive three-dimensional simulations.

Interview data confirm that application selection was guided by curriculum alignment and student characteristics. As stated by G-IA:

> *"We choose AR applications that match the environmental topics so students can directly see cause-and-effect relationships."*

Similarly, G-HT emphasized:

> *"If the application is not relevant to the material, students become distracted rather than understanding the concept."*

Classroom observations further revealed that AR functioned as a trigger for analytical discussions rather than merely a demonstration tool. Students were encouraged to interpret simulations and relate them to real environmental issues. This was reflected in student responses, for example, S-NL stated:

> *"I can see how pollution affects fish directly, so it is easier to understand than just reading."*

Teachers also demonstrated adaptive instructional planning. G-SM noted:

> *"Using AR requires more detailed lesson planning because we must guide exploration and discussion step by step."*

Increased student participation was consistently observed during AR-based learning. Students actively engaged in questioning, discussion, and collaborative analysis when interacting with virtual objects. However, technical challenges such as limited devices and unstable internet access were also identified, requiring strategies such as group rotation and structured usage time.

Table 2. Configuration of TPACK Dimensions in the Implementation of Augmented Reality in Environmental Science Learning

TPACK Dimension	Practice Indicator	Field Findings
TK	Selection of AR applications	Based on alignment with environmental content
PK	Problem-based discussion strategies	Students actively analyzed simulations
CK	Mastery of ecosystem concepts	Teachers linked concepts to local issues
TPACK	Integration of visualization and reflection	Deeper conceptual understanding observed

Pedagogical Dynamics and Environmental Literacy

The findings show that AR integration contributed to students' ecological understanding and learning engagement. Students reported improved comprehension of abstract environmental concepts through visual simulation. S-AR explained:

"The food chain becomes clearer because I can see how each organism is connected."

S-DP added:

"At first, I did not understand the water cycle, but after seeing the simulation, it became easier."

Teachers confirmed that AR supported deeper classroom interaction. G-IA stated:

"Students ask more critical questions after using AR compared to traditional teaching."

G-SM also observed:

"Students are more confident to express their opinions when they have visual references."

Variations in students' digital literacy were identified. Some students adapted quickly, while others required guidance. Teachers addressed this by forming heterogeneous groups to support peer learning.

Table 3. Students' Cognitive, Affective, and Participatory Responses to the Use of Augmented Reality

Initial Code	Cognitive Response	Affective Response	Discussion Engagement
S-AR	Understood food chain relationships	Enthusiastic	Active
S-NL	Explained the impact of pollution	Environmentally concerned	Active
S-FK	Connected simulations with local experiences	Interested	Moderately active
S-DP	Understood the water cycle after guidance	Motivated	Moderately active
S-RM	Quickly comprehend ecosystem concepts	Enthusiastic	Active

Follow-up interviews revealed behavioral reflection. S-NL stated:

"After seeing the simulation, I want to reduce plastic waste."

This indicates that AR-based learning not only enhances cognitive understanding but also fosters ecological awareness.

Sustainable Integration Model

The findings further reveal a progressive pattern of AR integration. Implementation evolved from initial technological exploration toward deeper conceptual and reflective learning.

G-SM explained:

"At the beginning, students only explored the application, but later they focused more on understanding the concepts."

Students also confirmed this progression. S-FK noted:

"At first we just tried the app, but later we discussed more about the meaning."

This process resulted in a three-stage integration model:

Table 4. Stages of the Sustainable Integration Model of Augmented Reality within the TPACK Framework

Implementation Stage	Teacher Practice	Student Response	Dominant TPACK Dimension
Initial Orientation	Introduction to AR applications	Enthusiastic, exploratory	TK
Concept Reinforcement	Simulation-based analytical discussion	Began explaining cause-and-effect relationships	TPK–PCK
Value Reflection	Connecting local issues and behavior	Emergence of ecological awareness	TPACK

The findings indicate that AR supports a gradual transformation from technical use toward reflective and value-based learning.

3.2 DISCUSSION

Configuration of Technological, Pedagogical, and Content Knowledge in the Implementation of Augmented Reality

The implementation of Augmented Reality (AR) in environmental science learning demonstrates that teachers' knowledge configurations do not operate in isolation but are dynamically intertwined across technological, pedagogical, and content dimensions. Teachers utilized AR applications to visualize ecosystem cycles, pollution processes, and food chains through three-dimensional simulations integrated with problem-based classroom discussions. This pattern reflects the construction of TPACK as an integrative framework that positions technology as a medium for meaning transformation rather than merely a presentation tool [12], [1]. Such practices indicate that teachers began to position AR as a conceptual representation supporting more contextual and reflective elaboration of science content.

Interviews with teachers revealed that the selection of AR applications was based on alignment with environmental curriculum content and students' characteristics. Teachers reported that interactive features enabled students to understand cause-and-effect relationships in environmental issues more concretely. These findings align with AR training studies that emphasize the importance of selecting applications based on pedagogical and content suitability [7], [13]. This process confirms that technological knowledge cannot be separated from pedagogical content knowledge in instructional design.

Classroom observations showed that teachers used AR not only as a demonstration tool but also as a trigger for critical discussions of local environmental issues. Students were encouraged to analyze water pollution simulations and their effects on food chains through open-ended questions that required reasoning. This approach reflects constructivist pedagogical integration consistent with AR development practices in elementary integrated science [14], [15]. The integration strengthened the relationship between visual experience and students' cognitive processes.

Teacher reflections indicated that AR use required more detailed lesson planning compared to conventional instruction. Teachers developed learning scenarios incorporating exploration, elaboration, and reflection through digital interaction. This practice is consistent with the findings of Ga et al. [5] and Cha et al. [6], who highlight the importance of planning and reflection in implementing VR and AR in elementary science. Clear instructional design emerged as a key determinant of successful TPACK integration in classroom practice.

Analysis of lesson plan documents revealed adjustments to learning indicators that simultaneously accommodate both digital and scientific literacy. Teachers integrated objectives emphasizing environmental conceptual understanding alongside digital visual interpretation skills. This pattern aligns with studies on science digital literacy that emphasize higher-order thinking skills [16]. The integration suggests that TPACK functions as a foundational framework for 21st-century instructional design.

Field findings demonstrated increased student participation when AR media were employed in environmental learning. Interaction with virtual objects stimulated critical questioning and peer collaboration. This condition reflects the relationship between TPACK and the enhancement of 4C skills identified in previous research [17]. AR acted as a catalyst, facilitating communication, collaboration, and critical thinking.

Teachers acknowledged technical challenges, including limited devices and unstable internet connectivity, during instruction. These constraints required adaptive strategies, including the use of a rotational device and structured time management for exploration. This situation aligns with policy analyses on technology integration in the Industrial Revolution 4.0 era, which emphasize infrastructure and curricular readiness [18], [19]. The implementation of AR in elementary science indicates that successful TPACK integration is influenced by systemic factors beyond the classroom.

The data indicate that AR integration does not merely enrich visualization but also reconstructs the relationships among teachers, students, and content. The implementation pattern demonstrates coherence between theory and practice as described in national and international TPACK literature [2], [10]. These dynamics affirm that successful technological integration depends on balancing conceptual competence and pedagogical strategy. The configuration illustrates a transformation in environmental science instruction toward a more immersive and reflective approach.

The TPACK configuration in AR implementation for environmental themes reflects a paradigm shift from expository to exploratory learning. Teachers assumed the role of facilitators, orchestrating digital experiences and conceptual discussions simultaneously. This practice aligns with the understanding of educational technology as the integration of theory and implementation [20]. AR-based science learning demonstrates that technology can strengthen pedagogical relationships when designed within a comprehensive TPACK framework.

Pedagogical Dynamics and the Construction of Environmental Literacy Based on Respondent Data

The implementation of Augmented Reality (AR) in environmental science learning was analyzed based on interview data from five students (S-AR, S-NL, S-FK, S-DP, S-RM) and three teachers (G-IA, G-HT, G-SM), as described in the research methodology. Teachers G-IA and G-SM explained that AR use was primarily focused on ecosystem and environmental pollution topics, which are often difficult for Grade IV and V students to comprehend abstractly. Meanwhile, G-HT emphasized the importance of reinforcing reflective discussions following digital visual exploration to ensure that learning does not remain at a merely technical level. These practices illustrate a pedagogical configuration aligned with TPACK construction in 21st-century learning [12], [21].

Students S-AR and S-NL reported that three-dimensional visualizations of food chains helped them understand inter-organism relationships more systematically. S-FK and S-DP stated that water pollution simulations heightened their awareness of the impact of human behavior on the environment. These responses indicate a connection between visual experience and the development of ecological awareness. The findings are consistent with reports on improved integrated science learning outcomes supported by AR within a TPACK framework [15], [14].

Teacher G-IA noted that group discussions following AR exploration generated critical questions that rarely emerged in conventional instruction. G-SM observed that students were more confident in expressing opinions when supported by concrete visual references. These interactions demonstrate the strengthening of communication and collaboration skills as examined in the relationship between TPACK and 4C competencies [17]. Classroom dynamics indicate that AR functions as a catalyst for more focused and meaningful scientific dialogue.

Interview data also revealed variations in students' digital literacy levels. S-RM and S-FK were relatively quick in operating the application, whereas S-DP required initial guidance. In response, G-HT adapted the strategy by forming heterogeneous groups to facilitate peer assistance. This situation confirms the importance of TPACK-based media needs analysis concerning students' cognitive readiness and technological competence [22].

Students' learning experiences further indicated that AR strengthened their understanding of cause-and-effect relationships in environmental issues. S-NL mentioned being able to observe how waste affects aquatic organisms directly through digital simulations. This statement reflects the internalization of ecological concepts through structured visual experience. The condition is relevant to enhancing scientific literacy and higher-order thinking skills (HOTS) in elementary science learning [16].

Teachers G-IA and G-SM emphasized that AR-based lesson planning requires more detailed scenarios than traditional lecture methods. They designed stages of exploration, discussion, and reflection to ensure that technology use was integrated with learning objectives. This approach correlates with TPACK implementation models in social studies and integrated science education that stress systematic instructional design [23], [21]. Such planning demonstrates that pedagogical knowledge mediates effective technology use.

The data indicate that all students demonstrated positive cognitive responses despite variations in technical readiness. Teachers facilitated differentiated instruction to ensure that AR integration remained inclusive. This pattern aligns with technology-based science learning innovation and deep learning approaches [24], [25]. The integration of AR into the TPACK framework significantly strengthens environmental literacy.

Teachers also connected the material to environmental issues surrounding the school to enhance contextual relevance. This practice demonstrates that the content knowledge dimension does not stand alone but is linked to students' social realities. Such an approach is consistent with the concept of educational technology integration as a contextual and reflective practice [20]. AR thus serves as a medium bridging digital simulations with local realities.

Follow-up interviews revealed that students began reflecting on their daily behaviors after participating in AR-based learning. S-AR and S-NL expressed their intention to reduce plastic use after understanding its environmental impact through simulation. These responses indicate that the learning process generated not only cognitive understanding but also ecological awareness. The findings align with character development initiatives that emphasize environmental responsibility in science education [26].

The pedagogical dynamics derived from respondent data demonstrate that AR integration within the TPACK framework fosters a more dialogic, contextual, and reflective learning experience. Teachers acted as facilitators, orchestrating interactions among technology, content, and environmental values. Empirical evidence suggests that environmental science learning gains deeper meaning when concepts are visualized in immersive ways. This implementation reinforces the argument that TPACK develops through authentic practice and direct classroom interaction [2], [10].

Sustainable Integration Model of Augmented Reality within the TPACK Framework Based on Respondent Data

Further analysis of respondent data indicates that the implementation of Augmented Reality (AR) in environmental science learning did not end at the stage of visual exploration but evolved toward a more systematic integration pattern. Teachers G-IA and G-HT emphasized that their initial experience using AR encouraged reflective evaluation of instructional design and the effectiveness of the strategies employed. This reflective process demonstrates that TPACK competence develops through repeated practice and continuous evaluation. Such dynamics align with studies positioning TPACK as a dynamic and contextual professional competence [12], [1].

Teacher G-SM explained that during the initial meeting, AR use focused primarily on exploring application features, whereas subsequent sessions emphasized strengthening analysis of environmental concepts. This shift reflects a pedagogical adaptation informed by student responses. Students S-FK and S-RM reported that discussions became more focused when teachers posed analytical questions following digital exploration. This pattern illustrates a progression from the dominance of technological knowledge toward full TPACK integration, as emphasized in VR and AR training models for elementary science education [6], [5].

Interview data further revealed that teachers selected AR applications by considering scientific content accuracy and age appropriateness. G-IA noted that overly complex applications were avoided to prevent distraction from learning objectives. This practice reflects evaluative awareness consistent with research on the impact of training on teachers' ability to assess AR-based STEM applications [7]. Careful selection underscores that content knowledge remains the primary foundation in technology integration.

Students S-AR and S-NL demonstrated improved ability to explain concepts verbally after multiple AR-based sessions. They were able to connect simulations with real phenomena such as flooding caused by waste and river pollution. This improvement indicates a correlation between visual experience and the construction of conceptual meaning. The findings intersect with research on AR integration across disciplines, highlighting enhanced conceptual competence through the TPACK framework [4], [11].

Teacher G-HT stressed that sustainable implementation requires institutional policy support in providing devices and continued professional training. Without structural support, AR-based practices risk discontinuation after the initial innovation phase. This perspective aligns with policy analyses of technology integration in elementary curricula in the digital era [18], [19]. Sustainable integration, therefore, demands synergy between individual competence and institutional systems.

Observations also indicated that AR use created opportunities for cross-value and character integration. Teachers linked environmental content with moral responsibility toward nature and clean living habits. This approach reflects the potential development of Technological-Pedagogical-Science Knowledge integrating value dimensions [27]. Environmental science thus becomes a strategic domain for integrating science, technology, and ecological ethics.

Implementation Stage Teacher Practice Student Response Dominant TPACK Dimension Initial Orientation Introduction to AR applications Enthusiastic, exploratory TK Concept Reinforcement Simulation-based analytical discussion Began explaining cause-and-effect relationships TPK–PCK Value Reflection Connecting local issues and behavior Emergence of ecological awareness TPACK.

The table illustrates a gradual progression from technical mastery toward conceptual and reflective integration. This pattern indicates that AR functions as a catalyst in bridging digital representation and scientific meaning-making. The progressively evolving integration highlights the adaptive nature of TPACK in classroom practice. These findings enrich existing research on AR development in integrated science and digital science learning at the elementary level [28], [29].

Teachers also connected the learning experience with the potential application of a flipped classroom model in subsequent environmental topics. G-IA suggested that students could explore simulations at home prior to classroom discussions, allowing face-to-face sessions to focus on deeper analysis. This idea aligns with AR-assisted flipped classroom models, which have been shown to enhance the effectiveness of elementary science learning [9]. Such integration opens opportunities for developing more flexible instructional designs oriented toward independent exploration.

The sustainability dimension is further reflected in teachers' efforts to adopt experiential learning approaches that are engaging and meaningful. This practice resembles technology-integrated and deep learning models, emphasizing personal and contextual experiences [30], [24]. AR enables students to construct understanding through structured visual experiences and collaborative reflection. Science learning is thus no longer perceived merely as a collection of facts but as a process of interpreting natural phenomena.

The sustainable integration model of Augmented Reality within the TPACK framework, based on respondent data, demonstrates that instructional transformation occurs gradually and reflectively. Teachers and students interact within a learning environment that combines digital visualization, analytical discussion, and reflection on environmental values. This integration reveals coherence between educational technology theory and contextual classroom practice [20], [2]. Environmental science learning, therefore, becomes a strategic domain for expanding the meaning of TPACK as an adaptive, sustainability-oriented pedagogical framework.

4. CONCLUSION

This study demonstrates that integrating Augmented Reality (AR) within the TPACK framework represents a pedagogical transformation in elementary environmental science learning, in which technology serves as an epistemic tool to support conceptual understanding and ecological awareness. The findings indicate that effective AR implementation is characterized by the progressive alignment of technological, pedagogical, and content knowledge, resulting in more interactive, reflective, and contextually meaningful learning experiences.

The implications of this study highlight the need for strengthening teachers' professional competence, particularly in designing instructional strategies that integrate AR meaningfully within the TPACK framework. Teachers require not only technical training but also pedagogical guidance in structuring exploration, discussion, and reflection stages to maximize learning outcomes. In addition, instructional design should emphasize the alignment between digital media, environmental content, and students' cognitive readiness to ensure inclusive and effective learning.

From a policy perspective, sustainable implementation of AR-based learning requires institutional support, including adequate technological infrastructure, access to digital devices, and continuous professional development programs. Educational stakeholders and policymakers should prioritize integrating emerging technologies into curriculum planning and provide systemic support to ensure that innovation is not limited to short-term experimentation but becomes part of long-term educational practice.

This study is limited by its small sample size and context-specific setting, which may restrict the generalizability of the findings to broader educational contexts. The focus on two schools with particular technological readiness also suggests that different results may emerge in less-supported environments.

Future research is recommended to expand the scope of investigation by involving larger, more diverse samples and by exploring comparative studies across different regions and educational levels. Further studies may also examine the long-term impact of AR integration on students' environmental literacy and learning outcomes using mixed-method or longitudinal approaches.

This research advances educational technology by providing an empirically grounded model of AR integration within the TPACK framework. It offers practical insights for teachers and policymakers while reinforcing the role of immersive technology in fostering meaningful, reflective, and sustainability-oriented science learning for the broader educational community.

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