Prisma Sains: Jurnal Pengkajian Ilmu dan Pembelajaran Matematika dan IPA IKIP Mataram
https://e-journal.undikma.ac.id/index.php/prismasains/index
e-mail: prismasains.pkpsm@gmail.com

July 2026. Vol. 14, No. 3
p-ISSN: 2338-4530
e-ISSN: 2540-7899
pp. 1966-1982

Integrating Augmented Reality into Problem-Based Learning: Effects on Elementary School Students' Critical Thinking in Science

[1]*Yuni Krisnawati, [2]Sandra Arhesa, [3]Hos Arie Rhamadhan Sibarani, [4]Ady Akbar, [5]Achmad Salido

[1] Faculty of Social Sciences and Humanities, Universitas PGRI Silampari, Lubuk Linggau, Indonesia
[2] Faculty of Teacher Training and Education, Universitas Majalengka, Majalengka, Indonesia
[3] Faculty of Social Sciences, Universitas Maritim Raja Ali Haji, Tanjung Pinang, Indonesia
[4] Faculty of Teacher Training and Education, Universitas Sawerigading, Makassar, Indonesia
[5] Faculty of Teacher Training and Education, Universitas Sembilanbelas November Kolaka, Kolaka, Indonesia

*Corresponding Author e-mail: yunikrisnawati.stkippgri@gmail.com

Received: May 2026; Revised: June 2026; Published: July 2026

Abstract

Developing students' critical thinking skills has become an increasingly important educational priority in the era of artificial intelligence. Despite the growing use of Augmented Reality (AR) in education, empirical evidence regarding its effectiveness in fostering elementary school students' critical thinking in science remains limited, particularly when integrated with Problem-Based Learning (PBL). This study investigated the effect of AR-assisted PBL on elementary students' critical thinking skills in science. A quasi-experimental design with a non-equivalent pretest–posttest control group was employed involving 62 fifth-grade students (experimental group = 32; control group = 30). Both groups received identical problem-based science instruction on flora and fauna topics, while AR was integrated only into the experimental group. Students' critical thinking skills were assessed using an essay-based instrument developed according to the RED framework (Recognizing Assumptions, Evaluating Arguments, and Drawing Conclusions). Descriptive statistics and inferential analyses were conducted using an independent-samples t-test for the pretest and a one-tailed Mann–Whitney U test for the posttest. The findings revealed that students receiving AR-assisted PBL achieved significantly higher critical thinking scores than those receiving problem-based learning without AR (posttest mean = 81.72 vs. 75.83; $p = 0.005$), with a moderate educational effect ($r = 0.329$). These findings suggest that integrating interactive three-dimensional visualization within a problem-based learning environment facilitates scientific reasoning and supports the development of critical thinking beyond conceptual understanding alone. This study contributes to the growing literature on technology-enhanced science education by providing empirical evidence that AR functions most effectively as a pedagogical tool when embedded within inquiry-oriented learning environments. The findings also offer practical implications for designing more interactive and student-centered science instruction in elementary schools.

Keywords: Augmented reality; Critical thinking; Problem-based learning; Science learning

How to Cite: Krisnawati, Y., Arhesa, S., Sibarani, H. A. R., Akbar, A., & Salido, A. (2026). Integrating Augmented Reality into Problem-Based Learning: Effects on Elementary School Students' Critical Thinking in Science. *Prisma Sains: Jurnal Pengkajian Ilmu Dan Pembelajaran Matematika Dan IPA IKIP Mataram*, *14*(3), 1966–1982. https://doi.org/10.33394/j-ps.v14i3.20928

https://doi.org/10.33394/j-ps.v14i3.20928

INTRODUCTION

Critical thinking skills are one of the essential skills that need to be developed in 21st-century students (Mullis et al., 2016; Salido, Sugiman, et al., 2025). Given the current rapid development of artificial intelligence technologies, fostering critical thinking skills has become an urgent educational priority (Darwin et al., 2024). Overreliance on AI for decision-making and problem-solving may create potential risks, highlighting the importance of cultivating strong critical thinking abilities These skills play a role in helping students analyze information, evaluate various arguments, solve problems, and make rational decisions based on available facts and evidence (Akbar et al., 2025). In the context of basic education, critical thinking skills have a strategic position because they are the foundation for building scientific literacy, problem-solving skills, and student readiness to face the ever-evolving developments in science and technology (Ennis, 1964). Therefore, the development of critical thinking skills needs to be a primary focus in the learning process, particularly in Natural Sciences (IPA) subjects, which are closely related to observation, experimentation, investigation, and scientific reasoning (Encabo-Fernández et al., 2023; Jegstad et al., 2025).

Various international studies show that students' critical thinking skills are still suboptimal (Arthi & Gandhimathi, 2025). Fan and See (2022) reported that students in China still experience weaknesses in the aspect of searching and processing information critically. Research by Baki et al. (2016) also showed that students in rural Malaysia have low critical thinking skills because the learning implemented does not provide sufficient space for discussion and exploration. Furthermore, Encabo-Fernández et al. (2023) found that elementary school students in the city of Murcia, Spain, still experience difficulty in evaluating arguments logically. Recent research conducted by Alkış-Küçükaydın (2026) from Necmettin Erbakan University also revealed that students' critical thinking skills in Turkey are still not optimally developed, requiring more extensive learning interventions. Meanwhile, research by Widaya et al. (2026) showed that students' critical thinking skills in Surabaya, Indonesia, are still low, leading researchers from Surabaya State University to recommend strengthening critical thinking skills as a key focus in educational development. These findings demonstrate that low critical thinking skills are a global issue that requires more active, contextual, and technology-based learning innovations.

Students' low critical thinking skills are largely influenced by learning practices that are still dominated by memorization methods and one-way material delivery (Prananta et al., 2024; Zuzano et al., 2025). In science learning, the learning process also tends to be teacher-centered, so students' opportunities for independent exploration, observation, and problem-solving are still limited (Sari et al., 2026). These conditions result in learning that does not provide meaningful learning experiences and is not fully able to encourage the development of students' higher-order thinking skills optimally (Agustiningsih et al., 2026; Salido, Syarif, et al., 2025). As a result, students tend to be passive during the learning process and are less accustomed to analyzing and evaluating the information obtained.

Various learning approaches have been implemented to improve students' critical thinking skills in science learning. Siswati et al. (2026) found that Gamified Inquiry-Based Learning can help develop students' reasoning skills, thereby enhancing their critical thinking skills in science learning. The STEM approach is also used to train students to solve problems and conduct scientific investigations systematically (Liu & Shen, 2026). Furthermore, inquiry mind maps are implemented to encourage student exploration and collaboration in completing science projects (Sari et al., 2021). The guided inquiry pedagogy approach is also utilized to develop scientific observation, experimentation, and conclusion-drawing skills (Kirk et al., 2023). Furthermore, the integration of online media and problem-posing has been shown to help students develop analytical skills and understand the interrelationships between concepts (Zhang et al., 2024). The use of interactive digital media is also beginning to be developed to create more engaging, contextual, and student-centered learning (Susanto & Hapudin, 2024).

Among the various instructional approaches, Problem-Based Learning (PBL) has been widely recognized as an effective pedagogical model for fostering higher-order thinking skills because it actively engages students in identifying authentic problems, investigating evidence, evaluating alternative explanations, and constructing reasoned conclusions (Wiraha & Sudarma, 2023). These learning processes closely correspond to the core components of critical thinking proposed in the RED framework, namely recognizing assumptions, evaluating arguments, and drawing conclusions. Nevertheless, elementary school students often experience difficulties during the investigation stage because many science concepts remain abstract and difficult to observe directly. Consequently, integrating PBL with interactive visualization technologies such as Augmented Reality may provide a more supportive learning environment for developing students' critical thinking skills (Li et al., 2023).

The development of digital technology provides a significant opportunity to create a more engaging and meaningful learning process (Barakah et al., 2026). One technology considered to have potential in supporting science learning is Augmented Reality (Mohammadpour-Rozehkhani et al., 2025). This technology allows virtual objects to be displayed directly in a real environment so that students can see the visualization of abstract concepts more concretely and interactively (Rusli et al., 2023). Beyond science learning, AR has also been shown to improve students' critical thinking skills in mathematics through more realistic and easily understood concept visualizations (Akbar et al., 2025). Cai et al. (2020) also stated that the use of AR has a positive impact on conceptual understanding and learning interactivity. Thus, the use of AR has great potential to help students understand scientific phenomena more deeply through visual and interactive learning experiences.

Although the educational application of Augmented Reality has expanded considerably in recent years, several important research gaps remain. First, previous studies have predominantly investigated AR for improving conceptual understanding, learning motivation, and academic achievement, whereas relatively few have examined its effectiveness in developing elementary school students' critical thinking skills (Coştu, 2025; Ilobinso et al., 2025; Wu et al., 2024). Second, most AR studies have been conducted in mathematics, particularly geometry, while empirical evidence regarding its implementation in elementary science learning remains comparatively limited (Akbar et al., 2025; Prananta et al., 2024). Third, although Problem-Based Learning has been widely acknowledged as an effective approach for promoting critical thinking, limited studies have integrated AR within a PBL environment to support scientific inquiry in elementary classrooms. Finally, only a few studies have assessed students' critical thinking using the RED framework, leaving limited empirical evidence regarding how AR-assisted PBL influences the development of recognizing assumptions, evaluating arguments, and drawing conclusions during science learning (Comstock & Grühn, 2026). Addressing these gaps is essential for understanding the pedagogical value of AR beyond conceptual visualization and for providing stronger evidence regarding its contribution to higher-order thinking skills.

Based on the description above, this study aims to analyze the effect of using Augmented Reality in elementary school science learning on improving students' critical thinking skills. This study is expected to fill the conceptual gap regarding how AR can be utilized to develop students' critical thinking skills in science learning. In addition, this study is also expected to enrich the literature on technology integration in science learning, particularly related to the development of higher-order thinking skills in elementary education. This study is also expected to provide empirical evidence regarding the relationship between AR-based interactive visualization and meaningful learning in supporting students' critical thinking skills.

Unlike previous studies that primarily examined AR as a visualization tool to improve conceptual understanding or general learning outcomes, the present study integrates AR into a problem-based learning environment to facilitate elementary students' scientific reasoning and critical thinking. Furthermore, this study evaluates critical thinking using the RED framework, enabling a more focused assessment of students' abilities to recognize assumptions, evaluate arguments, and draw evidence-based conclusions. Based on constructivist learning theory, the principles of problem-based learning, and previous empirical findings regarding the educational benefits of AR, this study hypothesized that students receiving AR-assisted problem-based learning would demonstrate significantly higher critical thinking skills than students receiving conventional problem-based learning.

Practically, this research is expected to contribute to teachers, schools, and curriculum developers in designing more innovative, interactive, and student-centered science learning. The results are also expected to provide an alternative solution to address low critical thinking skills through the use of engaging and contextual digital technology. Furthermore, this research can serve as a reference for elementary schools in integrating Augmented Reality technology as a learning medium to create a more active, exploratory, and meaningful learning experience for students.

METHOD

Design and Intervention

This study employed a quasi-experimental research design using a non-equivalent pretest–posttest control group design. Two existing fifth-grade classrooms from the same elementary school were assigned as the experimental group (n = 32) and the control group (n = 30), without random assignment of individual students. Both groups participated in problem-based learning activities covering the same science topics on flora and fauna and were taught by the same teacher over an equivalent instructional period. The only distinction between the two groups was the integration of Augmented Reality (AR) into the learning activities of the experimental group, whereas the control group received the same problem-based learning without AR support. A total of 62 fifth-grade students participated in the study, comprising 39 girls and 23 boys, with an average age of approximately 11 years.

The experimental intervention integrated a researcher-developed mobile-based Augmented Reality (AR) application into problem-based learning (PBL) activities during elementary science instruction. The application operated through a smartphone camera to recognize predefined image markers and display three-dimensional digital objects, allowing students to observe scientific objects interactively and explore abstract concepts through realistic visualization.

The intervention was conducted over four instructional sessions covering the topics of flora, fauna, biological classification, and ecosystem relationships. Each session lasted 70 minutes (two instructional periods) and followed the same problem-based learning procedures. At the beginning of each lesson, the teacher presented a contextual scientific problem related to the learning topic to stimulate students' curiosity and activate their prior knowledge. Students were then organized into collaborative groups consisting of four to five members to investigate the problem through discussion, observation, and evidence-based reasoning. Throughout the learning process, the teacher acted as a facilitator by guiding discussions, encouraging students to justify their arguments, monitoring group investigations, and providing scaffolding whenever necessary rather than directly providing solutions.

Within the experimental group, AR was integrated during the investigation stage of the learning process. Students explored three-dimensional virtual representations by scanning printed image markers with their smartphones. During the first session, students investigated the characteristics of local flora and fauna. The second session focused on classifying plants according to their habitats by examining virtual representations of plant structures, including roots, stems, leaves, flowers, and fruits. In the third session, students compared herbivores, carnivores, and omnivores using interactive three-dimensional animal models to identify differences in feeding habits. The fourth session examined ecosystem relationships through AR-supported visualizations and interactive videos illustrating interactions among living organisms. At the end of each lesson, each group presented and defended its findings through classroom discussions before reflecting on the scientific evidence obtained during the investigation. These learning activities were intentionally designed to develop the three components of the RED critical thinking framework by encouraging students to recognize assumptions during problem identification, evaluate arguments through collaborative discussion, and draw evidence-based conclusions during presentations and reflections.

To ensure implementation fidelity and minimize potential confounding variables, both the experimental and control groups were taught by the same science teacher using standardized lesson plans throughout the intervention. Both groups followed the same problem-based learning model, studied identical learning objectives and instructional content, completed the same learning tasks, received the same instructional duration of 70 minutes (two instructional periods) in each session, and were assessed using identical evaluation procedures. The only difference between the two groups was the integration of the AR application during the investigation and exploration stages. While students in the experimental group explored scientific concepts through interactive three-dimensional visualizations, students in the control group completed the same learning activities using conventional instructional resources, including textbooks and two-dimensional illustrations, without AR support.

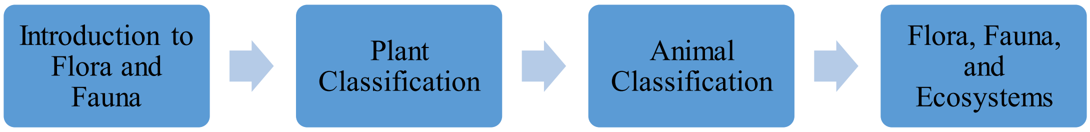

Figure 1. Learning Sequence During Intervention

Research Instruments

Students' science critical thinking skills were assessed using essay-based pretests and posttests developed according to the RED critical thinking framework proposed by Watson and Glaser (2012), which comprises three dimensions: Recognizing Assumptions (R), Evaluating Arguments (E), and Drawing Conclusions (D). The instrument consisted of three essay items, with each item intentionally designed to represent one dimension of the RED framework. This approach ensured that each critical thinking construct was assessed through an authentic open-ended task requiring students to analyze scientific situations, justify their reasoning, and formulate evidence-based conclusions rather than simply selecting predetermined responses. Furthermore, each essay item was evaluated using an analytic scoring rubric that assessed multiple aspects of students' reasoning performance within its corresponding RED dimension.

Although increasing the number of essay items may improve measurement precision, each item required students to produce relatively detailed written explanations and scientific reasoning. Considering the developmental characteristics, writing ability, and attention span of fifth-grade elementary school students, administering a larger number of essay questions could substantially increase testing time, cognitive fatigue, and response burden, potentially affecting the quality of students' responses. Therefore, the instrument was intentionally limited to three representative essay items to achieve an appropriate balance between construct representation and the practical constraints of classroom assessment in elementary schools.

Table 1. Results of Expert Agreement Analysis Using Cochran's Q Test

Type of Validation	Cochran's Q (p-value)	Interpretation
Content validity	0.08	Expert agreement achieved
Face validity	0.18	Expert agreement achieved

Prior to data collection, the instrument underwent face and content validation through expert judgment involving three validators, consisting of two science education experts and one language education expert. The science education experts evaluated the relevance, representativeness, and alignment of each item with the intended critical thinking constructs, whereas the language education expert assessed the clarity, readability, and linguistic appropriateness of the instrument. The consistency of the experts' evaluations was subsequently examined using Cochran's Q test. The results indicated no significant differences among the experts' judgments for either content validity ($p = 0.08$) or face validity ($p = 0.18$). Since both significance values exceeded 0.05, the experts demonstrated satisfactory agreement regarding the appropriateness of the instrument.

Following the expert review, all comments and suggestions provided by the validators were carefully incorporated to refine the wording, content, and presentation of the essay items. The revised instrument was then administered in a pilot study involving students with characteristics similar to those of the research participants to examine its psychometric properties. The pilot testing showed that the item validity coefficients ranged from 0.54 to 0.72, indicating acceptable to high item validity, while the overall reliability coefficient was 0.84, demonstrating high internal consistency. Based on these results, all three essay items were considered valid and reliable for assessing elementary school students' critical thinking skills in science learning.

Table 2. Science Critical Thinking Instruments

Dimensions/ item	Question	Validity coefficient	Reliability coefficient
R/ 1	Write the characteristics of the plant you observed, then explain how the plant can survive in its environment	0.63	
E/ 2	Write the type of food eaten by the animal you observed, then explain what might happen if the animal loses its food source	0.54	0.84
D/ 3	Write the relationship between plants, animals, and the environment in an ecosystem, then explain what might happen if one living thing in the ecosystem decreases or disappears	0.72	

The first question obtained a validity coefficient of 0.63, indicating that the item has a good level of validity in measuring students' ability to recognize assumptions. The second question obtained a validity coefficient of 0.54, which is in the moderately valid category and can still be used to measure students' ability to evaluate arguments. Meanwhile, the third question obtained a validity coefficient of 0.72, which is in the high category, making it very good for measuring students' ability to draw conclusions. Thus, all three questions are declared valid and can be used in research. The reliability coefficient of the instrument developed is0.84 is in the criteria of $0.80 < rxy \leq 1.00$ so it can be stated that this science critical thinking ability test instrument is very reliable.

The scoring guide used to assess students' critical thinking skills in flora and fauna material was adapted from Facione's (2009) critical thinking scoring guide. The assessment consists of three indicators: Recognizing Assumptions, Evaluating Arguments, and Drawing Conclusions (RED). Each indicator is scored on a scale of 0-4, with higher scores indicating better critical thinking skills. The Recognizing Assumptions indicator focuses on students' ability to write down important information from the given problem. The Evaluating Arguments indicator focuses on students' ability to write relevant and logical reasons or arguments based on observations of flora and fauna. Meanwhile, the Drawing Conclusions indicator assesses students' ability to write conclusions that are in accordance with the results of analysis or observations. A score of 0 is given if the student does not answer or the answer is inappropriate, while a score of 4 is given if the student's answer is complete, precise, logical, and systematic.

Table 3. Student Scoring Guidelines

Score	Recognizing Assumptions	Evaluating Arguments	Drawing Conclusions
4	Write important information accurately and completely	Writes logical, accurate, and complete arguments based on observations of flora and fauna	Writes clear, accurate, and appropriate conclusions based on the observations

Score	Recognizing Assumptions	Evaluating Arguments	Drawing Conclusions
3	Writes most of the important information, but it is not yet complete or systematic	Writes fairly accurate arguments, but they are not yet complete	Writes appropriate conclusions, but the explanation is incomplete
2	Write some important information about flora and fauna	Write simple arguments based on the available information	Writes fairly appropriate conclusions, but they are not complete
1	Writes information from the problem, but it is not accurate	Write opinions or arguments that are not yet relevant to the problem	Write conclusions that are less appropriate to the observation results
0	Does not write an answer or writes an inappropriate answer	Does not write relevant opinions or arguments	Does not write conclusions or writes incorrect conclusions

Data Analysis

The The collected data were analyzed using descriptive and inferential statistics with IBM SPSS Statistics. Descriptive statistics, including the mean and standard deviation, were computed to summarize students' critical thinking performance in both the experimental and control groups before and after the intervention. Although the subsequent inferential analysis employed non-parametric statistics, the mean and standard deviation were reported to facilitate comparison of students' learning outcomes and to maintain consistency with reporting practices commonly adopted in educational research. Prior to hypothesis testing, the assumptions for parametric analysis were examined. Data normality was assessed using the Shapiro–Wilk test because each group consisted of fewer than 50 participants, whereas homogeneity of variance was evaluated using Levene's test. These preliminary analyses were conducted to determine the most appropriate statistical procedure for hypothesis testing.

To examine the equivalence of students' initial critical thinking skills before the intervention, the pretest scores of the experimental and control groups were compared using an independent-samples t-test with a two-tailed significance level. A two-tailed test was selected because no directional difference between the two groups was assumed prior to the implementation of the intervention. Following the intervention, the posttest data did not fully satisfy the normality assumption. Therefore, differences between the experimental and control groups were analyzed using the Mann–Whitney U test. A one-tailed significance test was employed because the research hypothesis, established prior to data collection, explicitly predicted that students receiving AR-assisted problem-based learning would demonstrate higher critical thinking skills than those receiving conventional problem-based learning. Thus, the alternative hypothesis was directional, specifying superiority of the experimental group rather than merely the existence of a difference.

An alpha level of 0.05 was established a priori for all statistical analyses. In addition to hypothesis testing, the magnitude of the treatment effect was estimated using the effect size (r), calculated by dividing the standardized Z statistic by the square root of the total sample size. The effect size was interpreted according to Cohen's guidelines, with values of approximately 0.10, 0.30, and 0.50 representing small, medium, and large effects, respectively. Reporting both statistical significance and effect size provides a more comprehensive interpretation of the effectiveness of AR-assisted problem-based learning in improving elementary school students' critical thinking skills.

RESULTS AND DISCUSSION

Results

Based on the results of descriptive statistics, the critical thinking skills of students in both the experimental and control groups showed a change for the better after the learning process was implemented. In the experimental group, the average score shifted to a higher point, namely from 69.39 in the pretest stage to 81.72 in the posttest. This shift indicates that science learning assisted by Augmented Reality has a positive contribution to the development of students' critical thinking skills. In addition, the minimum score moved up from 50 to 65, while the maximum score increased from 80 to 95. This condition shows that the increase in critical thinking skills not only occurred in students with high abilities, but also experienced by students with low abilities. The median score also shifted from 70 to 80, while the mode moved from 75 to 80, indicating that most students achieved better achievements after the treatment was given. On the other hand, the standard deviation experienced a slight decrease from 8.06 to 7.99, indicating that the distribution of students' scores after the learning became more uniform or homogeneous.

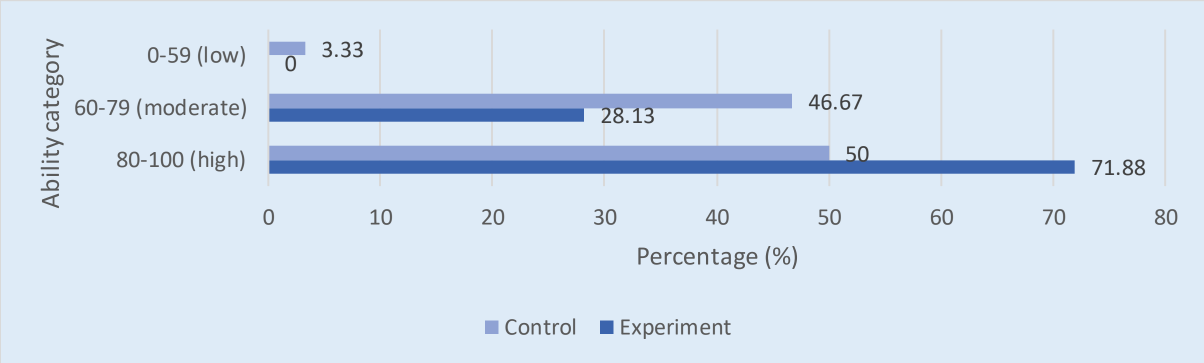

Figure 2. Distribution of Critical Thinking Ability Scores Based on Ability Categories

In the control group, students' critical thinking skills also showed a tendency to improve, although not as significantly as in the experimental group. The average score moved upwards from 69.17 in the pretest to 75.83 in the posttest. The maximum score increased from 85 to 90, while the minimum score remained at 55. This indicates that conventional learning can still encourage improvements in students' critical thinking skills, but the increase is not evenly distributed, especially for students with low abilities. The median in the control group shifted from 70 to 80, while the mode moved from 70 to 80, indicating that most students achieved better learning outcomes than before the learning. However, the standard deviation in the control group increased from 8.48 to 10.26. This increase indicates that the variation in students' abilities after the learning process became greater, so that the distribution of scores tended to be less homogeneous than before.

The distribution of critical thinking skills showed a difference in achievement between the experimental and control groups at the posttest stage. In the high category (80–100), the experimental group achieved a percentage of 71.88%, while the control group only achieved 50.00%. These results indicate that the majority of students in the experimental group successfully achieved high-level critical thinking skills after participating in science learning assisted by Augmented Reality.

In the medium category (60–79), the control group had a higher percentage, namely 46.67%, compared to the experimental group, which was 28.13%. This condition indicates that students in the control group were still mostly at the medium ability level, while in the experimental group there was a tendency for ability to shift towards the high category. Meanwhile, in the low category (0–59), the experimental group had no students in that category or 0%, while in the control group there were still 3.33% of students with low critical thinking skills.

Table 4. Descriptive Data on Science Critical Thinking Skills

Group	Phase	Min	Max	Mean	Median	Mode	Standard Deviation
Experimental	Pretest	50	80	69.39	70	75	8.06
	Posttest	65	95	81.72	80	80	7.99
Control	Pretest	55	85	69.17	70	70	8.48
	Posttest	55	90	75.83	80	80	10.26

Based on the results of Levene's homogeneity test, the significance value obtained for the pretest data was 0.944 and for the posttest data was 0.137. Both significance values are greater than 0.05, so the pretest and posttest data in the experimental and control groups are declared homogeneous. These results indicate that the variance or level of data distribution in both groups is relatively the same, both before and after the treatment is given. In other words, the abilities of students in the experimental and control groups have comparable levels of diversity, so the differences in results obtained are not influenced by differences in variance between groups.

In the pretest data, the very small Levene value indicates that the distribution of students' initial abilities in both groups was relatively similar before the learning was implemented. Meanwhile, in the posttest data, although the Levene value increased, the significance results still showed that the variance of both groups remained in the homogeneous category after the treatment was administered. This condition indicates that the learning process applied to the two groups did not cause significant differences in the distribution of data. Thus, the results of the homogeneity test show that the research data has met one of the prerequisites for statistical analysis and is therefore suitable for further hypothesis testing.

Table 5. Levene's Homogeneity Test

Data group	**Levene**	**Sig.**	**Criteria**
Pretest	0.005	0.944	Homogeneous
Posttests	2,271	0.137	Homogeneous

The results of the Shapiro–Wilk normality test showed that the research data had different distributions in each group. The significance value for the pretest of the experimental group was 0.013 and for the posttest of the control group was 0.035. Because both values were below 0.05, the data in both groups were declared not normally distributed. Meanwhile, the posttest data for the experimental group obtained a significance value of 0.162 and the pretest data for the control group was 0.128. Both values were greater than 0.05, so the data were declared normally distributed.

These findings indicate that not all data in the study met the assumption of normality. In the experimental group, the data distribution changed from an abnormal condition in the pretest to a normal condition in the posttest. This indicates a tendency for a more even distribution of scores after students participated in Augmented Reality-assisted learning. Conversely, in the control group, the data distribution changed from a normal condition in the pretest to an abnormal condition in the posttest, indicating that the distribution of student scores after learning was still uneven. Therefore, because some data did not meet the assumption of normality, hypothesis testing was continued using nonparametric Mann–Whitney analysis.

After the learning process was carried out, the posttest results showed a significance value of 0.005 (1-tailed). This value is smaller than 0.05, so H_0 is rejected. This result indicates that there is a difference in critical thinking skills between the experimental group and the control group after the treatment was given. Students who learned using Augmented Reality-assisted science learning achieved better results than students who learned using conventional methods. The Z value of -2.587 also shows that the difference in the results of the two groups after the learning process became more obvious.

Table 6. Data Normality Test

Statistic	**Group**			
	Experimental pretest	**Experimental posttest**	**Pretest control**	**Posttest control**
Shapiro-Wilk	0.912	0.952	0.945	0.925
Sig.	0.013	0.162	0.128	0.035
Interpretation	Non-normal	Normal	Normal	Non-normal

Furthermore, the effect size of 0.329 is considered moderate. This indicates that the use of Augmented Reality has a significant impact on improving students' critical thinking skills. Therefore, the use of AR in science learning not only makes a difference in learning outcomes but is also quite effective in helping students develop critical thinking skills in the flora and fauna topic.

Table 7. Intergroup Mean Difference Test

Data group	Mann-Whitney	Z	p-value	Decision	Effect size (r)
Pretest	463,500	-0.160	0.873 (2-tailed)	Accept H_0	0.329 (medium)
Posttest	312,500	-2,587	0.005 (1-tailed)	Reject H_0	

Discussion

The findings of this study provide evidence that integrating Augmented Reality (AR) into problem-based learning can facilitate the development of elementary school students' critical thinking skills in science. Students who participated in AR-assisted problem-based learning achieved significantly higher critical thinking scores than those receiving problem-based learning without AR ($p = 0.005$), with a moderate effect size ($r = 0.329$). This finding suggests that the integration of interactive visualization within a problem-based learning environment contributed meaningfully to students' ability to engage in scientific reasoning rather than merely improving learning performance statistically. From a constructivist perspective, the observed improvement can be explained by students' active involvement in constructing knowledge through exploration, observation, discussion, and reflection during the learning process (Steffe & Ulrich, 2020). Furthermore, these findings are consistent with Harel's (2008) Mental Action Theory, which posits that conceptual understanding develops through active mental actions rather than passive reception of information. In the present study, AR functioned not merely as a visualization medium but as a pedagogical tool that enabled students to observe scientific phenomena more concretely, relate visual evidence to contextual problems, and construct scientifically reasoned explanations. These learning experiences appear to have supported the development of students' critical thinking during science learning.

The observed improvement in students' critical thinking skills may be attributed to the complementary roles of problem-based learning and AR in supporting scientific inquiry. Problem-based learning encouraged students to identify authentic problems, discuss alternative explanations, and develop evidence-based solutions collaboratively, while AR enriched these processes by providing interactive three-dimensional representations that made abstract scientific concepts more observable and meaningful. During the investigation stage, students actively examined the characteristics of flora and fauna, compared visual evidence, and related their observations to the problems being discussed. These learning experiences required students to recognize underlying assumptions when interpreting visual information, evaluate alternative arguments during group discussions, and formulate evidence-based conclusions when presenting their findings. Consequently, the learning activities closely reflected the three dimensions of the RED critical thinking framework proposed by Watson & Glaser (2012). Rather than functioning solely as a visualization technology, AR appeared to scaffold students' reasoning processes by supporting observation, interpretation, and scientific argumentation throughout the problem-solving process.

The effectiveness of AR-assisted problem-based learning can also be understood from the perspective of how students construct scientific understanding through active interaction with learning objects. AR enables students to manipulate, observe, and examine three-dimensional representations of flora and fauna from multiple perspectives, thereby making abstract scientific concepts more accessible and meaningful (Pozzo et al., 2026). Such interactive experiences encourage students to connect visual observations with prior knowledge and contextual problems encountered during the learning process. According to Suryadi (2019), meaningful learning occurs when students actively engage in mental processes while constructing conceptual understanding rather than passively receiving information. This perspective is further supported by Harel's (2008) Mental Action Theory, which emphasizes that conceptual understanding emerges through mental actions generated during exploration, reasoning, and reflection. In the present study, AR appeared to facilitate these mental actions by allowing students to investigate scientific phenomena, discuss alternative interpretations, and justify their conclusions based on observable evidence. Therefore, the findings suggest that the educational value of AR lies not only in its capacity to enhance visualization but also in its ability to create learning experiences that stimulate scientific reasoning and knowledge construction through active cognitive engagement (Akbar et al., 2025; Wu et al., 2024).

The findings of this study are consistent with a growing body of research demonstrating the educational benefits of Augmented Reality in science learning. Previous studies have consistently reported that AR enhances students' engagement, conceptual understanding, and higher-order thinking by providing interactive and authentic learning experiences (Cufuna et al., 2025; Elford et al., 2022). Similarly, Kazlaris et al. (2025) argued that three-dimensional visualization enables students to comprehend abstract scientific concepts more effectively by transforming them into concrete learning experiences. Liikonen et al. (2026) further reported that AR contributes not only to conceptual understanding but also to the development of critical thinking skills and learning retention. Likewise, Zoya et al. (2026) found that students became more actively involved in exploring, analyzing, and interpreting information when AR was integrated into classroom instruction. The present findings extend this body of evidence by demonstrating that the educational value of AR is further strengthened when it is embedded within a problem-based learning environment. Rather than serving solely as an interactive visualization technology, AR functioned as a cognitive scaffold that supported students throughout the processes of observation, investigation, discussion, and evidence-based reasoning, thereby facilitating the development of critical thinking skills during elementary science learning.

Despite these consistent findings, the present study differs from several previous studies reporting that mobile AR primarily enhanced students' learning engagement rather than their critical thinking skills (Ivan & Maat, 2024; Syskowski et al., 2024). One possible explanation for this difference lies in the pedagogical integration of AR within the learning process. In many previous studies, AR was primarily employed as a visualization or presentation tool to improve students' interest and conceptual understanding. In contrast, the present study embedded AR within a problem-based learning environment that required students to investigate authentic problems, discuss alternative explanations, evaluate scientific evidence, and collaboratively construct solutions. Consequently, AR functioned not only as an interactive technology but also as a cognitive scaffold that supported inquiry, reasoning, and reflective thinking throughout the learning process. This interpretation is consistent with Adharini and Herman (2021), who argued that meaningful learning occurs when students actively construct knowledge through mental actions rather than passively receive information. Therefore, the findings suggest that the effectiveness of AR depends not only on the technology itself but also on how it is pedagogically integrated into meaningful learning activities that promote higher-order thinking.

The present findings have important implications for science teaching in elementary schools. Rather than being implemented merely as an instructional technology, AR should be integrated within pedagogically meaningful learning environments that actively engage students in scientific inquiry and reasoning. The findings suggest that combining AR with problem-based learning enables students not only to observe scientific phenomena more concretely but also to discuss evidence, evaluate alternative explanations, and construct reasoned conclusions collaboratively. Therefore, the educational value of AR depends largely on how teachers design learning experiences that promote active knowledge construction rather than on the technology itself. In practice, teachers should consider essential pedagogical aspects, including learning trajectories, students' prior knowledge, learning obstacles, and appropriate scaffolding strategies, to ensure that technology integration supports meaningful learning rather than simply increasing classroom engagement. These considerations reinforce the view that AR should be regarded as a pedagogical tool capable of supporting students' higher-order thinking when implemented within well-designed instructional activities.

Several limitations should be considered when interpreting the findings of this study. First, the intervention was conducted with a relatively small sample from a single elementary school, which may limit the generalizability of the findings to broader educational contexts. Second, the intervention consisted of only four instructional sessions, making it difficult to determine the long-term effects of AR-assisted problem-based learning on students' critical thinking development. Third, critical thinking was assessed using three essay items representing the RED framework, and although the instrument demonstrated satisfactory validity and reliability, a more comprehensive assessment may provide a richer representation of students' critical thinking performance. In addition, the use of identical pretest and posttest instruments may have introduced a testing effect, while students' first experience with AR may also have produced a novelty effect that influenced their engagement during learning. Therefore, future studies should involve larger and more diverse samples, implement longer intervention periods, employ more comprehensive critical thinking assessments, and include delayed posttests to examine the sustainability of learning outcomes. Further research may also investigate how different instructional designs, levels of teacher scaffolding, and science topics influence the effectiveness of AR-assisted problem-based learning in fostering elementary students' critical thinking skills.

CONCLUSION

This This study provides empirical evidence that integrating Augmented Reality (AR) into Problem-Based Learning (PBL) significantly enhances elementary school students' critical thinking skills in science. Students who participated in AR-assisted PBL achieved significantly higher critical thinking performance than those receiving the same problem-based learning without AR support, with a statistically significant difference ($p = 0.005$) and a moderate educational effect ($r = 0.329$). These findings indicate that the integration of interactive three-dimensional visualization within a problem-based learning environment creates meaningful learning experiences that facilitate students' abilities to recognize assumptions, evaluate arguments, and draw evidence-based conclusions.

The study contributes to the growing body of literature on technology-enhanced science education by demonstrating that the educational value of AR extends beyond improving conceptual understanding. When embedded within a problem-based learning environment, AR functions as a pedagogical scaffold that supports scientific inquiry, reasoning, and active knowledge construction. The use of the RED framework further provides more focused empirical evidence regarding the development of elementary students' critical thinking skills during science learning.

From a practical perspective, the findings suggest that teachers should integrate AR into well-designed inquiry-oriented learning activities rather than use it merely as a visualization technology. Effective implementation requires meaningful pedagogical planning, appropriate scaffolding, and active student engagement throughout the problem-solving process. Future research is encouraged to examine the long-term effectiveness of AR-assisted PBL across broader educational settings, different science topics, and larger, more diverse student populations.

RECOMMENDATION

The findings of this study have demonstrated the potential of Augmented Reality (AR) as a pedagogical tool for enhancing elementary school students’ critical thinking skills in science. Although the results are encouraging, the present study has several limitations. First, the experiment was conducted in a limited number of classrooms and over a relatively short intervention period. Second, the study involved students from urban communities who, in principle, were already familiar with and accustomed to interacting with technologies such as AR. Third, the integration of AR in this study was limited to science topics concerning flora and fauna. These limitations may restrict the extent to which the findings can be generalized to broader contexts.

Considering these limitations, several avenues for future research are recommended. Future studies could investigate the impact of AR on science learning using larger and more diverse samples, as well as longer intervention periods. Furthermore, the effectiveness of AR could be examined in learning contexts or subject matter beyond flora and fauna and among students from non-urban communities. In addition, the advantages offered by AR may be applicable to other educational fields, such as history education and arts education. Therefore, further exploration of AR in these areas is strongly recommended for future research.

We recommend that elementary school teachers, particularly those responsible for science instruction, utilize AR technology to create interactive, exploratory, and enjoyable learning experiences that foster students' science critical thinking skills. We also encourage school principals and educational authorities to provide the necessary support and infrastructure for the implementation of AR technology in schools. Furthermore, teachers should be given continuous opportunities to enhance their competence in using AR through workshops, professional development programs, and short courses.

ACKNOWLEDGMENTS
The authors would like to express their sincere gratitude to the principal, teachers, and fifth-grade students of the participating elementary school for their valuable cooperation, active participation, and support throughout the implementation of this research. The authors also gratefully acknowledge *Maga Institute* for facilitating the research collaboration, providing academic support, and fostering a collaborative research environment throughout the completion of this study. Their contributions were instrumental in the successful completion of this research.

FUNDING INFORMATION
This research received no external funding.

AUTHOR CONTRIBUTIONS STATEMENT

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Yuni Krisnawati	✓	✓		✓	✓	✓	✓	✓	✓	✓		✓	✓	
Sandra Arhesa		✓	✓						✓	✓				
Hos Arie Rhamadhan S	✓		✓	✓		✓	✓	✓		✓	✓	✓	✓	
Ady Akbar				✓	✓			✓			✓	✓		
Achmad Salido	✓		✓		✓	✓	✓				✓		✓	

CONFLICT OF INTEREST STATEMENT
The authors declare that they have no conflicts of interest regarding the publication of this study.

INFORMED CONSENT
We obtained approval from the relevant authorities prior to conducting this study. This approval included permission to carry out the research and authorization for the participation of individuals involved in the study.

ETHICAL APPROVAL
Research approval was obtained from the relevant educational authorities prior to the implementation of the study, while informed consent was obtained from all participants and/or their legal guardians before their involvement in the research activities.

DATA AVAILABILITY
The datasets generated and/or analyzed during the current study are available from the corresponding author upon reasonable request for legitimate scientific purposes.

REFERENCES

Adharini, D., & Herman, T. (2021). Didactical design of vectors in mathematics to develop creative thinking ability and self-confidence of Year 10 students. *Journal of Physics: Conference Series*, *1882*(1), 012089. https://doi.org/10.1088/1742-6596/1882/1/012089

Agustiningsih, E., Tobing, V. M. O. L., & Purnamasari, H. (2026). The Effect of Animated Video Learning Media on Students' Understanding and Independence in the Subject Science Lesson. *Prisma Sains : Jurnal Pengkajian Ilmu Dan Pembelajaran Matematika Dan IPA IKIP Mataram*, *14*(2), 555–569. https://doi.org/10.33394/j-ps.v14i2.19490

Akbar, A., Herman, T., Suryadi, D., Mursalim, ., Alman, ., Putra, E. D., & Blegur, J. (2025). Integrating Augmented Reality in Mathematics Learning to Improve Critical Thinking Skills of Elementary School Students. *Emerging Science Journal*, *9*(2), 764–779. https://doi.org/10.28991/ESJ-2025-09-02-014

Alkış-Küçükaydın, M. (2026). Science identity and critical thinking in primary school students: Serial mediating role of epistemic curiosity and need for cognition. *The Journal of Educational Research*, 1–10. https://doi.org/10.1080/00220671.2026.2628211

Arthi, M. P., & Gandhimathi, S. N. S. (2025). Research trends and network approach of critical thinking skills in English Language Teaching – A bibliometric analysis implementing R studio. *Heliyon*, *11*(2), e42080. https://doi.org/10.1016/j.heliyon.2025.e42080

Baki, N. U., Rafik-Galea, S., & Nimehchisalem, V. (2016). Malaysian Rural ESL Students Critical Thinking Literacy Level: A Case Study. *International Journal of Education and Literacy Studies*, *4*(4), 71–80. https://doi.org/10.7575/aiac.ijels.v.4n.4p.71

Barakah, N., Suyidno, S., & Mahtari, S. (2026). Effectiveness of a Web-Based Guided Inquiry Platform on Dynamic Fluid Material to Improve Students' Critical Thinking Skills. *Prisma Sains : Jurnal Pengkajian Ilmu Dan Pembelajaran Matematika Dan IPA IKIP Mataram*, *14*(2), 649–657. https://doi.org/10.33394/j-ps.v14i2.18129

Cai, S., Liu, E., Shen, Y., Liu, C., Li, S., & Shen, Y. (2020). Probability learning in mathematics using augmented reality: impact on student's learning gains and attitudes. *Interactive Learning Environments*, *28*(5), 560–573. https://doi.org/10.1080/10494820.2019.1696839

Comstock, G., & Grühn, D. (2026). Assessing critical thinking about argumentative essays: the Critical Reasoning and Inference Test (CRIT). *Assessment & Evaluation in Higher Education*, 1–14. https://doi.org/10.1080/02602938.2026.2653881

Coştu, F. (2025). Exploring augmented reality (AR) in science education: Perspectives from gifted students. *The Journal of Educational Research*, *118*(1), 19–36. https://doi.org/10.1080/00220671.2024.2431681

Cufuna, D. S. A., Rangel-de Lazaro, G., & Duart, J. M. (2025). Exploring the role of didactic strategies in the creation of augmented reality digital content by pre-service primary school teachers: A systematic literature review. *Journal of Digital Learning in Teacher Education*, *41*(2–3), 129–145. https://doi.org/10.1080/21532974.2025.2511600

Darwin, R. D., Mukminatien, N., Suryati, N., Laksmi, E. D., & Marzuki. (2024). Critical thinking in the AI era: An exploration of EFL students' perceptions, benefits, and limitations. *Cogent Education*, *11*(1). https://doi.org/10.1080/2331186X.2023.2290342

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

Encabo-Fernández, E., Albarracín-Vivo, D., & Jerez-Martínez, I. (2023). Evaluative research on the critical thinking of primary school students. *International Journal of Educational Research Open*, *4*, 100249. https://doi.org/10.1016/j.ijedro.2023.10024

Ennis, R. H. (1964). A definition of critical thinking. *The Reading Teacher*, *17*(8), 599–612.

Facione, P. A. (2009). Using the Holistic Critical Thinking Scoring Rubric to Train the Discovery of Evidence of Critical Thinking. *Insight Assessment, California Academic Press*, 1–5. https://www.insightassessment.com/wp-content/uploads/ia/pdf/Using-the-Holistic-Critical-Thinking-Scoring-Rubric-to-Train-Discovery-of-Evidence-of-Critical-Thinking.pdf

Fan, K., & See, B. H. (2022). How do Chinese students' critical thinking compare with other students?: A structured review of the existing evidence. *Thinking Skills and Creativity*, *46*, 101145. https://doi.org/10.1016/j.tsc.2022.101145

Harel, G. (2008). DNR perspective on mathematics curriculum and instruction, Part I: focus on proving. *ZDM*, *40*(3), 487–500. https://doi.org/10.1007/s11858-008-0104-1

Ilobinso, A., Lowell, V., White, S., & Jones, K. (2025). Impact of augmented reality-enhanced biological taxonomy instruction on students' knowledge gains and science motivation. *Journal of Research on Technology in Education*, 1–22. https://doi.org/10.1080/15391523.2025.2586526

Ivan, V., & Maat, S. M. (2024). The Usage of Augmented Reality Technology in Mathematics Education: A Systematic Literature Review. *International Journal of Academic Research in Progressive Education and Development*, *13*(1). https://doi.org/10.6007/IJARPED/v13-i1/20064

Jegstad, K. M., Heggernes, S. L., Jøsok, E., Ryen, E., Svanes, I. K., & Tørnby, H. (2025). Approaches to critical thinking in primary education classrooms: A systematic review. *Educational Research Review*, *48*, 100711. https://doi.org/10.1016/j.edurev.2025.100711

Kazlaris, G. C., Keramopoulos, E., Bratsas, C., & Kokkonis, G. (2025). Augmented Reality in Education Through Collaborative Learning: A Systematic Literature Review. *Multimodal Technologies and Interaction*, *9*(9), 94. https://doi.org/10.3390/mti9090094

Kirk, M., Tytler, R., & White, P. (2023). Critical thinking in primary science through a guided inquiry pedagogy: A semiotic perspective. *Teachers and Teaching*, *29*(6), 615–637. https://doi.org/10.1080/13540602.2023.2191181

Li, F., Wang, X., He, X., Cheng, L., & Wang, Y. (2023). How augmented reality affected academic achievement in K-12 education – a meta-analysis and thematic-analysis. *Interactive Learning Environments*, *31*(9), 5582–5600. https://doi.org/10.1080/10494820.2021.2012810

Liikonen, L., Erkkilä, A., Kamula, T., Honkanen, E., Liimatainen, K., Uhlgren, V.-V., Yrttimaa, T., Nummenmaa, T., Hamari, J., & Vastaranta, M. (2026). Augmented reality game mechanics influence the accuracy of crowdsourced LiDAR-based tree measurements. *Urban Forestry & Urban Greening*, *121*, 129466. https://doi.org/10.1016/j.ufug.2026.129466

Liu, L., & Shen, H. (2026). Fostering Critical Thinking Through STEM Undergraduate Research: Mechanisms and Challenges in a Chinese Research University. *Thinking Skills and Creativity*, *61*, 102173. https://doi.org/10.1016/j.tsc.2026.102173

Mohammadpour-Rozehkhani, Z., Sakian Mohamadi, H., Pouralvar, K., & Dadjoo, M. (2025). The effect of immersive technologies in the educational methods on the recall and recognition of sixth-grade students. *Interactive Technology and Smart Education*, *22*(3), 410–423. https://doi.org/10.1108/ITSE-12-2024-0329

Mullis, I. V. ., Martin, M. O., Foy, P., & Hopper, M. (2016). Timss 2015 International Results in Mathematics. In *TIMSS & PIRLS International Study Center*. http://timss2015.org/timss-2015/science/student-achievement/distribution-of-science-achievement/

Pozzo, V., Zanchetta-Balint, E., Benjoar, M.-D., Larcher, Q., Romano, G., & Lantieri, L. (2026). Microscope-integrated augmented reality for lymphaticovenous anastomosis: Improving identification, reproducibility, and efficiency control. *Journal of Plastic, Reconstructive & Aesthetic Surgery*, *117*, 219–221. https://doi.org/10.1016/j.bjps.2026.05.016

Prananta, A. W., Biroli, A., & Afifudin, M. (2024). Augmented Reality for Science Learning in the 21st Century: Systematic Literature Review. *Jurnal Penelitian Pendidikan IPA*, *10*(SpecialIssue), 38–44. https://doi.org/10.29303/jppipa.v10iSpecialIssue.8099

Rusli, R., Nalanda, D. A., Tarmidi, A. D. V., Suryaningrum, K. M., & Yunanda, R. (2023). Augmented reality for studying hands on the human body for elementary school students. *Procedia Computer Science*, *216*, 237–244. https://doi.org/10.1016/j.procs.2022.12.132

Salido, A., Sugiman, S., Firdaus, F. M., Prihatmojo, A., Herwanto, A., Yuni Andari, E., Wulandari, W. S., & Midani Rizki, L. (2025). Uncovering Critical Thinking and Mathematical Representation Skills of Pre-Service Elementary Teachers Through Cognitive Style. *Qubahan Academic Journal*, *5*(2), 188–203. https://doi.org/10.48161/qaj.v5n2a1505

Salido, A., Syarif, I., Sitepu, M. S., Suparjan, Wana, P. R., Taufika, R., & Melisa, R. (2025). Integrating critical thinking and artificial intelligence in higher education: A bibliometric and systematic review of skills and strategies. *Social Sciences & Humanities Open*, *12*, 101924. https://doi.org/10.1016/j.ssaho.2025.101924

Sari, F. I., Herlina, K., Rosidin, U., Distrik, I. W., & Festiana, I. (2026). Needs Analysis for Developing STEM-PjBL-Based Student Worksheets to Support Creative Problem Solving in Alternative Energy Learning. *Prisma Sains : Jurnal Pengkajian Ilmu Dan Pembelajaran Matematika Dan IPA IKIP Mataram*, *14*(2), 491–503. https://doi.org/10.33394/j-ps.v14i2.19051

Sari, R. M., Sumarmi, S., Astina, I. K., Utomo, D. H., & Ridhwan, R. (2021). Increasing Students Critical Thinking Skills and Learning Motivation Using Inquiry Mind Map. *International Journal of Emerging Technologies in Learning (IJET)*, *16*(03), 4. https://doi.org/10.3991/ijet.v16i03.16515

Siswati, B. H., Amalia, D. R., Kurniawan, A., & Naohiro, O. (2026). Gamified Inquiry-Based Learning to Enhance Critical Thinking in Biology Education. *Journal of College Science Teaching*, 1–14. https://doi.org/10.1080/0047231X.2026.2662021

Steffe, L. P., & Ulrich, C. (2020). Constructivist Teaching Experiment. In *Encyclopedia of Mathematics Education* (pp. 134–141). Springer International Publishing. https://doi.org/10.1007/978-3-030-15789-0_32

Suryadi, D. (2019). *Penelitian Desain Didaktis (DDR) dan Implementasinya*. Gapura Press.

Susanto, R., & Hapudin, M. S. (2024). Improving Primary School Students Critical Thinking Abilities with the Help of Online Media: Effective Learning Strategies in Elementary Schools. *Mimbar Sekolah Dasar*, *11*(2), 252–267. https://doi.org/10.53400/mimbar-sd.v11i2.71790

Syskowski, S., Wilfinger, S., & Huwer, J. (2024). Impact and Classification of Augmented Reality in Science Experiments in Teaching—A Review. *Education Sciences*, *14*(7), 760. https://doi.org/10.3390/educsci14070760

Watson, G., & Glaser, E. (2012). *Critical Thinking Appraisal User-Guide and Technical Manual*. Pearson Education.

Widaya, N. R., Istianah, F., & Prahani, B. K. (2026). Elementary School Students' Critical Thinking Skills Through Food Chain Learning Indicators. *Jurnal Cakrawala Pendas*, *12*(1), 141–147. https://doi.org/http://dx.doi.org/10.31949/jcp.v12i1.16472

Wiraha, M. A., & Sudarma, I. K. (2023). Augmented Reality-Oriented Problem-Based Learning in Natural Science Materials. *International Journal of Elementary Education*, *7*(3), 458–466. https://doi.org/10.23887/ijee.v7i3.60618

Wu, J., Jiang, H., Long, L., & Zhang, X. (2024). Effects of AR mathematical picture books on primary school students' geometric thinking, cognitive load and flow experience. *Education and Information Technologies*, *29*(18), 24627–24652. https://doi.org/10.1007/s10639-024-12768-y

Zhang, C., Zhou, Y., Wijaya, T. T., Chen, J., & Ning, Y. (2024). Effects of a problem posing instructional interventions on student learning outcomes: A three-level meta-analysis. *Thinking Skills and Creativity*, *53*, 101587. https://doi.org/10.1016/j.tsc.2024.101587

Zoya, K., A., E. P., Max, W., Christoph, H., Stefan, K., Jochen, K., & I., H. S. (2026). Exploring the role of conceptual knowledge and representational competence in an augmented reality physics environment. *Computers & Education*, *252*, 105658. https://doi.org/10.1016/j.compedu.2026.105658

Zuzano, F., Musdi, E., & Lufri, L. (2025). Designing a Hypothetical Learning Trajectory with Open-Ended Tasks: An Approach to Teaching Angle Measurement. *International Journal of Innovative Research and Scientific Studies*, *8*(3), 1563–1572. https://doi.org/10.53894/ijirss.v8i3.6837