DIDAKTIKA
Vol. 6 No. 1, Maret 2026, pp. 1-18
https://ejournal-serang.upi.edu/didaktika

Accelerating Elementary School Students' Critical Thinking Skills through Visual Scaffolding Integrated with Assemblr Edu Augmented Reality in Science Learning

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Article Info

History Articles
Received:
02 March 2026
Accepted:
10 March 2026
Published:
15 March 2026

Abstract

This study aims to develop an interactive learning medium integrated with Augmented Reality (AR) through Assemblr Edu and to evaluate its effectiveness in enhancing elementary school students' critical thinking skills regarding the states of matter. The research was prompted by the low level of students' critical thinking skills, caused by the prevalence of conventional teaching methods and the abstract nature of the subject matter. This study employed a Research and Development (R&D) approach using the ADDIE model. Field testing was conducted at SD Negeri 1 Sukarame using a Quasi-Experimental design, involving Grade IV B as the control class and Grade IV C as the experimental class. Data were collected through expert validation, questionnaires, and essay tests. The results indicate that the AR-integrated visual scaffolding product is highly feasible, with expert validation scores of 93.3% for media and 96.74% for content, and a practicality score of 94%. The effectiveness test using the Paired Sample T-Test yielded a significance value of 0.000 ($p < 0.05$), with an N-Gain increase of 0.62 (Moderate category) in the experimental class, which was significantly higher than that in the control class. It is concluded that the application of AR learning media is effective and practical in enhancing students' critical thinking skills. The practical implications of this research suggest that educators can adapt AR technology as visual scaffolding to facilitate meaningful science learning in primary education, even within contexts of limited digital infrastructure.

Keywords: Augmented Reality, Assemblr Edu, Critical Thinking Skills, Visual Scaffolding

How to cite: Restiyanita, R., Nurwahidin, M., Firdaus, R., Fitriawan, H., & Saputra, B. (2026). Accelerating elementary school students' critical thinking skills through visual scaffolding integrated with Assemblr Edu augmented reality in science learning. *Didaktika, 6*(1), 1-18.

Info Artikel

Riwayat Artikel
Dikirim:
02 Maret 2026
Diterima:
10 Maret 2026
Diterbitkan:
15 Maret 2026

Abstrak

Penelitian ini bertujuan mengembangkan media pembelajaran interaktif terintegrasi Augmented Reality (AR) berbantuan Assemblr Edu serta menguji efektivitasnya dalam meningkatkan kemampuan berpikir kritis siswa pada materi perubahan wujud benda. Penelitian dilatarbelakangi oleh rendahnya kemampuan berpikir kritis siswa akibat dominasi metode konvensional dan materi yang bersifat abstrak. Penelitian ini merupakan Research and Development (R&D) dengan model ADDIE. Uji coba lapangan dilaksanakan di SD Negeri 1 Sukarame menggunakan desain Quasi Experimental pada kelas IV B sebagai kelas kontrol dan kelas IV C sebagai kelas eksperimen. Data dikumpulkan melalui validasi ahli, angket, dan tes uraian. Hasil penelitian menunjukkan produk visual scaffolding yang terintegrasi AR sangat layak dengan validitas ahli media 93,3%, ahli materi 96,74%, dan kepraktisan 94%. Uji efektivitas menggunakan Paired Sample T-Test menunjukkan signifikansi 0,000 < 0,05, dengan peningkatan N-Gain kelas eksperimen sebesar 0,62 (kategori Sedang), jauh lebih tinggi dibandingkan kelas kontrol. Disimpulkan bahwa penerapan media pembelajaran AR efektif dan praktis dalam meningkatkan kemampuan berpikir kritis siswa. Implikasi praktis dari penelitian ini menunjukkan bahwa pendidik dapat mengadaptasi teknologi AR untuk memfasilitasi pembelajaran sains yang bermakna pada tingkat pendidikan dasar sebagai scaffolding visual meskipun dengan infrastruktur digital yang terbatas.

Kata Kunci: Augmented Reality, Assemblr Edu, Keterampilan Berpikir Kritis, Scaffolding Visual

Cara mengutip: Restiyanita, R., Nurwahidin, M., Firdaus, R., Fitriawan, H., & Saputra, B. (2026). Accelerating elementary school students' critical thinking skills through visual scaffolding integrated with Assemblr Edu augmented reality in science learning. *Didaktika, 6*(1), 1-18.

e-ISSN: 2775-9024, p-ISSN: 2987-9388

INTRODUCTION

Twenty-first-century education demands a paradigmatic transformation toward the development of Higher Order Thinking Skills (HOTS), where critical thinking serves as a vital core competency for addressing complex problems in the Era of Industry 4.0 and Society 5.0 (Ikenga & van der Sijde, 2024). Critical thinking is a reflective cognitive process used in decision-making that involves interpreting, analyzing, and evaluating empirical information (Anggraeni et al., 2023). Within the context of Science and Social Studies (IPAS) learning, this ability is essential for enabling students to perform problem-solving and comprehend natural phenomena dynamically (Ma, 2023). Cultivating these skills from an early age correlates positively with cognitive readiness in subsequent academic levels.

However, reality indicates that Indonesian students' critical thinking performance remains concerning. The 2018 PISA study ranked Indonesia's scientific literacy 71st out of 79 countries. Research by Rahmadani et al. (2022) revealed that students' abilities to explain phenomena and interpret scientific data remain low. This is further supported by Yunita & Nurita's (2021) analysis, which highlighted students' difficulties with advanced inquiry, such as formulating hypotheses and drawing conclusions. The conditions at the elementary school level are increasingly alarming, as the majority of students encounter significant difficulties with high-level reasoning tasks (Rahmadani et al., 2022). This skill deficiency is evidenced by students' inability to analyze contextual problems and complete HOTS-standard evaluation instruments (Susanti et al., 2025). Most students are more accustomed to basic rote memorization, leaving them inadequately trained to develop systematic and critical thinking abilities.

The subject matter of "states of matter" in fourth-grade elementary education is characterized by its abstract nature, as it involves the dynamics of molecular particles at the invisible microscopic level. This condition creates pedagogical challenges for students aged 9–11, who are in the concrete operational stage and require visual representations to process logical operations. This is corroborated by the research of Pakpahan & Saragih (2022) and findings by Putri et al. (2022), which indicate that more than 60% of students struggle to comprehend this concept due to a lack of concrete media and active engagement.

Tragically, instructional practices remain dominated by teacher-centered, conventional methods, which lead to cognitive overload. Consequently, students tend to engage in mechanical rote learning rather than constructing analytical understanding. Data from the Ministry of Education, Culture, Research, and Technology confirms that only approximately 30% of elementary school teachers routinely optimize digital media in the classroom. Similar challenges were observed at SD Negeri 1 Sukarame, where only 30% of students were able to answer analytical questions, while the remaining 70% were confined to basic understanding. Teacher interviews confirmed that these low achievement levels are caused by a lack of interactive media that supports the concrete operational stage of development.

As a revolutionary solution, immersive Augmented Reality (AR) technology has emerged to bridge the gap between cognitive limitations and scientific abstraction. According to Al-Ansi et al. (2023), AR functions by synthesizing 3D virtual objects and animations into the real-world environment in real-time through mobile devices. Through this capability, phase transition phenomena—previously presented as descriptive text—can now be visualized into dynamic, interactive 3D particle model simulations that can be observed from various perspectives.

Empirical support for the effectiveness of Augmented Reality (AR) in science education is robust. Research by Hidayati et al. (2023) demonstrates that the integration of AR into media enhances students' critical thinking skills by 25% compared to conventional methods. This is further corroborated by Ashari's (2023) findings, which showed a significant surge in mean critical thinking scores from 70.00 to 87.50 following AR-based visual exploration. In addition to improving conceptual understanding by up to 30% (Azmi et al., 2025), the use of AR has been proven to increase student motivation and enthusiasm during in-depth discussions (Islawati et al., 2024). Specifically, AR visualization significantly reduces the abstraction of "states of matter" topics (Kurniasari & Suryanti, 2023).

Theoretically, AR technology aligns with Vygotsky's constructivism, which emphasizes the construction of independent knowledge through active interaction with cultural tools (Tohari & Rahman, 2024). The manipulative features of AR act as scaffolding that supports elementary students' reflective understanding in accordance with their concrete operational stage. However, a critical synthesis reveals a research gap; the majority of AR studies in primary schools remain limited to affective evaluations and basic-level cognitive domains. There is a notable scarcity of comprehensive developmental research that deliberately designs AR media based on contemporary ecosystems, such as Assemblr Edu, to evaluate specific critical thinking indicators—such as analytical explanation and inference—through rigorous experimental designs.

Therefore, the present study is designed to bridge this existing gap in the literature. This research aims to describe the development of an interactive learning medium fully integrated with Augmented Reality (AR) technology using the Assemblr Edu ecosystem, specifically focusing on the "states of matter" topic for fourth-grade students. Furthermore, the central objective of this study is to analyze and assess the feasibility, practicality, and effectiveness of implementing this digital artifact to bolster the critical thinking skills of fourth-grade elementary school students.

METHODS

This study employs the Research and Development (R&D) method to produce an instructional product, followed by feasibility evaluations to ensure its educational suitability (Sarpong et al., 2023). The resulting AR-integrated interactive media on "states of matter" was designed and tested for its effectiveness in enhancing fourth-grade students' critical thinking skills.

Research Procedure

This study employs the ADDIE instructional development model, which encompasses five primary stages: Analysis, Design, Development, Implementation, and Evaluation. The selection of the ADDIE model is based on its systematic characteristics and high flexibility in the developmental process of technology-integrated learning products. Firdaus & Firdaus (2024) demonstrated that a systematic approach through the stages of analysis to evaluation within the ADDIE framework is capable of producing valid media that significantly enhance student engagement, thereby reinforcing the selection of this model for Augmented Reality (AR) media development research. Furthermore, the ADDIE framework allows for modifications at each stage to optimize developmental outcomes and ensure that the learning media remain focused on improving student skills (Islahiyah et al., 2021). The ADDIE development model workflow is presented in Figure 1.

Figure 1. ADDIE Developmental Model

Analysis Stage

The analysis stage aims to identify various learning needs by evaluating teaching materials, student characteristics, the curriculum in use, and the learning environment. First, a learning needs analysis was conducted through observations and interviews with the fourth-grade teacher at SD Negeri 1 Sukarame. It was discovered that the Science and Social Studies (IPAS) material concerning the states of matter is difficult for students to comprehend because it is delivered through conventional, non-interactive methods, causing students to remain passive and unmotivated. Second, a curriculum analysis was performed on the Phase B IPAS Learning Outcomes (*Capaian Pembelajaran* or CP) within the *Kurikulum Merdeka* (Independent Curriculum). This framework mandates that students must be able to analyze changes in the states of matter and the factors influencing them through simple observations and experiments. Third, the student characteristics analysis referred to Piaget's theory of cognitive development; fourth-grade students are in the concrete operational stage, necessitating learning that integrates visual, manipulative, and contextual elements. Fourth, the learning environment analysis ensured the availability of supporting infrastructure, including Android devices, projectors, and stable internet connectivity within the school.

Design Stage

The design stage aims to formulate the initial concept of the learning medium, serving as a comprehensive guide for the product development process. The researcher developed a storyboard to function as the media's blueprint. The user interface (UI) was designed in Canva to ensure a child-friendly visual aesthetic, while three-dimensional holographic objects were assembled using the Assemblr Edu platform. The design includes the presentation of "states of matter" content, a 'Virtual Experiment' feature that allows students to manipulate variables in real time, and evaluation instruments consisting of essay questions that assess critical thinking indicators (Anggraeni et al., 2023). During this stage, validation forms for subject-matter and media experts, as well as student response questionnaires, were systematically developed.

Development Stage

The development stage involves assembling all design assets into a complete application package using the Assemblr Edu platform, followed by a validation audit conducted by subject-matter and media experts. Concurrently, an empirical validity test of the essay instrument was conducted with 30 students outside the research sample. This procedure ensured that each test item accurately and consistently measured critical thinking skills prior to its utilization in the primary data collection phase.

Implementation Stage

The implementation stage involves applying the developed learning media in a real classroom setting. This phase employed a quasi-experimental design involving two sample classes at SD Negeri 1 Sukarame: Grade IV B as the control group and Grade IV C as the experimental group. To ensure internal validity and mitigate potential confounding effects, several rigorous controls were established:

1. Instructional Control: Both the experimental and control groups were taught by the same instructor. This ensured that teaching style, intonation, and personal pedagogical approaches did not act as confounding variables influencing the learning outcomes.
2. Temporal and Curricular Control: Both classes received identical time allocations (2 x 35 minutes per session) and utilized the exact same syllabus and learning objectives based on the Phase B IPAS Learning Outcomes.

The intervention difference resided exclusively in the media employed. In the experimental group, learning was student-centered, utilizing AR-integrated interactive media through the Assemblr Edu platform, where students engaged in object manipulation and virtual experiments. Conversely, the control group followed a teacher-centered approach using conventional methods. Treatment control in this group was maintained by having students listen to verbal explanations (lectures), read from standard Ministry of Education printed textbooks, and complete exercises on the blackboard or in notebooks without 3D visualization or digital technology intervention. Both groups were administered an identical pretest before the instructional sequence to ensure baseline equivalence. Following the completion of all learning sessions, a posttest was administered to assess the significance of the improvement in students' critical thinking skills resulting from the different media interventions.

Evaluation Stage

The evaluation stage constitutes the final phase, conducted both formatively and summatively. Formative evaluation was conducted continuously throughout each stage of the ADDIE process to ensure product quality, whereas summative evaluation measured the overall effectiveness of the media implementation. Revisions and refinements were made based on feedback from teachers, students, and validators to ensure that the resulting learning media could better support the teaching and learning process and align more accurately with student needs.

Research Participants

The participants of this study were fourth-grade students at SD Negeri 1 Sukarame, Bandar Lampung. The sampling process resulted in two treatment groups: Grade IV B (n = 30) was designated as the control group, receiving conventional instruction without AR media, while Grade IV C (n = 30) served as the experimental group, utilizing AR-integrated interactive media. The selection of these two classes was based on the assumption that the students had relatively equivalent baseline abilities and no prior experience with AR technology in learning about the states of matter. Product validation was conducted by two groups of experts: three media specialists and three subject matter experts, selected for their professional expertise and experience in their respective fields.

Data Collection Techniques

Data collection in this study was conducted through five complementary techniques designed to obtain comprehensive and relevant information:

1. Observation: Conducted to track student progress and engagement throughout the learning process, with a specific focus on problem-solving activities that require critical thinking.
2. Structured Interviews: Performed with the fourth-grade teachers at SD Negeri 1 Sukarame to conduct an in-depth exploration of learning needs and challenges.
3. Questionnaires: Utilized to gather validation data from experts (media and subject matter validation sheets) as well as practicality data from the experimental group's responses.
4. Documentation: Used to collect data related to assessment records, teacher manuals, and information regarding the number of students involved in the study.
5. Critical Thinking Tests: Constructed in the form of open-ended essay questions (essay tests), these were administered in two phases: a pretest to map baseline abilities prior to treatment and a posttest to measure final achievement following the intervention.

Research Instruments

The research instruments were specifically developed to align with the data collection requirements and the study's objectives. These instruments were adjusted based on the required data types to ensure that the generated information was both accurate and relevant. The details of the instruments used are presented in Table 1.

Table 1. Data Collection Instruments

No.	Formative Assessment Aspects	Objectives	Instruments
1	Subject Matter Expert Validation	To obtain expert feedback regarding the developed AR media content.	Subject matter expert validation sheet
2	Media Expert Validation	To obtain expert feedback regarding the visual design, interface, and interactivity of the developed AR product.	Media expert validation sheet

The study used a 5-point Likert scale (1-5) to assess respondents' levels of agreement across several categories: highly feasible, feasible, moderately feasible, less feasible, and not feasible (Simamora, 2022). Validation grids for each expert were structured as systematic assessment guides. The critical thinking test instrument consisted of 15 essay items strictly designed to evaluate critical thinking indicators, including students' ability to interpret phenomena, analyze the causal effects of temperature changes on matter, and draw conclusions.

Data Analysis Techniques

The content validity of the instruments was analyzed using Aiken's V formula, with a criterion of $V \geq 0.80$ for validity. Furthermore, empirical validity was tested using the Pearson Product-Moment Correlation technique via IBM SPSS Statistics version 26.0. Data from expert validation and practicality tests were analyzed using descriptive percentage techniques, comparing accumulated empirical scores against ideal maximum scores to determine feasibility levels. Meanwhile, cognitive test data were analyzed using inferential statistics. Prior to hypothesis testing, pretest and posttest data underwent normality tests using the Shapiro-Wilk test to ensure normality of the data. The significance of the media's effectiveness was analyzed by applying a parametric Paired Sample T-Test to detect probabilistic differences in mean scores. As a complementary step to assess the magnitude of improvement in students' cognitive understanding and to mitigate baseline-score bias, the Normalized Gain (N-Gain) was calculated. These N-Gain values were subsequently classified into low, moderate, or high interpretation ranges.

RESULT AND DISCUSSION

This developmental research produced an interactive learning medium integrated with Augmented Reality (AR) for the "States of Matter" topic in fourth-grade elementary school, which met the criteria for being highly feasible, highly practical, and effective. The developmental procedure followed the ADDIE model, consisting of five stages: Analysis, Design, Development, Implementation, and Evaluation.

Analysis Stage

A comprehensive analysis was conducted based on four parameters: learning needs, curriculum, student characteristics, and the learning environment. The learning needs analysis, performed through observations and structured interviews with the fourth-grade teacher at SD Negeri 1 Sukarame, revealed that the "States of Matter" instruction was predominantly conventional, relying on lectures and textbooks. Consequently, students remained passive and struggled to comprehend abstract concepts such as melting, evaporation, condensation, and sublimation.

Based on formative assessment results, only 9 out of 30 students (30%) correctly answered analysis (C4) and evaluation (C5) level questions, while the majority (70%) were confined to lower-order cognitive levels. The curriculum analysis aligned with the Phase B IPAS Learning Outcomes of the *Kurikulum Merdeka*, which mandates that students analyze state changes through simple observations and experiments. The student characteristics analysis referenced Piaget's theory, noting that fourth-grade students are in the concrete operational stage and require visual and manipulative support. Finally, the learning environment analysis confirmed that all 30 students had access to Android devices, and the school provided adequate projectors and internet connectivity for AR implementation. A summary of the needs analysis is presented in Table 2.

Table 2. Learning Needs Analysis Summary

Aspect	Findings	Learning Requirements	Supporting Data	Recommendation
Content Needs	Matter-transformation concepts are difficult to grasp due to conventional delivery methods.	Materials must be presented in more interactive, visual ways.	75% of students reported difficulties (Observation).	Utilize visual and interactive AR media.
Interactivity Needs	Students tend to be passive and unmotivated in conventional settings.	Learning must be more engaging with interactive elements.	60% of students were inactive (Teacher interview).	AR to enhance engagement through direct virtual interaction.
Visualization Needs	Students require visualization to understand abstract concepts.	Integration of visual and manipulative learning is necessary.	80% of students learn better through images/videos.	AR to display 3D visual transitions clearly.

Technology Needs	School has Android devices and projectors; internet connectivity varies.	Media must be accessible offline and compatible with school hardware.	School owns 10 Android devices and 2 projectors.	Develop AR with offline access and Android compatibility.
Contextual Needs	Learning should support direct experiments and observations.	Media must facilitate observation and experimental activities.	Only 25% of students were active in classroom experiments.	AR to provide safe virtual experimental simulations.

Design Stage

The design stage produced a storyboard as the primary media blueprint. The user interface (UI) was designed in Canva to ensure a child-friendly visual aesthetic, while three-dimensional holographic objects were assembled on the Assemblr Edu platform. The final design comprises six simulation modules for state transitions (melting, freezing, evaporation, condensation, sublimation, and deposition), alongside a 'Virtual Experiment' feature that enables students to manipulate variables—such as heat intensity—in real time. Furthermore, the development included hyperlink-based interactive quizzes with visual and audio feedback, as well as AR-integrated Student Worksheets (LKPD) to serve as guides for scientific observation.

Figure 2. Start Page and Main Menu Interface of the Media

Figure 3. Display of Learning Competencies, Objectives, and Subject Matter Content

Figure 4. AR Virtual Experiment Navigation Menu and User Instructions

Figure 5. Simulation of 3D Object Scanning Barcode and Assessment Items

Figure 6. Interactive Quiz Interface

Figure 7. Visual and Audio Feedback Display for Student Responses

Development Stage

The development stage involved the assembly of all design assets into a comprehensive application package through the Assemblr Edu platform, followed by a series of expert validations. Concurrently, an empirical validity test of the assessment instrument was conducted with 30 students outside the primary research sample. The following sections present the results of the media expert validation, subject matter expert validation, and instrument quality testing. Media validation was performed by three specialists, focusing on visual and linguistic feasibility. Subject matter validation was conducted by three experts, evaluating content and presentation feasibility; both utilized a 5-point Likert scale. The results of these validations are presented in Table 3.

Tabel 3. Summary of Media & Subject Matter Expert Validation Results

		Media Expert		
No.	**Aspect**	**Indicator Scope**	**Mean Score**	**Category**
1	Visual Feasibility	Interface, layout, color palette, animation, AR 3D object quality, readability, interactivity, and visual professionalism.	4.667	Highly Feasible
2	Linguistic Feasibility	Language clarity, communicative instructions, text interactivity, and compliance with Indonesian linguistic standards.	4.667	Highly Feasible
	Total Average		4.667 (93.3%)	Highly Feasible
		Subject Matter Expert		
1	Content Feasibility	Alignment with *Kurikulum Merdeka* Learning Outcomes (CP), conceptual accuracy, scientific references, and curiosity-building potential.	4.820	Highly Feasible
2	Presentation Feasibility	Presentation techniques, completeness, active learning approach, flow coherence, and critical thinking stimulation.	4.830	Highly Feasible
	Total Average		4.824 (96.74%)	Highly Feasible

Media validation yielded a percentage of 93.3%, while subject matter validation reached 96.74%, both categorized as Highly Feasible. Key recommendations for improvement from the media experts included refining definition texts and numbering systems, whereas subject matter experts emphasized the need for more communicative phrasing and the inclusion of integrated HOTS-based questions within the AR display. All suggestions were addressed and implemented prior to field testing. Before the implementation phase, the critical thinking skills test instrument (consisting of 15 essay items) underwent quality testing, which encompassed content validity, empirical validity, and reliability. A summary of these results is presented in Table 4.

Tabel 4. Results of Instrument Validity and Reliability Testing

Type of Test	**Criteria**	**Result**	**Decision**
Content Validity (Aiken's V)	≥ 0.80$ (Valid)	Average V = 0.87	All items are valid
Empirical Validity (Product-Moment)	r_count ≥ r_table = 0.361	r = 0.443 – 0.872	15 items are valid (100%)
Reliability (Cronbach's Alpha)	≥ 0.70	α = 0.925	Very High / Excellent

All 15 test items were declared valid, with a Cronbach's Alpha coefficient of 0.925 (categorized as Very High). Consequently, the instrument is deemed both feasible and reliable for measuring students' critical thinking skills accurately.

Implementation Stage

The implementation stage was conducted at SD Negeri 1 Sukarame using a quasi-experimental design. Grade IV C (n = 30), serving as the experimental group, received instruction via AR-integrated interactive media, while Grade IV B (n = 30), acting as the control group, followed conventional instructional methods. The process commenced with a pretest to measure baseline abilities, followed by the learning intervention and student response questionnaires, and concluded with a posttest.

Descriptive Analysis of Pretest and Posttest Results

The descriptive statistics for the pretest and posttest results in both groups are presented in Table 5.

Table 5. Descriptive Statistics of Pretest and Posttest Scores

Descriptive Statistics	Control Group (Conventional)	Experimental Group (AR Media)
Sample Size (N)	30	30
Mean Pretest Score	44.30	43.57
Mean Posttest Score	60.37	78.00
Minimum Posttest Score	50	60
Maximum Posttest Score	70	94
Average Improvement (Gain)	16.07	34.43

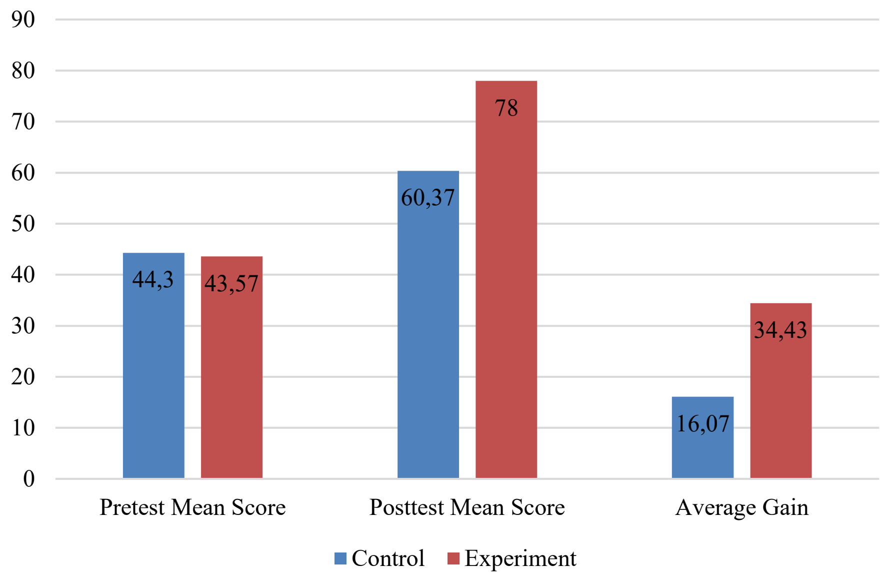

Figure 8. Comparative Graph of Test Results

Based on Figure 8, both groups demonstrated relatively equivalent baseline abilities, with mean pretest scores ranging between 43 and 44. However, in the final stage, the experimental group showed a significantly higher improvement, reaching a mean posttest score of 78.00, whereas the control group only achieved an average of 60.37. This 17.63-point disparity indicates a substantial positive influence from the utilization of AR media.

Media Practicality (Student Responses)

Based on the response questionnaires administered to the 30 students in the experimental group following the learning process, a mean media practicality score of 94.00% was obtained. This score falls into the "Highly Practical" category. Students reported that the integration of AR eliminated logistical complexities; they were able to conduct scientific observations without the need to bring physical equipment such as stoves, pots, ice cubes, or camphor into the classroom, as the virtual experiments provided an immersion equivalent to real-world experiences.

Evaluation Stage

The evaluation stage was conducted through a series of inferential statistical analyses to empirically test the effectiveness of the AR media. This included normality testing, the Paired Sample T-Test, and the N-Gain score analysis.

Normality Test (Shapiro-Wilk)

The normality test utilized the Shapiro-Wilk method, as the sample size was below 50 (N = 30). The results are presented in Table 6.

Tabel 6. Normality Test Results

Group	Data Set	Statistic	df	Sig.	Conclusion
Control Group	Pretest	0.988	30	0.979	Normal
	Posttest	0.974	30	0.663	Normal
Experimental Group	Pretest	0.972	30	0.600	Normal
	Posttest	0.972	30	0.604	Normal

Based on Table 6, the significance values for the pretest and posttest data in both groups exceed the 0.05 threshold; therefore, all data sets are deemed normally distributed. Fulfilling the normality assumption allowed for hypothesis testing using parametric statistics, specifically the Paired Sample T-Test.

Hypothesis Testing (Paired Sample T-Test)

Hypothesis testing was conducted at a significance level of $\alpha = 0.05$. The formulated hypotheses were: H_0: There is no significant difference between the mean pretest and posttest scores; H_a: There is a significant difference between the mean pretest and posttest scores. The results are shown in Table 7.

Table 7. Paired Sample T-Test Results

Pair	Pre-Data	Post-Data	Mean Diff.	t-count	Sig. (2-tailed)
Pair 1	Control Pretest	Control Posttest	-0.633	-1.245	0.223 (H_0 accepted)
Pair 2	Experimental Pretest	Experimental Posttest	-34.433	-40.744	0.000** (H_a accepted)

Table 7 shows that for the control group (Pair 1), the significance value was 0.223 ($p > 0.05$); thus, H_0 was accepted, indicating no significant improvement under conventional instruction. For the experimental group (Pair 2), the significance value was 0.000 ($p < 0.05$); therefore, H_0 was rejected, signifying a highly significant difference in critical thinking skills before and after the implementation of AR media, with a mean increase of 34.43 points.

Table 8. N-Gain Comparison between Experimental and Control Groups

Statistic	Control Group	Experimental Group	Category (Exp.)
Average (Mean N-Gain)	1.18%	62.10% (0.62)	Moderate
Minimum Value	-8.62%	39.39%	–
Maximum Value	11.11%	86.05%	–

The experimental group achieved an average N-Gain of 0.62 (Moderate category), while the control group only reached 0.0118 (Very Low category). All students in the experimental group recorded positive N-Gains (Min = 39.39%). In contrast, the control group even exhibited negative N-Gains (Min = -8.62%), indicating stagnation in critical thinking skills without AR media intervention.

Although the effectiveness test proved significant, the N-Gain acquisition in the experimental group remained in the Moderate category (0.62). This indicates that cognitive acceleration toward higher-order thinking (HOTS) is not an instantaneous process but requires time and prolonged exposure to scientific literature. This moderate category was also influenced by technical constraints in the field. Limited infrastructure, such as unstable school internet connectivity, caused some students to experience latency (lag) when loading large-scale 3D virtual assets. These interruptions momentarily disrupted student focus during virtual experiments. Therefore, an N-Gain achievement of 0.62 is a highly realistic and positive result for an initial intervention, proving that AR remains effective even when implemented within a limited school technology ecosystem.

Discussion

The developed AR-integrated interactive learning media met exceptionally high criteria for both feasibility and practicality. This achievement reflects the media's alignment with three superior characteristics. First, the concrete visualisation aligns with Piaget's concrete operational stage, in which students rely heavily on physical objects and visual representations. In line with Pakpahan & Saragih (2022), AR media presents 3D virtual objects in real time, transforming invisible phenomena into observable visualisations. This has proven effective to reduce students' cognitive load when processing abstract concepts, as confirmed by Kurniasari & Suryanti (2023). Second, the high interactivity provided through user-control features in Assemblr Edu fosters active learning, aligning with Vygotsky's constructivist principle that knowledge is constructed through active interaction with the environment. Third, the curricular relevance facilitates a scientific approach through virtual experimental simulations, overcoming the limitations of physical teaching aids in elementary schools.

The effectiveness of AR media implementation was significantly higher than conventional methods. This improvement in critical thinking skills occurs because AR operates specifically within the students' cognitive domain. In conventional learning, students often experience cognitive overload as they are forced to engage in complex mental abstraction to imagine particle motion. AR media mitigates this barrier by providing interactive 3D visualisations that serve as cognitive scaffolding, redirecting students' cognitive energy toward higher-order thinking processes such as analysis and evaluation. These findings are consistent with research by Amalia et al. (2023), which confirms that AR exerts a progressive influence on the surge of critical thinking abilities among elementary school students.

The mechanism of this improvement synergizes with Facione's critical thinking indicators, where students perform interpretation, causal analysis, predictive evaluation, and evidence-based inference through independent visual observation. This approach supports Vygotsky's constructivism and Ausubel's Meaningful Learning Theory through direct student engagement (Bryce & Blown, 2024). The achievement of effectiveness in the moderate category aligns with the findings of Qorimah & Sutama (2022) and Wiliyanti et al. (2024), indicating a consistent pattern that high-level cognitive improvement follows a gradual learning curve. Given that critical thinking is a complex HOTS (Higher Order Thinking Skill), the transition from rote memorization to analysis requires sustained habituation. This positive cognitive acceleration can be optimized through long-term AR integration or by pairing it with Problem-Based Learning (PBL) models.

Despite the statistically significant results, the moderate effectiveness achieved opens a critical discourse regarding field constraints. In-depth analysis reveals technical and ergonomic limitations that hindered maximal cognitive acceleration. First, regarding ergonomics, prolonged use of touch-screen AR media poses a risk of visual fatigue. This finding is supported by Souchet et al. (2023), who assert that intense visual interaction with immersive objects can trigger eye strain and mild cognitive fatigue, potentially disrupting student focus and motivation during the latter stages of the experiment. Beyond ergonomics, digital infrastructure remains a pivotal confounding variable. The platform's dependence on data traffic caused several students to experience asset-loading latency (lag) due to unstable school internet connectivity. This technical disruption indirectly interrupted the continuity of students' critical thinking flow while formulating hypotheses. This phenomenon proves that the pedagogical effectiveness of AR remains heavily tethered to the readiness of its supporting infrastructure.

Furthermore, a comparative analysis is necessary to evaluate why this study did not reach "High" effectiveness. Systematic reviews by Anggraeni et al. (2023) and experimental research by Nurwijaya (2022) indicate that higher-order cognitive gains are optimized when AR is anchored to specific instructional approaches. In this study, AR was primarily implemented as a standalone visualisation tool. In contrast, research with high effectiveness typically integrates immersive technology holistically within Problem-Based Learning (PBL) syntaxes. The absence of complex triggering problems and the relatively short experimental duration meant that students' inquiry instincts were not fully escalated toward critical problem-solving. This reinforces the conclusion that technology, regardless of its sophistication, yields a more revolutionary impact when structurally integrated into problem-based collaborative models.

Ultimately, this study provides empirical evidence that, even in primary schools with limited facilities, mobile-integrated AR via Assemblr Edu is an effective solution for overcoming barriers to abstract thinking. Its novelty lies in the specific integration of the Assemblr Edu platform with critical thinking indicators within the context of fourth-grade "states of matter" topics, providing detailed evidence on cognitive development through AR interaction.

CONCLUSION

Based on the research and development conducted, it is concluded that the AR-integrated interactive learning media using the Assemblr Edu platform for the "states of matter" topic has met exceptionally high feasibility criteria. Expert validation indicates that the media is theoretically and substantively robust, achieving average scores of 93.3% from media specialists and 96.74% from subject-matter experts. Beyond feasibility, the media demonstrated an excellent level of practicality in fourth-grade elementary school implementation, as evidenced by a 94% positive student response rate. Furthermore, the implementation of this AR-based learning media proved significantly more effective than conventional instructional methods in enhancing students' critical thinking skills. Statistical analysis revealed a distinct performance gap between the experimental and control groups, with the experimental group's mean posttest score reaching 78.00, surpassing the control group's score of 60.37. The superiority of this media is also reflected in the experimental group's N-Gain score of 0.62 (Moderate category), while the control group showed only a negligible improvement. Consequently, the integration of AR technology through the Assemblr Edu ecosystem serves as an effective pedagogical solution for visualizing abstract scientific concepts while simultaneously stimulating the analytical and evaluative dimensions of elementary school students' thinking.

Based on the study's findings, several recommendations are proposed to enhance science education and future research. For educators, it is highly recommended to integrate Augmented Reality (AR) platforms like Assemblr Edu as a visual scaffolding tool to overcome students' barriers to abstract thinking in science. However, teachers should balance AR usage with eye-rest intervals to mitigate potential visual fatigue. For school administrators, improving digital infrastructure and internet stability is crucial to ensure seamless interactive learning experiences. For future researchers, it is suggested to investigate the long-term impact of AR integration and explore its effectiveness when holistically combined with Problem-Based Learning (PBL) or Inquiry-Based Learning models. Such integration could potentially escalate students' critical thinking from the "Moderate" to the "High" effectiveness category by providing more complex, real-world problem-solving challenges.

ACKNOWLEDGMENTS

The author expresses sincere gratitude to the Master's Program in Educational Technology at Universitas Lampung for the academic support provided throughout this research. Special thanks are also extended to the principal, teachers, and students of SD Negeri 1 Sukarame for their willingness to participate as research subjects and for facilitating the experimental process. Furthermore, the author would like to thank the expert validators for their constructive feedback, which was instrumental in the optimal development of this Augmented Reality-based learning media.

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