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The Effectiveness of Augmented Reality in Improving Elementary School Students' Science Literacy: A Systematic Literature Review

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ABSTRACT

Science literacy among primary school pupils remains low, largely due to conventional teaching approaches and challenges in understanding abstract scientific concepts. Augmented Reality (AR) provides an interactive and engaging learning experience that helps make these concepts more concrete. Although numerous studies have highlighted the potential of AR in science education, systematic reviews examining its effectiveness in improving science literacy among primary school pupils are still limited. This study aims to analyze the effectiveness of AR in improving primary school pupils' science literacy, identify the characteristics of existing research, and examine the challenges of its implementation in learning. The study employed a Systematic Literature Review (SLR) method following the PRISMA guidelines. Data were obtained from the Google Scholar and Scopus databases for the period 2021–2025 using the keywords "Augmented Reality" and "science literacy" and "primary school". Inclusion criteria included research articles relevant to the topic, focusing on primary school pupils, available in full text, and indexed in Scopus or at least SINTA 3. Following the process of identifying, screening, and selecting articles, 10 articles that met the criteria were identified and systematically analyzed. Data were extracted using a pre-defined extraction form capturing details such as study design, AR type, sample characteristics, measured variables, and key findings. Subsequently, extracted data were synthesized using thematic analysis to identify recurring patterns, challenges, and optimal implementation strategies across the selected studies. The results indicate that AR is effective in improving students' science literacy by enhancing their understanding of scientific concepts, motivation and engagement in learning, scientific process skills, and 21st-century skills, which include critical thinking, creativity, collaboration, and communication (the 4Cs). Furthermore, the effect of AR tends to be more optimal when integrated with innovative learning models, such as inquiry-based and discovery learning. However, the implementation of AR still faces several challenges. These include limitations in technological facilities and teacher competence. Consequently, AR is a promising teaching tool for supporting the science literacy of primary school pupils and, as such, requires support in the form of adequate facilities and professional development for teachers.

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■ INTRODUCTION

Science education plays a strategic role in preparing students with crucial 21st-century skills, including critical thinking, problem-solving, and evidence-based decision-making (Saunders et al., 2025; Ewais & Troyer, 2019). One key competency that absolutely needs to be developed is scientific literacy, a skill encompassing an understanding of scientific concepts, the ability to interpret data, and the application of knowledge in everyday contexts (Huang et al., 2025; Zaini et al., 2025; Roy et al., 2025). Scientific literacy encompasses more than simply knowing scientific facts; it also includes the ability to use scientific knowledge, identify scientific questions, and draw evidence-based conclusions to understand and make decisions about science-based issues. This competency provides a crucial foundation for students to actively participate as informed citizens in an increasingly complex society dependent on science and technology.

However, various studies consistently indicate that elementary school students' scientific literacy skills in many regions remain low, ultimately leading to difficulties in understanding scientific concepts deeply and applying them to life (Gómez et al., 2024; Suwargiani et al., 2026; Abualrob, 2019; Setiawan et al., 2023). This is concerning given that elementary school is a fundamental period for instilling an initial understanding and positive attitudes toward science.

The issue of low scientific literacy is exacerbated by the often abstract nature of scientific materials, such as the solar system, atomic structure, the water cycle, or microscopic natural phenomena (Lan et al., 2021; Yang et al., 2026; Chang & Hwang, 2018; Krenn et al., 2022; Wulandari et al., 2025). For elementary school students, who are at the concrete operational stage of cognitive development, understanding these abstract concepts presents a significant challenge. According to Jean Piaget's theory of cognitive development, elementary school students are generally in the concrete operational stage (around 7-11 years of age). At this stage, their logical thinking skills have developed, but they still rely heavily on concrete objects and experiences that they can touch, see, and manipulate directly. Abstract scientific concepts, such as atomic structure, the water cycle, or the process of photosynthesis, become very difficult to understand without concrete visual and interactive representations. This limitation hinders the formation of deep conceptual understanding and often encourages students to learn by rote, rather than critical thinking and problem-solving. (Add relevant citations here, for example, Piaget himself or modern interpretations of his theory). Therefore, a learning approach that can bridge the gap between abstract concepts and concrete experiences is urgently needed. In this context, the three-dimensional visual interactions offered by AR become very relevant. AR allows students to 'see' and 'interact' with virtual models of abstract scientific phenomena as if they were real objects in their physical environment. This multisensory experience not only reduces the cognitive load in processing abstract information, but also facilitates the construction of stronger and more durable knowledge, in line with constructivist learning principles. Science learning practices in elementary schools are often dominated by conventional methods that are less interactive and tend to be teacher-centered, such as lectures or purely text-based learning. As a result, students tend to struggle to build meaningful conceptual understanding and often focus solely on memorizing facts without being able to connect them to reality (Ndruru et al., 2025). This condition results in learning being more oriented towards information transfer rather than developing thinking skills and in-depth understanding, which ultimately hinders the optimal development of students' scientific literacy (Purnawati & Yakin, 2025). Limited teaching aids, teachers' difficulties in simplifying abstract concepts, and the lack of authentic and engaging learning experiences also contribute to this problem.

With the rapid development of digital technology, Augmented Reality (AR) has emerged as a promising innovation with significant potential to revolutionize and improve the quality of science learning (Wen et al., 2023; Kuanbayeva et al., 2024; Osadchyi et al., 2021; Prasetya & Hidayati, 2024). AR enables the real-time integration of virtual objects into real-world environments, creating interactive, immersive, and context-rich learning experiences that transcend the limitations of traditional textbooks. The power of AR lies in its ability to transform abstract concepts into 3D visual representations that students can directly manipulate and explore (Chen et al., 2025; Fitrianto & Saif, 2024). For example, with AR, students can visualize the detailed structure of a plant cell on their desks, “hold” a rotating model of the solar system, or even “observe” the process of photosynthesis occurring in a leaf, as if the object were actually there in front of them. This approach is well suited to the learning characteristics of elementary school-aged children, who require concrete, multisensory experiences to build a strong understanding. AR offers the opportunity to bridge the gap between the real world and the digital world, allowing students to interact with learning content in ways never before possible. Recent research indicates that the use of AR in science education can effectively aid the visualization of abstract concepts, increase student engagement, and significantly enrich their conceptual understanding (Heshinta et al., 2026; Putra & Kaltsum, 2026; Ga et al., 2024). The interactive nature of AR not only stimulates students' cognitive aspects but also their affective aspects. Through engaging and game-like learning experiences, AR has been shown to increase students' motivation and develop their science process skills (Jiang et al., 2025; Lai et al., 2019; Savitri et al., 2019; Ziden et al., 2022; Rukayah et al., 2021; Dratsiou et al., 2024). The three-dimensional visualization and direct interaction offered by AR enable students to not only observe but also experiment and manipulate scientific phenomena in a more concrete and in-depth manner. This has positive implications for improving scientific literacy, particularly in the dimensions of conceptual understanding and scientific thinking skills, such as the ability to observe, classify, measure, infer, and communicate observation results. Furthermore, AR can support inquiry-based and discovery-based learning, where students become active agents in constructing their own knowledge, in accordance with the principles of constructivist learning (Aflahah & Wahyudi, 2026; Ndruru.

However, research into using AR to teach science still has several limitations. Most studies have been conducted in limited contexts and have employed a variety of research designs. Consequently, these studies do not offer a complete picture of the efficacy of AR as a whole. Furthermore, some studies emphasize improving learning outcomes in general without specifically examining the dimensions of scientific literacy affected. Existing literature reviews also tend to be narrative in nature and do not utilize a rigorous systematic approach, potentially introducing bias in the synthesis of findings. To address this gap and prevent potential biases in our own synthesis, this systematic literature review incorporates a rigorous risk of bias assessment. Specifically, we evaluated the methodological quality of the 10 included articles using the Mixed Methods Appraisal Tool (MMAT). By applying this standardized instrument, we validated the evidence and ensured that our conclusions are drawn from a robust and rigorously appraised foundation.

Based on these identified gaps and the promising potential of AR, a systematic, transparent, and structured study capable of synthesizing empirical evidence is imperative. This Systematic Literature Review (SLR) aims to analyze the effectiveness of Augmented Reality in improving scientific literacy in elementary school students. The novelty of this research lies in: (1) its specific focus on primary schools, (2) a comprehensive analysis of various dimensions of scientific literacy affected, and (3) identification of factors influencing the effectiveness of AR implementation in science learning. Thus, this study seeks to answer the following key questions:

RQ1: What are the main characteristics of existing research on the application of Augmented Reality in science learning in elementary schools?

RQ2: How effective is Augmented Reality in improving elementary school students' scientific literacy across its various dimensions?

RQ3: What are the challenges and implications associated with implementing Augmented Reality to improve scientific literacy in elementary education contexts?

■ METHOD

Research Design

This study employed a Systematic Literature Review (SLR) approach, adhering to the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines to ensure that the processes of identifying, screening, and synthesizing articles are carried out systematically (Avella et al., 2016; Syawaludin & Rintayati, 2019). This study aims to analyze the effectiveness of Augmented Reality in improving primary school pupils' science literacy and to identify opportunities for further research. Data were obtained through a search of the Google Scholar and Scopus databases conducted in April 2026.

Search Strategy

The search strategy was tailored to the characteristics of each database. In Scopus, the search was conducted using Boolean operators with the search string: ('Augmented Reality') AND ('Science Literacy') AND ('Elementary School'), applied to the titles, abstracts, and keywords of the articles. Meanwhile, on Google Scholar, the search was conducted via the Advanced Search feature using the keyword phrases "Augmented Reality", "science literacy", and "elementary school", and limiting the publication year range to 2021–2025. To minimize irrelevant results (noise), articles were filtered based on the relevance of the title, abstract, and research focus to science literacy among primary school pupils

Subsequently, articles were selected based on inclusion and exclusion criteria covering topic relevance, type of research article, journal indexing, research subject, and year of publication. The inclusion criteria comprised articles discussing the use of Augmented Reality in science learning among primary school pupils, published between 2021 and 2025, available in full text, and published in journals indexed in Scopus or at least SINTA 3. Articles that did not meet these criteria were excluded from the analysis process.

The articles reviewed in this study were obtained through searches of Google Scholar and Scopus databases. The initial search was conducted using the keyword "Augmented Reality," which yielded various articles and scientific publications. The search was then limited to publication years from 2021 to 2025 to obtain relevant and up-to-date literature. To narrow and enrich the scope of the study, a further search was conducted by adding the keywords “science literacy” and “elementary school,” thus obtaining articles relevant to the research focus.

The search results were then further filtered by applying several criteria: the articles had to be scientific papers, published in journals indexed in SINTA 1–3 or Scopus, have an adequate citation count, and be relevant to the topic. Augmented Reality’s effect on improving science literacy among primary school pupils. Books, conference proceedings, theses, and non-article sources were excluded from the selection process. After applying the inclusion and exclusion criteria and completing the filtering stage in accordance with the PRISMA flowchart, ten articles were identified as the most relevant for analysis and served as the basis for this study; these are presented in the PRISMA flowchart.

Data Analysis

Based on PRISMA, a search on May 15, 2026, using the Google Scholar database and the keyword “Augmented Reality” with publication years 2021–2025 yielded a total of 292,000 articles. The initial large number of results 292,000 was filtered in stages using Google Scholar's advanced search feature. This figure represents the initial number of hits for the single keyword 'Augmented Reality' within a specified timeframe. Subsequently, adding the keyword 'scientific literacy' within the advanced search feature drastically reduced the number of results to 297 articles. The addition of a third keyword, 'elementary school', further narrowed the scope to 120 articles. This initial filtering process was conducted directly within the Google Scholar platform, utilizing its built-in Boolean search capabilities. While software such as Publish or Perish is often used for large-scale metadata extraction, in this study, we relied on Google Scholar's step-by-step filtering to achieve a more manageable number of hits before manual screening. This ensured that our search remained focused on the combination of all three keywords simultaneously from the outset, although the results are presented sequentially to account for data attrition. Furthermore, the addition of the keyword “scientific literacy” resulted in 297 articles, and the keyword “elementary school” resulted in 120 articles. Of the 120 articles, the selection criteria were based on the following: relevant scientific articles indexed in Scopus or at least SINTA 3. After going through the screening process according to the PRISMA process, 10 articles were deemed suitable and used as sources of analysis in this study.

During the eligibility phase, a more in-depth selection process was carried out to review the articles that passed the first screening. 110 articles were excluded during this stage based on systematic and strict exclusion criteria. Some did not fit the research focus, as these studies did not specifically address science literacy, but merely highlighted general learning outcomes or aspects of technology use without a direct link to science literacy. Furthermore, several articles were excluded because the educational level studied was not relevant to the focus of this study, namely secondary or tertiary education.

Furthermore, exclusions were also made for articles with research designs that did not meet standards, such as opinion articles, non-systematic literature reviews, proceedings, or studies that did not present clear empirical data. In terms of publication quality, several articles were excluded because they were not indexed in reputable databases such as Scopus or at least SINTA 3. Furthermore, some articles were eliminated because they did not adequately explain the validity of the instruments or data collection methods, potentially introducing bias into the research results.

Following this rigorous selection process, 10 articles that met all criteria for inclusion and were deemed suitable for further analysis in this study were identified. Combining articles from the Scopus database (Q1, Q3, Q4) and SINTA 2-3 requires special attention to potential differences in methodological and reporting quality. To address this, we assessed the methodological quality of all ten included articles using the Mixed Methods Appraisal Tool (MMAT), as mentioned in the Introduction. The results of this MMAT assessment served as the basis for critically evaluating the findings of each article.

Although this study is a Systematic Literature Review and not a quantitative meta-analysis that allows for formal statistical comparisons using software such as RevMan, we recognize the importance of reviewing potential differences in reporting quality between international (Scopus) and national (SINTA) journals. In synthesizing the findings, we carefully considered the MMAT scores and the strength of the evidence presented by articles from each journal category. If there are significant differences in research rigor or clarity of reporting between Scopus and SINTA 3 articles, these will be discussed qualitatively in the Discussion section to inform the interpretation of the results. For example, we would note if articles from Scopus Q1/Q3/Q4

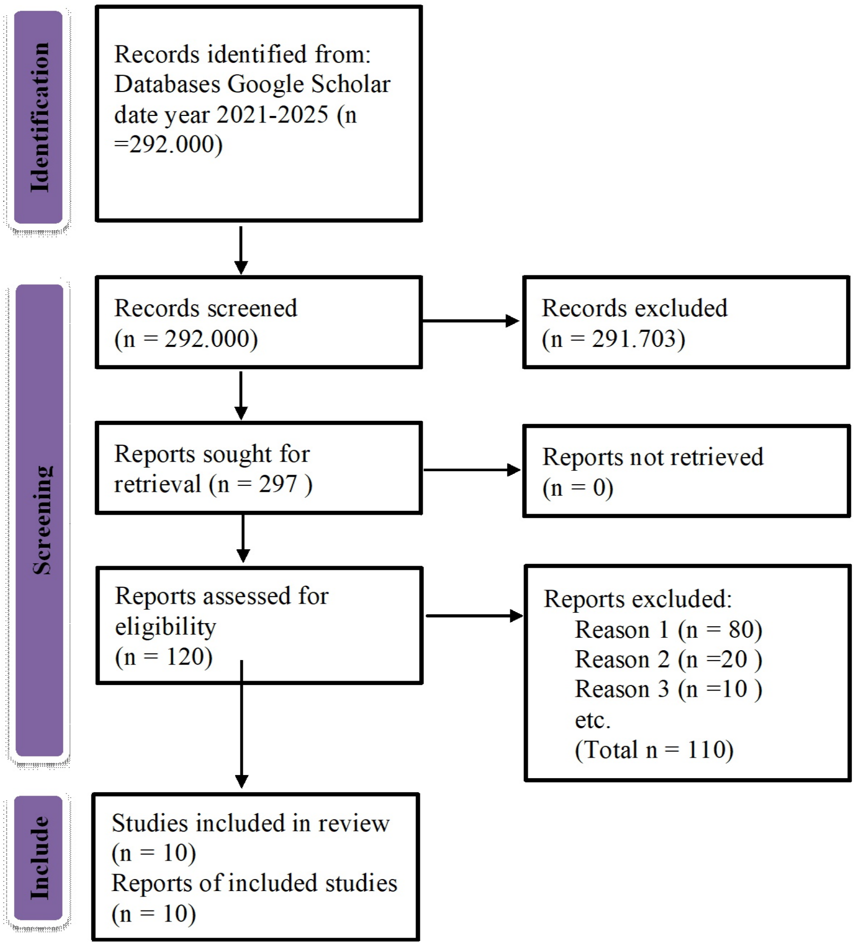

Figure 1. Inclusion and exclusion process

journals tended to present more robust research designs or more comprehensive measures of scientific literacy compared to articles from SINTA 3 journals.

For future research, or if more detailed quantitative data (such as effect sizes and standardized risk of bias indicators) are available from individual studies, quantitative subgroup analysis using meta-analysis software would be invaluable for empirically examining differences in reporting quality between journal types.

■ RESULTS AND DISCUSSION

The findings of the review indicate that research into the use of Augmented Reality (AR) to improve science literacy among primary school pupils has developed rapidly over the past five years. In addition to demonstrating the effectiveness of AR in supporting conceptual understanding, learning motivation and scientific process skills, various studies also indicate a growing interest among academics in this topic. The trend in the number of publications analyzed for the period 2021–2025 is presented in Figure 2.

Based on Figure 2, the development of articles in 2021–2025 shows an increasing trend in the number of publications from year to year. In 2021, the number of articles was relatively low at 5, then increased to 16 in 2022. The increase occurred again in 2023 and 2024, with 30 articles. The peak occurred in 2025, with 39 articles published. Thus, 2025 was the year with the highest number of publications on the topic of increased effectiveness of AR in boosting science literacy among primary school pupils. Furthermore, the mean number of articles published over the past five years was calculated to determine the trend in the development of literature on this topic on the Google Scholar platform. Furthermore, the percentage of articles discussing the effectiveness of augmented reality in increasing science literacy among primary school pupils is shown in Figure 2.

Based on the percentage diagram of cited articles on the research topic from 2021 to 2025, differences in publication contributions are evident each year. In 2021, there were 5

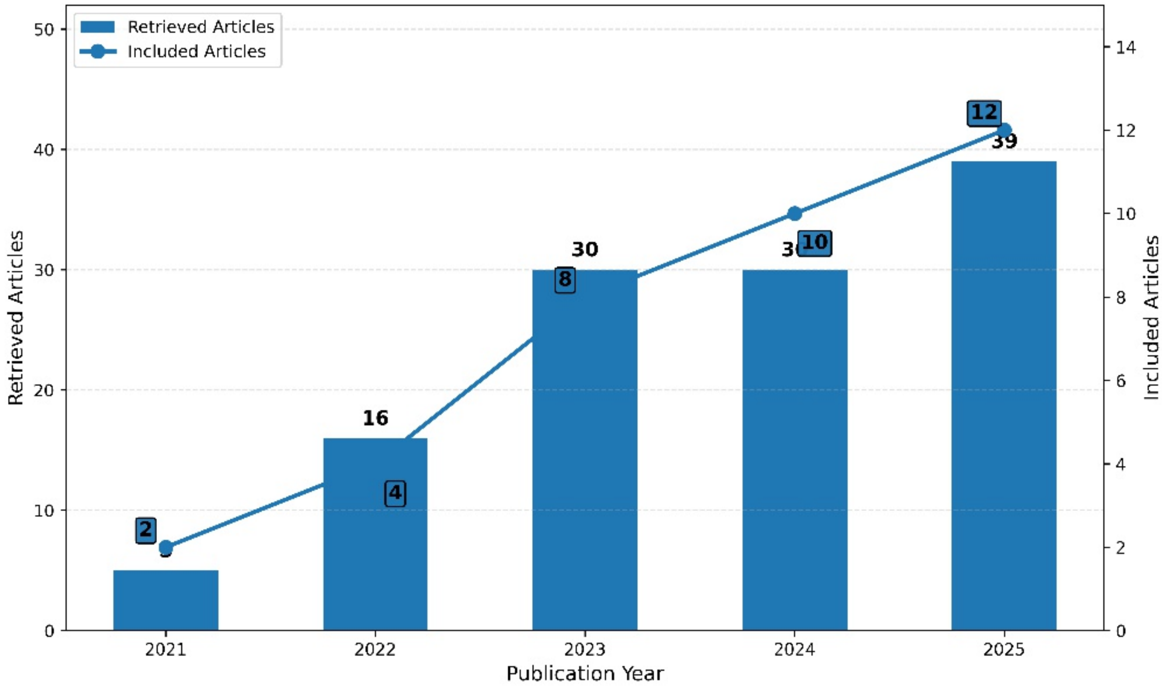

Figure 2. Percentage of article development from 2021-2025

articles, or approximately 4% of the total; then in 2022, this figure increased to 16 articles, or approximately 13%. Furthermore, in 2023, this figure increased to 30 articles, representing a 25% increase. The same number also occurred in 2024, with 30 articles, or approximately 25%. Meanwhile, in 2025, the number of articles reached 39 publications, representing 33% of the total, the highest number during that period. Overall, these data indicate a growing trend in research interest in examining Augmented Reality's effectiveness in boosting science literacy among primary school pupils.

In line with this increasing publication trend, this study focused on the articles most relevant to the research topic. Using the SLR process, a systematic screening process was conducted to identify 10 articles that met the inclusion and eligibility criteria for further analysis. The results were presented in a table to provide a concise and structured overview, as shown in Table 1.

Based on a rigorous selection process and analysis of the 10 articles included in this study (as presented in Table 1), several common characteristics were identified that reflect the trends and focus of research related to Augmented Reality (AR) in improving elementary school students' scientific literacy. Consistently, all articles examined the effectiveness or development of AR as a learning medium for elementary school students, particularly in science subjects.

In terms of methodology, the majority of studies, such as those by Rahmah & Maarif (2025), Setiawan et al. (2025), Firdaus et al. (2024), Minsih et al. (2025), and Marini et al., (2022), are AR-based media development studies, which attempt to create and test AR prototypes or products for science learning. Several other studies, Revalestina & Suwono (2025), Ismail et al. (2025), and Anggara et al., focus more on investigating the impact of AR, either independently or integrated with specific learning models such as discovery learning or inquiry. Additionally, one systematic review of virtual learning environments (Mafarja, 2025) and one review of media and teaching approaches for scientific literacy (Dian et al., 2024) provide a broader perspective on this topic.

The science materials tested varied, ranging from specific topics such as photosynthesis, fungi, and biological cells, to more general science concepts, demonstrating the flexibility of AR across a wide range of curriculum content. These articles were published in a variety of journals, including accredited national journals (SINTA 2 and SINTA 3) and reputable international journals (Scopus Q1, Q3, and Q4), indicating that research in this area is attracting attention from the scientific community at various levels. All included articles are also highly recent publications, with publication dates ranging from 2022 to 2025, reflecting the relevance and

Table 1. Results of analysis on the effectiveness of augmented reality in improving elementary school students' science literacy

No.	Article Title Journal	Status Research	Methodology AR	Type (Media) Main	Variables Measured	MMAT Score
1	Development of Fotar (Photosynthesis Augmented Reality) Learning Media to Improve Science Literacy Skills in Elementary School Students (Rahmah & Maarif, 2025)	Sinta 3	Developmental Research & Quasi-Experiments	AR App	Science Literacy Skills (photosynthesis topic)	80%
2	Developing Augmented Reality-Based Flashcards to Enhance Science Literacy in Elementary Schools (Setiawan et al., 2025)	Sinta 3	Developmental Research & Quasi-Experiments	AR-Based Flash Cards (Marker-based)	Conceptual Understanding, Learning Interest	80%
3	The study of AR-based learning for natural science inquiry activities in Taiwan's elementary school from the perspective of sustainable development (Lo et al., 2021)	Q1	Mixed Methods / Quasi-Experimental Research	AR-Based Inquiry Learning System (Mobile Augmented Reality)	Inquiry Skills, Learning Achievement, Environmental Awareness, Sustainable Development Competencies	100%
4	The Effect of Augmented Reality-Assisted Discovery Learning Model on Digital Literacy and Cognitive Knowledge About Fungi (Revalestina & Suwono, 2025)	Sinta 2	Quasi-Experiment	AR App	Digital Literacy	80%
5	The Development of E-Flipbook Multirepresentative Augmented Reality In Biology Cells to Enhance Technology Literacy and Student Learning Outcomes (Firdaus et al., 2024)	Q4	Quasi-Experiment	AR-Based E-Flipbook	Technology Literacy, Learning Outcomes	80%
6	Scientific Literacy in Science Instruction: Media and Teaching Approach Employed (Dian et al., 2024)	Sinta 2	Quasi-Experiment	AR App	Scientific Literacy	80%
7	AR-Enhanced Inquiry Learning in Elementary Science:	Q3	Quasi-Experiment	AR App	4C Skills (CT, Creativity, Collaboration, Communication),	80%

	Developing Students' 4C Skills (Ismail et al., 2025)				Science Understanding	
8	Development of Augmented Reality Learning Media to Increase Elementary School Students' Scientific Literacy Ability (Minsih et al., 2025)	Q4	Quasi-Experiment	AR App	Scientific Literacy	80%
9	Augmented Reality: Its Effect on Satisfaction and Interest in Learning Natural Science for Elementary School Children (Anggara et al., 2024)	Q3	Quasi-Experiment	AR App	Learning Satisfaction, Interest in Learning Science	80%
10	Mobile Augmented Reality Learning Media with Metaverse to Improve Student Learning Outcomes in Science Class (Marini et al., 2022)	Q3	Quasi-Experiment	AR App	Student Learning Outcomes	80%

urgency of this topic in contemporary educational research.

Effectiveness of Augmented Reality in Improving Elementary School Students' Scientific Literacy

Mapping of AR types and science literacy dimensions

To provide a more comprehensive synthesis of the reviewed studies, a matrix analysis was conducted to identify the relationship between AR types and the dimensions of science literacy affected by their implementation. The results are presented in Table 3. The matrix analysis reveals that conceptual understanding is the most consistently reported outcome across all AR types. Mobile AR and AR integrated with discovery learning show the strongest contribution to conceptual understanding, while AR combined with inquiry learning demonstrates broader impacts on science process skills and 4C competencies. Meanwhile, AR-based e-flipbooks primarily contribute to students' digital literacy. These findings suggest that the educational benefits of AR are influenced not only by technological features but also by the pedagogical approaches accompanying its implementation.

Effectiveness profile of AR across science literacy dimensions

To further examine the effectiveness of AR, the dimensions of science literacy reported in the reviewed studies were quantified based on the proportion of articles reporting positive

Table 2. MMAT analysis

No	Study	MMAT Criteria Met	MMAT Score
1	Rahmah & Maarif (2025)	4/5	80
2	Setiawan et al. (2025)	4/5	80
3	Lo et al. (2021)	5/5	100
4	Revalestina & Suwono (2025)	4/5	80
5	Firdaus et al. (2024)	4/5	80
6	Dian et al. (2024)	4/5	80
7	Ismail et al. (2025)	4/5	80
8	Minsih et al. (2025)	4/5	80
9	Anggara et al. (2024)	4/5	80
10	Marini et al. (2022)	4/5	80

Table 3. Mapping of ar types and science literacy dimensions

AR Type	Concept Understanding	Motivation & Interest	Science Process Skills	4C Skills	Digital Literacy
Marker-Based AR (Flashcards)	✓✓	✓✓	–	–	–
Mobile AR	✓✓✓	✓	✓✓	–	✓
AR + Inquiry Learning	✓✓	✓	✓✓✓	✓✓✓	✓
AR + Discovery Learning	✓✓✓	✓	✓✓	✓	✓✓
AR-Based E-Flipbook	✓	–	–	–	✓✓✓

Note: ✓ indicates positive effects reported in one study; ✓✓ indicates positive effects reported in two studies; ✓✓✓ indicates positive effects reported in three or more studies

impacts. Figure 3 presents the effectiveness profile of AR across different dimensions of science literacy.

The results indicate that conceptual understanding is the dominant outcome of AR implementation, appearing in 80% of the reviewed studies. Digital literacy was reported in 30% of the studies, whereas motivation, learning interest, and science process skills each appeared in 20% of the articles. The least frequently reported outcome was the development of 4C skills (10%). This pattern suggests that current AR research in primary science education remains largely focused on improving students' conceptual understanding, while affective, procedural, and higher-order competencies have received comparatively less attention.

Conceptual framework of AR effectiveness in science literacy learning

Based on the synthesis of the ten reviewed studies, a conceptual framework was developed to explain how AR contributes to the improvement of science literacy among primary school students.

The conceptual framework illustrates that AR features, such as three-dimensional visualization, interactivity, immersion, and real-time feedback, influence students' cognitive processing, motivation, engagement, and knowledge construction. These mediating variables subsequently affect multiple dimensions of science literacy, including conceptual understanding, science process skills, digital literacy, 4C skills, and learning interest. The effectiveness of AR is further

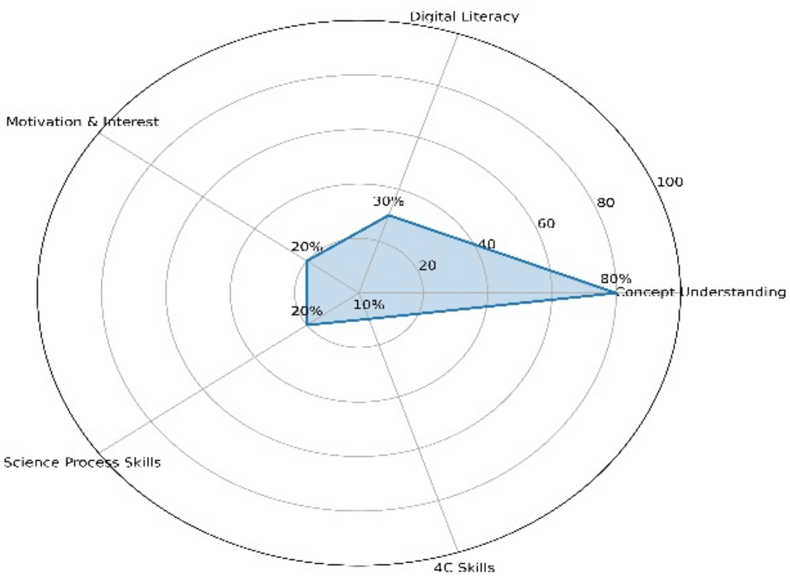

Figure 3. Effectiveness profile of ar across different dimensions of science literacy

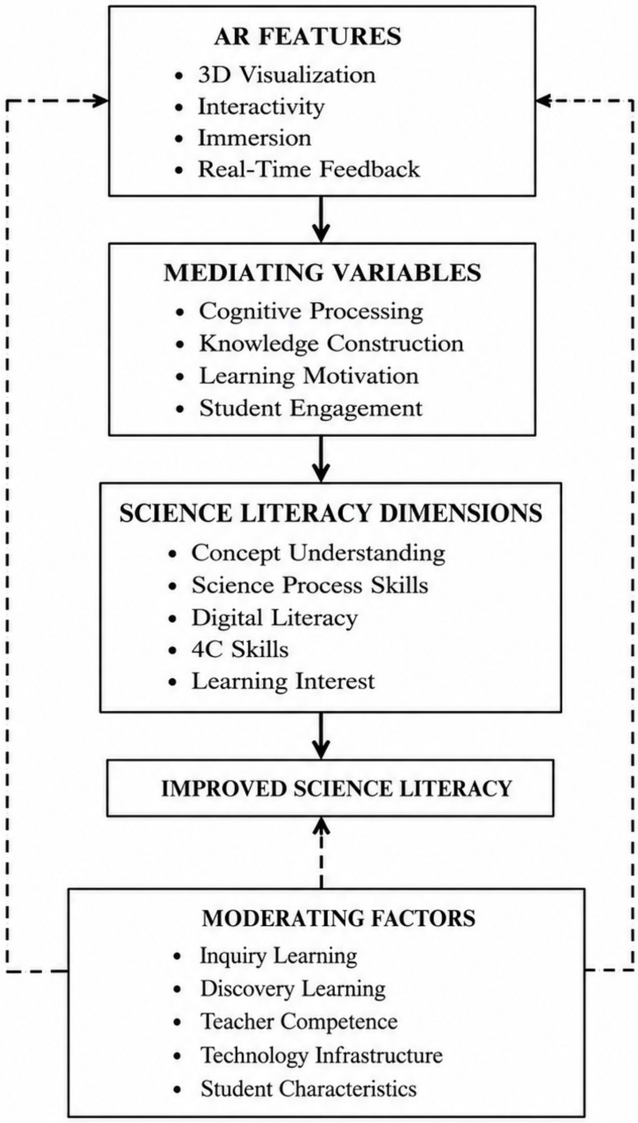

Figure 4. Conceptual framework of ar effectiveness in science literacy learning

moderated by contextual factors such as learning models, teacher competence, technological infrastructure, and student characteristics. Therefore, the successful implementation of AR depends not only on technological affordances but also on the pedagogical and environmental conditions in which the technology is used.

Improving understanding of science concepts through interactive visualization

Augmented Reality (AR) has consistently proven effective in bridging the gap between abstract scientific concepts and the concrete understanding of primary school pupils. The common thread running through the various studies analyzed indicates that the effectiveness of AR lies not only in its ability to display three-dimensional (3D) objects, but also in its ability to create active and multimodal learning experiences. Through interactive visualization, pupils can observe, rotate, and explore objects directly, making previously abstract concepts easier to mentally represent. (2025), Minsih et al. (2025), and Lo et al. (2021) demonstrate that interaction with virtual objects enhances science literacy because students receive information not only verbally but also through concrete visual representations. These findings are reinforced by Setiawan et al. (2025), who developed AR-based flashcards to link virtual objects with the real environment

Cognitively, interactive AR visualizations help reduce students' cognitive load when understanding complex concepts by presenting information in a more structured and easily comprehensible manner. Furthermore, the combination of visual information, text, and direct interaction supports the dual-coding process, making it easier for information to be stored and recalled in long-term memory. These characteristics are particularly relevant for primary school pupils who are still at the concrete operational stage, where learning is more effective when supported by objects and experiences that can be observed directly. Thus, the literature review indicates that the success of AR in enhancing science literacy stems not only from its technological aspects but also from its ability to support the processes of knowledge construction and memory retention through concrete, interactive, and meaningful learning experiences.

Impact of AR on students' motivation, interest, and affective skills

In addition to affecting cognitive aspects, the analyzed literature indicates that Augmented Reality (AR) also makes a positive contribution to motivational and psychological factors in science learning. Anggara et al. (2024) found that the use of AR significantly increased students' learning satisfaction and interest in science subjects. This increased interest is closely linked to the level of student engagement in the learning process. In line with these findings, Setiawan et al. (2025) reported that the use of AR-based flashcards was able to increase the learning interest of primary school pupils, which in turn led to a strengthening of conceptual understanding. These findings suggest that interactive and engaging learning experiences through AR can boost learning motivation, foster curiosity, and help maintain students' attention on the material being studied. With increased student motivation and engagement, the learning process becomes more meaningful and has the potential to support the improvement of science literacy more effectively.

Developing science process skills and 21st-century skills

In addition to enhancing conceptual understanding and motivation to learn, AR also contributes to the development of various skills that support learning. In the context of digital literacy, (2024) demonstrate that AR-based e-flipbooks can improve students' technological literacy, whilst Revalestina & Suwono (2025) found that the integration of AR with the discovery learning model not only enhances cognitive knowledge but also students' digital literacy. These findings indicate that AR can help students interact more effectively with digital technology in the learning process.

Meanwhile, Ismail et al. (2025) reported that AR-assisted inquiry-based learning contributes to the development of primary school pupils' 4C skills. However, these findings should be interpreted with caution, as the measurement of all 4C aspects was conducted within a single research context and does not indicate that each skill develops at the same rate. Given the characteristics of AR that enable exploration, manipulation of virtual objects, and independent investigation of phenomena, the aspects most strongly influenced appear to be critical thinking and creativity. Conversely, collaboration and communication skills are likely to be influenced more by the design of learning activities, such as group discussions or inquiry-based activities, than by the AR technology itself. Thus, the literature review suggests that the primary contribution of AR lies in strengthening higher-order thinking skills and digital literacy, whilst the development of other 4C skills is highly dependent on the pedagogical strategies accompanying its use.

Integrating AR with innovative learning models

The findings of the study indicate that the effectiveness of Augmented Reality (AR) is significantly influenced by the accompanying learning model (Dian et al., 2024). From the articles analyzed, the two approaches most frequently combined with AR are discovery learning and inquiry learning. Revalestina & Suwono (2025) found that integrating AR with discovery learning is effective in enhancing students' conceptual understanding and digital literacy. In this model, AR functions as a means of exploration that helps students discover concepts independently through observation and interaction with virtual objects. Meanwhile, Ismail et al. (2025) reported that the use of AR in inquiry-based learning not only supports conceptual understanding but also contributes to the development of critical thinking, problem-solving, and scientific process skills.

By comparison, discovery learning appears to be more effective in helping students build conceptual understanding, as AR provides visual representations that facilitate the process of discovering concepts. Conversely, inquiry-based learning provides students with greater scope to ask questions, investigate phenomena, test hypotheses, and draw conclusions based on evidence obtained through interaction with AR. Therefore, the inquiry model has the potential to have a stronger impact on the dimensions of scientific literacy related to scientific reasoning and higher-order thinking skills.

Nevertheless, the number of studies directly comparing the two models remains very limited; therefore, it cannot yet be conclusively stated that inquiry-based learning is superior to discovery-based learning when combined with AR. A review of the literature suggests that the successful implementation of AR depends not only on the technology used, but also on the extent to which the learning model is able to utilize AR's visualization, exploration, and interactivity features to support students' knowledge construction process.

■ CONCLUSION

Based on the findings of a systematic literature review of 10 selected articles, Augmented Reality (AR) shows strong potential as a learning medium to support the improvement of science literacy among primary school pupils. Most of the studies analyzed reported that AR helps pupils understand abstract scientific concepts through interactive visualization, increases interest and motivation to learn, and supports the development of critical thinking skills and digital literacy. The findings also suggest that the effectiveness of AR tends to be more optimal when combined with active learning models, such as inquiry-based learning and discovery learning. However, these results must be interpreted with caution as there remains variation in research design, implementation context, and the measurement instruments used in the reviewed studies. Therefore, although AR shows promising prospects, further research with stronger methodologies is required to confirm its effectiveness more broadly.

The effectiveness of AR tends to be optimized when combined with active learning models, such as inquiry-based learning and discovery learning. However, several studies indicate that the implementation of AR is still hampered by limitations in digital devices, internet access, and teachers' competence in integrating technology into teaching. Therefore, the development of AR resources should focus on applications that are lightweight, user-friendly, and can be run on smartphones or tablets commonly available in primary schools. Furthermore, teacher training should be directed towards the use of AR in learning activities that encourage exploration and problem-solving. In this way, the implementation of AR can be carried out more effectively and in line with the conditions of primary schools.

■ DECLARATION OF ARTIFICIAL INTELLIGENCE USE

The authors used several Artificial Intelligence (AI)-based tools during the preparation of this manuscript. ChatGPT (OpenAI) and Gemini (Google) were utilized to assist with idea development, paraphrasing, language refinement, and improving the clarity of academic writing. In addition, Google Translate was used to support translation and language checking. All outputs generated by these AI tools were carefully reviewed, verified, and edited by the authors. The authors take full responsibility for the content, interpretation, analysis, and conclusions presented in this manuscript. AI tools were used solely to support the writing and language-editing process and were not used to generate, analyze, or interpret the research data.

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