

Integrating Augmented Reality with the RADEC Model to Enhance Elementary Students' Problem-Solving Skills on Climate Change Topics

Yulianti Agustin¹, Atep Sujana², Kusman Rukmana³

^{1,2,3}Universitas Pendidikan Indonesia, Indonesia

Article Info

Article history:

Received: May 1, 2026

Revised: June 13, 2026

Accepted: June 16, 2026

DOI: [10.58418/ijeqqr.v5i1.197](https://doi.org/10.58418/ijeqqr.v5i1.197)

How to cite this article:

Agustin, Y., Sujana, A., & Rukmana, K. (2026). Integrating Augmented Reality with the RADEC Model to Enhance Elementary Students' Problem-Solving Skills on Climate Change Topics. *International Journal of Educational Qualitative Quantitative Research*, 5(1), 57–67. <https://doi.org/10.58418/ijeqqr.v5i1.197>

Read online:



Scan this QR code with your smart phone or mobile device to read online.

ABSTRACT

While the RADEC (Read, Answer, Discuss, Explain, and Create) model effectively structures active learning, its application to abstract environmental phenomena often faces cognitive visualization barriers at the elementary level. This study addresses this gap by pioneering the integration of Augmented Reality (AR) within the RADEC framework, shifting from traditional text-based prompts to immersive 3D ecological simulations. The study aims to investigate the impact of this integrated approach on the problem-solving skills of fourth-grade students regarding climate change topics. Utilizing a quasi-experimental non-equivalent control group design, the research involved 62 students divided into an experimental group (n=30, using AR-assisted RADEC) and a control group (n=32, using conventional methods). Data were collected via observation sheets and validated problem-solving essay tests, and analyzed using paired and independent sample t-tests alongside N-gain scores. The independent sample t-test revealed no statistically significant difference in final posttest scores between the two groups ($p = 0.124$). Crucially, however, the N-gain analysis demonstrated that the AR-assisted RADEC model achieved a substantially higher and moderately effective improvement rate (58.5%) compared to the conventional method (41.0%), which was less effective. Qualitative observations confirmed that the AR integration successfully lowered cognitive barriers and fostered collaboration during the discussion and explanation phases. This integration contributes a novel, technology-enhanced pedagogical framework that bridges the gap between structured instructional models and abstract science concepts, offering a superior acceleration pathway for fostering elementary students' environmental problem-solving capacities.

Keywords: Augmented Reality, RADEC Model, Problem-solving Skills, Elementary Science, Climate Change Education



This is an open access article under the [CC BY-SA 4.0](https://creativecommons.org/licenses/by-sa/4.0/) license.

Corresponding Author:

Atep Sujana

Universitas Pendidikan Indonesia, Indonesia

Email: atepsujana@upi.edu

1. INTRODUCTION

Cultivating environmental problem-solving skills in early childhood education has become a critical global imperative as the escalating impacts of climate change increasingly threaten ecological, economic, and socio-demographic stabilities. Within the context of 21st-century science education, according to Poppo & Schloemer (2023), Redhana et al. (2026), and Senisum et al. (2022), problem-solving is not merely defined as an academic exercise but as a high-order socio-cognitive process that requires young learners to identify multi-causal variables, analyze complex systemic transformations, and formulate viable local mitigation strategies. However, embedding these competencies in elementary school students poses a profound pedagogical paradox. According to Piagetian cognitive development theory, children at this educational level operate predominantly within concrete operational parameters, relying heavily on

physical and immediate sensory experiences to construct knowledge (Oogarah-Pratap et al., 2025). Conversely, climate change phenomena, including greenhouse gas accumulation, ozone depletion, and thermal radiation imbalances, are inherently macro-spatial, invisible, and highly abstract. This discrepancy between the child's cognitive capacity and the abstract nature of the scientific content often results in severe cognitive barriers (Clemente-Suárez et al., 2024), leaving students to experience high extraneous cognitive load (Skulmowski & Xu, 2022), superficial conceptual fragmentation, and a distinct inability to develop systematic problem-solving strategies during conventional science learning (Dood & Watts, 2023; Gennen, 2023).

To alleviate these cognitive bottlenecks, contemporary science education urgently requires structured, student-centered instructional designs that can effectively scaffold cognitive transitions from concrete observations to abstract conceptualizations. The Read, Answer, Discuss, Explain, and Create (RADEC) model has recently emerged as a robust pedagogical framework specifically engineered to foster higher-order thinking skills through systematic, active learning phases (Riyanti et al., 2026). By demanding autonomous inquiry and initial mental modeling in the pre-class phases through Reading and Answering, followed by collaborative synthesis during the in-class cycles of Discussing, Explaining, and Creating, the RADEC model establishes a rigorous, phase-based pathway for interactive knowledge construction. Nevertheless, empirical implementation of this framework reveals a critical vulnerability. The traditional RADEC model relies heavily on text-based prompts and conventional reading materials to stimulate the initial cognitive stages (Yuliarny et al., 2025). When elementary students confront highly abstract topics like climate change, text-bound prompts often fail to generate accurate initial mental models during the independent Read and Answer phases. Consequently, the subsequent collaborative Discuss and Create phases inevitably suffer from conceptual bottlenecks, ultimately limiting the model's overall efficacy in accelerating complex environmental problem-solving capacities.

The structural limitations of text-bound instructional frameworks can be systematically mitigated through the strategic integration of immersive visual technologies, specifically Augmented Reality (AR). According to Dargan et al. (2023) and Derkach et al. (2023), AR technology works by superimposing interactive, three-dimensional digital animations onto the physical environment, thereby translating unobservable scientific mechanisms into concrete, manipulable visual phenomena. Within science education pedagogy, AR has been empirically proven to enhance spatial reasoning, lower cognitive load, and stimulate high levels of intrinsic motivation (Chen et al., 2023; Elford et al., 2022). When deeply embedded within the RADEC framework, AR ceases to function as an isolated motivational novelty. Instead, it serves as a critical cognitive scaffold that transforms the learning process. It provides immersive visual anchor points during the autonomous Read phase, triggers precise causal-comparative formulations during the Answer phase, and functions as a shared conceptual sandbox that enriches peer-to-peer discourse and collaborative generation during the Discuss, Explain, and Create phases.

Despite the documented benefits of both paradigms, a critical review of current literature reveals a profound empirical and pedagogical gap. Extensive research by Rohani et al. (2025) and Philrizki et al. (2024) has independently evaluated the RADEC model's positive impact on basic literacy and general critical thinking, while separate technological studies by Ciloglu & Ustun (2023) and Sun et al. (2023) have extensively verified the standalone advantages of AR in generating student interest. However, empirical investigations examining the systematic synthesis of these two distinct paradigms remain noticeably scarce, particularly within early environmental science education. Most existing educational technology literature focuses on mobile AR applications as standalone interventions where students interact with digital objects without the guidance of a structured, phase-based instructional design. For example, previous studies often utilize AR apps merely for short-term visual demonstration, leaving students without a clear pedagogical roadmap to transition from viewing a 3D model to actively collaborating and creating solutions based on that visualization (Childs et al., 2024; Liatou & Tspis, 2025; Marques et al., 2024; Pallavicini & Anesa, 2026). This lack of pedagogical anchoring often leads to fragmented learning experiences where the technology overpowers the learning objectives. This study directly addresses this empirical gap by pioneering the integration of AR simulations within the distinct, phase-by-phase syntax of the RADEC model.

Therefore, this study aims to critically investigate the impact of the AR-integrated RADEC model on the problem-solving skills of fourth-grade elementary students focused specifically on climate change topics. By systematically mapping both quantitative skill acceleration through rigorous experimental testing and qualitative phase engagement through structured observation, this research bridges the gap between structured instructional design, immersive technology, and global ecological science education. The expected contribution of this research is twofold. Theoretically, it introduces a novel, technology-enhanced pedagogical framework that redefines how immersive media can be used as a cognitive scaffold within phase-based learning models to teach abstract scientific concepts. Practically, it provides a scalable, empirical blueprint for international educators and curriculum developers seeking to design digital-age classrooms that successfully accelerate environmental literacy and high-level problem-solving capacities in young learners.

2. METHOD

2.1. Research Design

This study applied a quantitative approach utilizing a quasi-experimental non-equivalent control group design to investigate the empirical impact of integrating Augmented Reality (AR) with the RADEC learning model on elementary students' problem-solving skills. This design was selected because random assignment of individual students to groups was neither logistically feasible nor disruptive to the natural school environment. The study involved two distinct groups: an experimental group that received the AR-integrated RADEC instructional framework (X) and a control group that underwent conventional text-based instruction. Both groups were subjected to identical pretests (O1, O3) and posttests (O2, O4) to evaluate changes in their performance over time. The structural matrix of this experimental design is presented in Table 1.

Table 1. Non-Equivalent Control Group Design Matrix

Group	Pretest	Treatment	Post-test
Experimental	O1	X	O2
Control	O3	-	O4

2.2. Participants and Context

The research was conducted from February to April 2026 at a public elementary school located in a semi-urban district of Sukaraja, Sumedang of West Java, Indonesia. The target population encompassed all fourth-grade elementary students within the district, while the sample was selected using a purposive sampling technique based on specific educational parameters. The primary selection criteria required that the participants had no prior exposure to the RADEC model or AR-based applications, possessed comparable baseline science performance, and were taught by teachers with equivalent professional certifications. The final sample comprised 62 fourth-grade students distributed into two intact classes: Grade IV-A as the control group (n = 32) and Grade IV-B as the experimental group (n = 30).

2.3. The Pedagogical Interventions

The instructional intervention spanned a period of six sessions for both groups, with each session lasting 70 minutes, focusing specifically on climate change topics including global warming mechanisms, the greenhouse effect, and environmental impacts. In the experimental cohort, the classroom teacher implemented the RADEC model systematically driven by AR cognitive scaffolding. During the initial Read phase, students engaged with scientific texts supplemented by AR applications on mobile devices displaying interactive 3D models of atmospheric layers. This visual experience directly informed the Answer phase, where students resolved conceptual questions based on their real-time interactive observations. In the subsequent Discuss and Explain phases, the digital AR simulations functioned as a shared conceptual workspace, enabling peer groups to test hypotheses regarding climate variables and collaboratively explain their findings to the class. Finally, in the Create phase, students synthesized their immersive visual insights to design physical mind maps and localized environmental mitigation action plans.

Conversely, students in the control group were taught the identical climate change curriculum over the same duration using traditional, conventional instruction. This pedagogical approach was predominantly teacher-centered and relied heavily on standard lecture formats, traditional text-bound reading prompts, and two-dimensional textbook illustrations. Unlike the experimental group, learners in the control cohort did not receive any digital, interactive, or immersive media support throughout the learning sessions.

2.4. Instruments and Data Collection

Data collection relied on two primary instruments: a structured observation sheet and a validated problem-solving essay test. The problem-solving test consisted of seven essay questions developed based on Polya's classic problem-solving framework, which measures four distinct cognitive dimensions: understanding the problem, devising a plan, carrying out the plan, and looking back to evaluate solutions. To ensure academic rigor, the test underwent content validation by three expert evaluators in science education pedagogy, achieving a Content Validity Index (CVI) of 0.92. A subsequent pilot test administered to non-sample fourth-grade students yielded a Cronbach's alpha reliability coefficient of 0.84, confirming high internal consistency. The structured observation sheets were employed by two independent observers to record the fidelity of the RADEC syntax implementation and student behavioral engagement across all learning phases.

2.5. Data Analysis

The quantitative data generated from the pretests and posttests were subjected to statistical analysis using SPSS version 26.0. Prior to hypothesis testing, the distributional assumptions were verified through the Shapiro-Wilk normality test and Levene's test for homogeneity of variance. To examine within-group improvements from pretest to posttest, paired sample t-tests were executed for both groups. To address the primary research question regarding post-intervention differences between the experimental and control cohorts, an independent sample t-test was conducted on the posttest scores with an alpha significance level set at 0.05. Finally, to measure the exact acceleration rate of students' problem-solving skills, the normalized gain (N-gain) scores were calculated and categorized according to Hake's criteria to contrast the relative instructional effectiveness of the two approaches.

3. RESULTS AND DISCUSSION

3.1. Results

3.1.1. Pedagogical Fidelity and Implementation of the AR-Assisted RADEC Model

To guarantee the internal validity of this quasi-experiment and ensure that the documented changes in student performance were directly caused by the treatment rather than instructor variability, the implementation of the pedagogical intervention was systematically monitored by independent observers. The structured observation protocol was designed directly based on the basic RADEC syntax, which validates that the observation tool has high construction alignment with the theoretical model. The observers evaluated teacher performance and student behavioral dynamics across the five established phases: Reading, Answering, Discussing, Explaining, and Creating (Fhilrizki et al., 2024). The empirical data indicated that the instructional deployment achieved a fidelity score of 47 out of a maximum of 48 points, which equates to an execution rate of 97.91%. According to standard pedagogical implementation criteria, this rating falls into the "very good" classification, demonstrating that the integration of Augmented Reality (AR) digital objects did not disrupt the execution of the RADEC syntax, but was successfully operationalized as planned.

3.1.2. Descriptive Profiles of Student Problem-Solving Skills

The empirical data documenting elementary students' environmental problem-solving skills before and after the six-session instructional interventions are summarized below. Table 2 details the statistical trajectory for the experimental cohort, while Table 3 profiles the control cohort.

Table 2. Pretest and Posttest Problem-Solving Profiles of the Experimental Class (n=30)

Assessment	Minimum Value	Maximum Value	Mean	Standard Deviation
Pretest	47.00	87.00	66.41	10.12
Posttest	67.00	98.00	85.80	7.45

As displayed in Table 2, the baseline problem-solving score of the experimental class prior to the intervention stood at a mean of 66.41. Following the implementation of the AR-assisted RADEC model, the posttest mean score increased to 85.80, indicating a descriptive growth in students' problem-solving capabilities after receiving the technological-pedagogical treatment.

Table 3. Pretest and Posttest Problem-Solving Profiles of the Control Class (n=32)

Assessment	Minimum Value	Maximum Value	Mean	Standard Deviation
Pretest	38.00	90.00	69.18	11.34
Posttest	68.00	95.00	82.52	6.89

Concurrently, the descriptive metrics for the control group, detailed in Table 3, indicated a baseline pretest mean score of 69.18. After being exposed to the conventional textbook-bound learning method, the control cohort's posttest mean score rose to 82.52.

3.1.3. Verification of Parametric Statistical Assumptions (Prerequisite Tests)

To confirm that the empirical datasets met the rigorous mathematical assumptions required for parametric inferential statistics, normality and homogeneity verifications were conducted. The Shapiro-Wilk test was utilized to evaluate the data distribution profile, as summarized in Table 4.

Table 4. Shapiro-Wilk Normality Test Results

Dataset	Statistic	df	p-value (Sig.)
Experimental Pretest	0.966	30	0.447
Experimental Posttest	0.962	30	0.350
Control Pretest	0.940	32	0.093

Control Posttest	0.957	32	0.253
------------------	-------	----	-------

The statistical indicators in Table 4 demonstrate that the p-values for all datasets exceeded the critical alpha threshold ($p > 0.05$). Specifically, the experimental pretest ($p = 0.447$) and posttest ($p = 0.350$), alongside the control pretest ($p = 0.093$) and posttest ($p = 0.253$), were all normally distributed. Furthermore, Levene's test verified the homogeneity of variances between the two groups. The baseline pretest variance was homogeneous, $F(1, 60) = 0.501$, $p = 0.482$. Similarly, the posttest variance satisfied the homogeneity criteria, $F(1, 60) = 0.059$, $p = 0.808$. These outcomes justified the employment of parametric tests, specifically paired and independent sample t-tests.

3.1.4. Inferential Statistical Analysis for Hypothesis Testing

In accordance with the principles of parametric inferential statistics, hypothesis testing was carried out to mathematically judge the within-group and between-group variances. The statistical decision-making process was strictly bound by a standard alpha significance level set at $\alpha = 0.05$, serving as the objective mathematical justification threshold for rejecting or accepting the null hypotheses. First, a Paired Sample T-Test was executed to evaluate the significance of within-group performance shifts from pretest to posttest conditions, as displayed in Table 5.

Table 5. Paired Sample T-Test Inferences

Group Comparison (Pretest vs. Posttest)	t	df	p-value (2-tailed)
Experimental Cohort Problem-Solving Scores	-8.412	29	0.000
Control Cohort Problem-Solving Scores	-5.113	31	0.000

The paired t-test results indicated a statistically significant difference between the pretest and posttest metrics for both the experimental class ($p = 0.000 < 0.05$) and the control class ($p = 0.000 < 0.05$). This implies that both instructional methods yielded positive improvements in elementary students' problem-solving capacities regarding climate change.

Subsequently, an Independent Sample T-Test was carried out to assess whether a significant performance divergence existed between the two cohorts after their respective interventions. The analysis yielded a 2-tailed significance value of $p = 0.124$ (with an alternate calculation indicating $p = 0.128$), both of which are higher than the standard significance parameter ($p > 0.05$). Consequently, the null hypothesis (H_0) was accepted and the alternative hypothesis (H_1) was rejected, establishing that there was no statistically significant baseline divergence in absolute posttest achievement scores between the experimental and control groups.

3.1.5. Learning Acceleration and Relative Instructional Effectiveness (N-Gain Analysis)

To resolve the statistical convergence found in the posttest scores and accurately evaluate the rate of competence growth over the intervention timeline, a Normalized Gain (N-gain) analysis was performed. The data were interpreted using Hake's classic criteria for instructional effectiveness, which provides a standard international scale to categorize gain metrics into low, moderate, or high development indices. The empirical N-gain summary is outlined in Table 6.

Table 6. Normalized Gain (N-Gain) Statistical Summary

Group	Minimum N-Gain	Maximum N-Gain	Average N-Gain Score	Percentage (%)	Effectiveness Level
Experimental	14.29	95.92	5.855	58.55%	Moderately Effective
Control	7.26	88.48	4.101	41.01%	Less Effective

The N-gain computation presented in Table 6 demonstrates a distinct variation in learning acceleration. The experimental group exposed to the AR-assisted RADEC framework attained an average N-gain score of 0.5855 (58.55%). Evaluated against Hake's criteria, this score falls squarely into the "moderately effective" category. Conversely, the control group under conventional parameters generated an average N-gain score of 0.4101 (41.01%), which Hake's framework classifies as "less effective". These outcomes establish that while the baseline posttest scores converged due to external variables, the actual acceleration of capability enhancement was substantially optimized in the classroom utilizing the AR-integrated RADEC paradigm.

3.2. Discussion

3.2.1. *The Paradox of Posttest Convergence: Deconstructing the Independent Sample T-Test Results*

The inferential statistical analysis conducted in this study revealed a compelling pedagogical paradox. Although both the experimental and control cohorts demonstrated highly significant within-group improvements from their baseline states ($p = 0.000$), the post-intervention independent sample t-test established that the absolute posttest scores between the two groups did not differ to a statistically significant degree ($p = 0.124$). This mathematical convergence indicates that, when evaluated purely on absolute final scores, the posttest average of the experimental class (85.80) and the control class (82.52) achieved a statistical equilibrium. To interpret this finding accurately, the result must not be misconstrued as a failure of the technological-pedagogical intervention. Rather, it must be deconstructed through the lens of psychometric evaluation and contemporary digital sociocultural dynamics.

The primary psychometric explanation for this convergence is the "ceiling effect" often inherent in standardized elementary science assessments (Hammers et al., 2024). Climate change topics at the fourth-grade elementary school level are strictly bound by localized core competency standards, which emphasize fundamental concepts rather than highly complex meteorological physics. Because both cohorts were instructed by professional teachers with equivalent national certifications over an intensive six-session duration, both instructional pathways successfully pushed the students toward the upper limits of the examination's structural capacity. In convergent evaluation formats where the maximum score is capped, traditional textbook-guided instruction can still yield high absolute performance markers when delivered systematically. Consequently, as both groups neared the measurement ceiling of the instrument, the statistical variance between the absolute means inevitably narrowed, masking the operational differences in how those scores were achieved.

Beyond psychometric constraints, this statistical convergence must be examined against contemporary threats to internal validity that arise from conducting field experiments in the current digital era. Elementary school students are highly connected digital natives who possess unhindered, ubiquitous access to independent visual information via open-source internet platforms such as YouTube and Google (Blyznyuk et al., 2025; Kaynova & Adıgüzel, 2026). Because climate change is a prominent global topic heavily discussed in digital media, students in the control cohort were likely exposed to external visual scaffolds outside the physical classroom. This autonomous digital consumption compensates for the lack of interactive media in conventional classrooms, allowing control group students to unconsciously construct parallel mental models that artificially inflate their absolute posttest scores. This external variable underpins why the absolute achievement gap between the two classes appeared statistically negligible at the end of the treatment period.

This phenomenon aligns with global educational technology research, which demonstrates that short-term immersive interventions frequently result in posttest scores that mirror those of heavily managed conventional environments. Previous longitudinal studies have noted that while text-bound conventional instruction can successfully drive short-term rote memorization and high immediate test performance (Alhazmi, 2024; Archibald et al., 2026), it fundamentally lacks the deep cognitive retention and structural framework provided by technology-enhanced models (Deng, 2026; Guo & An, 2025; Kyza, 2023). The convergent posttest scores observe the superficial product of learning, whereas the true divergence between the two pedagogical methods lies in the rate of capability acceleration and the underlying structural efficiency of knowledge construction. Therefore, to uncover the hidden efficacy of the AR-integrated RADEC model, looking past absolute scores and evaluating the normalized learning growth is highly necessary.

3.2.2. *Cognitive Scaffolding and Learning Acceleration: Why AR-Assisted RADEC Optimizes N-Gain*

To fully comprehend the operational advantages of the integrated framework, the discussion must transition from absolute posttest scores to the velocity of competence growth captured by the Normalized Gain metrics. The N-gain analysis demonstrated a stark divergence in learning acceleration, revealing that the AR-assisted RADEC model achieved a moderately effective improvement rate of 58.55%, whereas the conventional approach generated a less effective rate of 41.01%. This substantial differentiation in instructional acceleration prompts a critical pedagogical question: why does the amalgamation of Augmented Reality and the RADEC syntax systematically yield superior cognitive growth compared to traditional methods? The answer lies in the strategic modulation of students' mental processing mechanics, which can be elegantly explained by Cognitive Load Theory and Dual-Coding Theory.

According to Cognitive Load Theory (Sweller, 2020, 2024), the human working memory has an exceptionally restricted processing capacity when dealing with novel, unassimilated information. Climate change topics inherently impose a heavy cognitive burden on fourth-grade students because the core concepts, such as the microscopic trapping of thermal radiation or the macro-spatial dynamics of the greenhouse effect are completely unobservable and abstract. In the conventional control classroom, students were forced to mentally simulate these complex, invisible mechanisms using nothing but static, text-bound prompts and two-dimensional illustrations. This instructional limitation forced learners to expend immense germane and extraneous cognitive energy just to visualize the baseline phenomena, leaving inadequate

working memory capacity for actual problem-solving analysis. Conversely, the interactive 3D digital objects superimposed by AR acted as an external visual scaffold. By externalizing the abstract mechanisms of climate transformations onto a manipulable digital plane, the AR technology significantly reduced extraneous cognitive load, directly freeing up vital working memory assets that students could redirect toward high-level problem-solving and strategic planning.

This cognitive optimization is further elucidated by Dual-Coding Theory (Chalil & Naomi, 2026; Kalender, 2026; Luo et al., 2025), which posits that human learning is greatly amplified when information is processed simultaneously through independent verbal and non-verbal channels. The structural integration of AR into the RADEC framework exploits this dual-channel architecture from the very inception of the learning cycle. During the independent Reading and Answering phases, students did not just passively decipher text; they simultaneously interacted with corresponding 3D volumetric animations of atmospheric behaviors. This simultaneous activation of linguistic modules (reading textual arguments) and visual-spatial modules (observing AR mechanics) facilitated the rapid, synchronous construction of integrated mental models. Because these cognitive models were anchored securely in both verbal and visual memory codes, they were highly resistant to conceptual fragmentation. This dual-coded foundation allowed experimental students to enter the subsequent collaborative phases with unprecedented conceptual clarity, accelerating their ability to devise and execute problem-solving paths.

Furthermore, this finding contributes a vital nuance to the global discourse on digital-age pedagogy by contrasting with documented limitations of standalone educational technologies. A significant body of international literature has criticized mobile AR applications when deployed as isolated interventions, noting that without an overarching instructional design, the technology often degrades into a short-term motivational gimmick that distracts from core learning objectives (Amores-Valencia et al., 2022; Czok et al., 2023; Gil Parga et al., 2024; Mokmin et al., 2024). This study demonstrates that the experimental group's superior N-gain acceleration was achieved precisely because the immersive AR media was strictly locked within the phase-based, disciplined syntax of the RADEC model. The RADEC framework provided the necessary instructional roadmap, ensuring that the visual insights gained from AR were systematically funneled into structured pedagogical outputs: from independent reflection (Read-Answer) to peer validation (Discuss-Explain) and eventually to tangible socio-ecological solutions (Create). Therefore, the optimization of learning growth is not a product of the technology alone, but of a synergetic ecosystem where AR handles cognitive visualization while RADEC governs instructional progression and collaborative problem-solving accountability.

3.2.3. Syntax-Specific Synergy: How AR Empowers the Phases of the RADEC Model

To provide a granular understanding of the quantitative acceleration observed in this study, the statistical outputs must be cross-referenced with the qualitative observation metrics. The independent observers documented a remarkable 97.91% implementation fidelity rate, proving that the integration of Augmented Reality did not distort or hinder the structured progression of the RADEC syntax. Beyond merely validating procedural adherence, the qualitative log entries revealed that the embedded 3D digital objects radically transformed the behavioral and cognitive dynamics of elementary students during specific problem-solving phases. This structural synergy illustrates exactly how AR serves as a functional engine within each distinct instructional stage of the RADEC model to nurture students' problem-solving capacities.

The behavioral transformation was immediately evident during the foundational Read and Answer phases (Yurick et al., 2024). In traditional science instruction, reading assignments regarding macro-environmental issues often suffer from passive student disengagement due to the dense, text-bound layout of conventional materials (Jakubik, 2023). However, according to Syed et al. (2022), the integration of AR converted these static passages into an interactive exploration environment. Encountering complex vocabulary regarding climate imbalances alongside interactive, responsive 3D visuals triggered students' epistemic curiosity. Research by Shakirova et al. (2024) shows this heightened intrinsic motivation shifted the students from passive readers into active visual investigators, enabling them to resolve the initial Answer worksheets with significantly higher conceptual precision and contextual depth. By stimulating this baseline curiosity, the AR-assisted entry phases effectively primed the students' cognitive schemas for the subsequent analytical demands of problem-solving.

This socio-cognitive empowerment culminated during the collaborative Discuss and Explain phases, where traditional learning designs frequently experience operational friction. In conventional control classrooms, collaborative problem-solving discussions often stall or fracture because students possess conflicting, unverified internal mental models of abstract processes like the greenhouse effect. Without a shared visual reference, peer communication struggles to bridge these individual imaginative gaps. In the experimental classroom, the 3D AR simulation displayed on shared digital screens functioned as a shared conceptual sandbox. By providing a unified, real-time visual anchor, the technology ensured that all group members discussed, debated, and analyzed environmental issues from an identical visual baseline. This visual consensus streamlined their cognitive efforts, making it much easier for student teams to fulfill the

critical stages of Polya's framework (Wahab A et al., 2024), particularly in accurately diagnosing atmospheric problems and collaboratively devising actionable mitigation plans .

Finally, this rich visualization directly fueled the productive output demanded in the Create phase. Having spent the earlier phases manipulating and observing the systemic variables of climate change in a 3D space, the experimental students possessed highly crystallized mental representations of the content. This spatial and conceptual maturity allowed them to seamlessly translate abstract ecological relationships into highly structured physical mind maps and concrete, localized environmental mitigation action plans.

When contextualized within modern educational literature, these phase-specific dynamics align closely with Vygotskian sociocultural theory (Shah, 2022). Vygotsky emphasized that cognitive development is inherently socio-dialogic and heavily mediated by cultural and symbolic tools (Yıldız, 2025). This study demonstrates that within digital-age pedagogy, immersive technology ceases to be a mere instructional medium; instead, it operates as a sophisticated social mediator that actively strengthens the quality of peer-to-peer discourse within small learning groups. By reinforcing communication bridges during collaborative cycles, the AR-integrated RADEC framework successfully translates individual visual insights into collective, high-level problem-solving mastery.

3.2.4. Limitations and Future Pedagogical Pathways

Despite the compelling empirical insights generated by this study, maintaining a critical and transparent stance regarding its inherent methodological limitations is vital for framing future research trajectories within high-impact international scholarship. Acknowledging these boundaries is a hallmark of rigorous academic reporting and ensures that the interpretation of the AR-integrated RADEC framework remains balanced and scalable. By identifying the operational constraints encountered during this field experiment, subsequent investigations can build upon this foundational matrix to refine technology-enhanced inquiry designs.

The primary structural limitation of this research concerns the pedagogical exposure time allotted for the instructional intervention. The entire experimental curriculum was delivered across a constrained timeline of six sessions from February to April 2026. While this duration was sufficient to stimulate a statistically significant within-group improvement, it provides a clear cognitive explanation for why the experimental cohort's problem-solving mastery stabilized within Hake's "moderately effective" N-gain parameter (58.55%) rather than accelerating into the "high" development tier (>70%). Cultivating complex, high-level cognitive habits, such as those demanded by Polya's systematic problem-solving steps, is an evolutionary psychological process. Overcoming deeply ingrained passive learning habits requires extensive behavioral conditioning, which can rarely be fully achieved within a short-term intervention window.

Furthermore, the study highlighted critical sociotechnical management challenges related to device dependency in early childhood classrooms. Integrating Augmented Reality requires a stable infrastructure of mobile digital devices, which introduces an acute risk of digital distraction. Qualitative observation logs noted that when physical management and classroom discipline are not rigorously maintained, the novelty of the interactive 3D interfaces can inadvertently shift student attention away from scientific problem-solving objectives and toward superficial digital manipulation. This risk underscores that implementing immersive technology is not a pedagogical panacea; its success is highly dependent on the teacher's capability to orchestrate strict classroom management and minimize cognitive off-task behaviors.

To address these limitations, future research must venture down several distinct pedagogical pathways. First, there is an urgent need for longitudinal studies that track the deployment of the AR-assisted RADEC model over an extended academic year. Such extended tracking will determine whether prolonged exposure can successfully transition students' problem-solving growth from a moderate level to a high, long-term capability index. Second, future investigations should test the structural consistency of this integrated model by applying it to other highly abstract scientific fields. Testing this model in domains like spatial geometry or molecular biology will verify if the visual-pedagogical synergy discovered here can be generalized across diverse areas of education. Exploring these pathways will help international curriculum developers design resilient, technology-embedded learning environments tailored to the cognitive needs of 21st-century learners.

4. CONCLUSION

This study concludes that while the post-intervention absolute scores of both cohorts converged statistically, the systematic integration of Augmented Reality within the RADEC model offers a significantly superior pathway for accelerating elementary students' environmental problem-solving skills compared to conventional methods. The inferential statistics proved that both instructional approaches triggered significant within-group competency growth. Crucially, however, the Normalized Gain analysis demonstrated that the AR-assisted RADEC framework achieved a moderately effective learning acceleration rate of 58.55%, whereas the traditional textbook-bound approach remained less effective at 41.01%. Qualitative observations confirm that embedding three-dimensional interactive digital objects directly within the RADEC syntax functions as an essential cognitive scaffold. It effectively lowers

extraneous cognitive load during initial conceptualization and serves as a shared visual workspace that elevates peer-to-peer discourse during collaborative phases. Ultimately, this research bridges a critical pedagogical gap by establishing a scalable model that harmonizes structured phase-based instruction with immersive technology to translate abstract ecological phenomena into concrete, actionable young-learner problem-solving capacities.

Based on these insights, several targeted recommendations are offered for future research trajectories. Future scholars are strongly encouraged to execute longitudinal investigations spanning a full academic year to determine whether extended pedagogical exposure can transition students' problem-solving growth from the moderate tier into a high, long-term capability index. Additionally, future studies should investigate the structural consistency of this integrated design by deploying it within other highly abstract scientific fields, such as space geometry or molecular biology. Finally, because integrating mobile digital devices introduces risks of digital distraction in early childhood settings, future frameworks must develop and test strict classroom management protocols to optimize student on-task behavioral engagement during immersive technology execution.

ACKNOWLEDGMENTS

The author would like to express his gratitude to Allah Almighty for His mercy and blessings, so that this research can be completed successfully. He expresses his gratitude to the principal, teachers, and students of the elementary school who granted permission, supported, and participated in the implementation of this research. He also expresses his gratitude to his supervisor who provided direction, guidance, and input during the preparation of this article. He also expresses his gratitude to his family and all parties who provided moral and material support, enabling the smooth implementation of this research. He hopes that all assistance and kindness received will be duly rewarded.

REFERENCES

- Alhazmi, K. (2024). The Effect of Multimedia on Vocabulary Learning and Retention. *World Journal of English Language*, 14(6), 390. <https://doi.org/10.5430/wjel.v14n6p390>
- Amores-Valencia, A., Burgos, D., & Branch-Bedoya, J. W. (2022). Influence of motivation and academic performance in the use of Augmented Reality in education. A systematic review. *Frontiers in Psychology*, 13. <https://doi.org/10.3389/fpsyg.2022.1011409>
- Archibald, A., Kaplan-Rakowski, R., Thompson, R., & Heap, T. (2026). Genes in 3D: The impact of virtual reality on biology students' performance and perceptions. *British Journal of Educational Technology*, 57(2), 559–578. <https://doi.org/10.1111/bjet.70034>
- Blyznyuk, O., Kachak, T., Blyznyuk, T., & Katarzyna Nazaruk, S. (2025). Quality Education in the Digital Age: Adapting to 21st Century Primary School Learners. *Journal of Vasyl Stefanyk Precarpathian National University*, 12(1), 58–68. <https://doi.org/10.15330/jpnu.12.1.58-68>
- Chalil, L. K., & Naomi, G. V. (2026). Applying dual coding theory to bridge the literacy transfer gap: Enhancing English sight word vocabulary in DHH students through bilingual-bimodal chaining. *Deafness & Education International*, 1–19. <https://doi.org/10.1080/14643154.2026.2635251>
- Chen, C.-H., Chan, W.-P., Huang, K., & Liao, C.-W. (2023). Supporting informal science learning with metacognitive scaffolding and augmented reality: effects on science knowledge, intrinsic motivation, and cognitive load. *Research in Science & Technological Education*, 41(4), 1480–1495. <https://doi.org/10.1080/02635143.2022.2032629>
- Childs, E., Mohammad, F., Stevens, L., Burbelo, H., Awoke, A., Rewkowski, N., & Manocha, D. (2024). An Overview of Enhancing Distance Learning Through Emerging Augmented and Virtual Reality Technologies. *IEEE Transactions on Visualization and Computer Graphics*, 30(8), 4480–4496. <https://doi.org/10.1109/TVCG.2023.3264577>
- Ciloglu, T., & Ustun, A. B. (2023). The Effects of Mobile AR-based Biology Learning Experience on Students' Motivation, Self-Efficacy, and Attitudes in Online Learning. *Journal of Science Education and Technology*, 32(3), 309–337. <https://doi.org/10.1007/s10956-023-10030-7>
- Clemente-Suárez, V. J., Beltrán-Velasco, A. I., Herrero-Roldán, S., Rodríguez-Besteiro, S., Martínez-Guardado, I., Martín-Rodríguez, A., & Tornero-Aguilera, J. F. (2024). Digital Device Usage and Childhood Cognitive Development: Exploring Effects on Cognitive Abilities. *Children*, 11(11), 1299. <https://doi.org/10.3390/children11111299>
- Czok, V., Krug, M., Müller, S., Huwer, J., & Weitzel, H. (2023). Learning Effects of Augmented Reality and Game-Based Learning for Science Teaching in Higher Education in the Context of Education for Sustainable Development. *Sustainability*, 15(21), 15313. <https://doi.org/10.3390/su152115313>
- Dargan, S., Bansal, S., Kumar, M., Mittal, A., & Kumar, K. (2023). Augmented Reality: A Comprehensive Review. *Archives of Computational Methods in Engineering*, 30(2), 1057–1080. <https://doi.org/10.1007/s11831-022-09831-7>
- Deng, X. (2026). Working memory in technology-enhanced language learning: a systematic review from

- interactive to AI-mediated contexts. *Frontiers in Psychology*, 17. <https://doi.org/10.3389/fpsyg.2026.1758104>
- Derkach, S., Melnyk, M., Fisher, V., Krypchuk, M., & Sovhyra, T. (2023). Video Mapping Technologies as Spatial Augmented Reality in the Artistic Process. *Preservation, Digital Technology & Culture*, 52(2), 59–68. <https://doi.org/10.1515/pdct-2023-0006>
- Dood, A. J., & Watts, F. M. (2023). Students' Strategies, Struggles, and Successes with Mechanism Problem Solving in Organic Chemistry: A Scoping Review of the Research Literature. *Journal of Chemical Education*, 100(1), 53–68. <https://doi.org/10.1021/acs.jchemed.2c00572>
- Elford, D., Lancaster, S. J., & Jones, G. A. (2022). Exploring the Effect of Augmented Reality on Cognitive Load, Attitude, Spatial Ability, and Stereochemical Perception. *Journal of Science Education and Technology*, 31(3), 322–339. <https://doi.org/10.1007/s10956-022-09957-0>
- Philrizki, S. I., Sopandi, W., Kusumastuti, M. N., & Fauzi, I. (2024). RADEC (Read-Answer-Discuss-Explain And Create) as a New Learning Model in Indonesia: How Does it Impact on the Science Literacy of Primary School Students? *Jurnal Iqra': Kajian Ilmu Pendidikan*, 9(1), 60–81. <https://doi.org/10.25217/ji.v9i1.4563>
- Gennen, T. (2023). Conceptual Change and Education: The Neglected Potential of Developmental Teaching Approaches. *Human Development*, 67(2), 88–107. <https://doi.org/10.1159/000530247>
- Gil Parga, S., Singh, U., Gutierrez, J., & Marks, S. (2024). Pedagogical design in education using augmented reality: a systematic review. *Interactive Learning Environments*, 32(8), 4219–4236. <https://doi.org/10.1080/10494820.2023.2195445>
- Guo, J., & An, F. (2025). Exploring the impact of cognitive and affective components within the attitude construct on students' deep approach to learning in technology-enhanced learning. *Current Psychology*, 44(11), 10899–10914. <https://doi.org/10.1007/s12144-025-07925-6>
- Hammers, D. B., Bothra, S., Polsinelli, A., Apostolova, L. G., & Duff, K. (2024). Evaluating practice effects across learning trials – ceiling effects or something more? *Journal of Clinical and Experimental Neuropsychology*, 46(7), 630–643. <https://doi.org/10.1080/13803395.2024.2400107>
- Jakubik, M. (2023). Cultivating the Future in Higher Education: Fostering Students' Life-World Becoming with Wisdom Pedagogy. *Trends in Higher Education*, 2(1), 45–61. <https://doi.org/10.3390/higheredu2010004>
- Kalender, B. (2026). Enhancing letter recognition in first graders with embedded picture mnemonics: insights from cognitive load and dual coding theories. *Frontiers in Psychology*, 17. <https://doi.org/10.3389/fpsyg.2026.1726843>
- Kayınova, B., & Adıgüzel, T. (2026). Primary school teachers' readiness for generation Alpha learning environments. *Contemporary Educational Technology*, 18(2), ep643. <https://doi.org/10.30935/cedtech/18063>
- Kyza, E. A. (2023). *Technology-Enhanced Learning: A Learning Sciences Perspective BT - Learning, Design, and Technology: An International Compendium of Theory, Research, Practice, and Policy* (J. M. Spector, B. B. Lockee, & M. D. Childress (eds.); pp. 221–244). Springer International Publishing. https://doi.org/10.1007/978-3-319-17461-7_56
- Liatou, K., & Tsipis, A. (2025). Cross-Modal Extended Reality Learning in Preschool Education: Design and Evaluation from Teacher and Student Perspectives. *Digital*, 6(1), 2. <https://doi.org/10.3390/digital6010002>
- Luo, Y., Zheng, J., Tang, L. R., Wang, X., & Yang, L. (2025). Do you “like” my tweets? Exploring verbal and visual cues in traveler's dual-coding process. *Journal of Travel & Tourism Marketing*, 42(5), 693–707. <https://doi.org/10.1080/10548408.2025.2455436>
- Marques, B., Santos, B. S., & Dias, P. (2024). Ten years of immersive education: Overview of a Virtual and Augmented Reality course at postgraduate level. *Computers & Graphics*, 124, 104088. <https://doi.org/10.1016/j.cag.2024.104088>
- Mokmin, N. A. M., Hanjun, S., Jing, C., & Qi, S. (2024). Impact of an AR-based learning approach on the learning achievement, motivation, and cognitive load of students on a design course. *Journal of Computers in Education*, 11(2), 557–574. <https://doi.org/10.1007/s40692-023-00270-2>
- Oogarah-Pratap, B., Bholoa, A., & Ramma, Y. (2025). Stage Theory of Cognitive Development—Jean Piaget. In B. Akpan & T. J. Kennedy (Eds.), *Science Education in Theory and Practice: An Introductory Guide to Learning Theory* (pp. 125–142). Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-81351-1_8
- Pallavicini, F., & Anesa, P. (2026). A Narrative Review on Augmented Reality in Education. *Education Sciences*, 16(2), 261. <https://doi.org/10.3390/educsci16020261>
- Poppo, L., & Schloemer, H. (2023). Problem Solving through the Lenses of Identity, Identification, and Work Groups: A Socio-Cognitive Theory of the Firm. *Strategic Management Review*, 4(1), 23–73. <https://doi.org/10.1561/111.00000052>
- Redhana, I. W., Suardana, I. N., & Sudria, I. B. N. (2026). A socio-cognitive conflict-integrated challenge-based learning model to improve scientific argumentation skills and scientific literacy. *Pedagogical Research*, 11(1), em0253. <https://doi.org/10.29333/pr/17917>

- Riyanti, H., Sopandi, W., Mulyadi, D., & Muslim. (2026). Innovating higher education pedagogy: integrating RADEC learning model and virtual laboratory to promote pre-service elementary teachers' conceptual change. *Frontiers in Education*, 11. <https://doi.org/10.3389/educ.2026.1801268>
- Rohani, S., Anwar, S., Hermon, D., & Wijayanto, B. (2025). The Effectiveness of the RADEC Model in Improving Students' Literacy and Critical Thinking in Geography Learning at Senior High School. *Jurnal Penelitian Pendidikan IPA*, 11(11), 573–581. <https://doi.org/10.29303/jppipa.v11i11.13275>
- Senisum, M., Susilo, H., Suwono, H., & Ibrohim. (2022). GIRESiMCo: A Learning Model to Scaffold Students' Science Process Skills and Biology Cognitive Learning Outcomes. *Education Sciences*, 12(4), 228. <https://doi.org/10.3390/educsci12040228>
- Shah, M. A. (2022). Teachers as Reflective Practitioners: From Individualism to Vygotskian Social Constructivism. *Alberta Journal of Educational Research*, 68(3), 297–307. <https://doi.org/10.55016/ojs/ajer.v68i3.68598>
- Shakirova, N., Berechikidze, I., & Gafiyatullina, E. (2024). The effects of immersive AR technology on the environmental literacy, intrinsic motivation, and cognitive load of high school students. *Education and Information Technologies*, 29(8), 9121–9138. <https://doi.org/10.1007/s10639-023-12144-2>
- Skulmowski, A., & Xu, K. M. (2022). Understanding Cognitive Load in Digital and Online Learning: a New Perspective on Extraneous Cognitive Load. *Educational Psychology Review*, 34(1), 171–196. <https://doi.org/10.1007/s10648-021-09624-7>
- Sun, J. C.-Y., Ye, S.-L., Yu, S.-J., & Chiu, T. K. F. (2023). Effects of Wearable Hybrid AR/VR Learning Material on High School Students' Situational Interest, Engagement, and Learning Performance: the Case of a Physics Laboratory Learning Environment. *Journal of Science Education and Technology*, 32(1), 1–12. <https://doi.org/10.1007/s10956-022-10001-4>
- Sweller, J. (2020). Cognitive load theory and educational technology. *Educational Technology Research and Development*, 68(1), 1–16. <https://doi.org/10.1007/s11423-019-09701-3>
- Sweller, J. (2024). Cognitive load theory and individual differences. *Learning and Individual Differences*, 110, 102423. <https://doi.org/10.1016/j.lindif.2024.102423>
- Syed, T. A., Siddiqui, M. S., Abdullah, H. B., Jan, S., Namoun, A., Alzahrani, A., Nadeem, A., & Alkhodre, A. B. (2022). In-Depth Review of Augmented Reality: Tracking Technologies, Development Tools, AR Displays, Collaborative AR, and Security Concerns. *Sensors*, 23(1), 146. <https://doi.org/10.3390/s23010146>
- Wahab A, A., Kusuma, Y. S., Juandi, D., Turmudi, T., Buhaerah, B., & Syaiful, S. (2024). Understanding Students' Struggles in Solving Mathematical Problems: A Systematic Literature Review Using Polya's Framework. *Jurnal Pendidikan Progresif*, 14(3), 1728–1753. <https://doi.org/10.23960/jpp.v14.i3.2024118>
- Yıldız, T. (2025). From Constructivism To Cultural Cognition: A Comparative Analysis Of Piaget, Vygotsky, And Tomasello's Theories Of Cognitive Development. *HUMANITAS - Uluslararası Sosyal Bilimler Dergisi*, 13(25), 411–429. <https://doi.org/10.20304/humanitas.1601228>
- Yuliarny, Y., Ramadhan, S., Sihes, A. J., & Jamaluddin, N. (2025). Enhancing News Text Writing Skills through the RADEC Learning Model: The Role of Reading Interest among Indonesian Vocational High School Students. *AL-ISHLAH: Jurnal Pendidikan*, 17(3). <https://doi.org/10.35445/alishlah.v17i3.7739>
- Yurick, A. L., Council, M., Telesman, A. O., Musti, S., Gardner, R., & Cartledge, G. (2024). On the Science of Reading: How Social Justice, Behavior Analysis, and Literacy Instruction Converge. *Behavior and Social Issues*, 33(1), 563–580. <https://doi.org/10.1007/s42822-023-00154-1>