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Augmented Reality in Elementary Science Education: A Systematic Review of Inquiry-Based Learning, Challenges, and Opportunities

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ABSTRACT

Digital transformation in education demands learning innovations that can increase student engagement and understanding in a more interactive manner. In the context of science learning in elementary schools, integrating Augmented Reality (AR) into Inquiry-Based Learning (IBL) is a potential approach to support the visualization of abstract concepts and exploration-based learning activities. This study aims to analyze research trends, implementation challenges, and opportunities for AR integration in inquiry-based science learning in elementary schools using a Systematic Literature Review (SLR). The study was conducted in accordance with the PRISMA 2020 protocol for articles published between 2021 and 2025. The initial search process yielded 424 articles from the Scopus and Google Scholar databases. These were then selected based on inclusion and exclusion criteria, resulting in 10 final articles, which were analyzed using a qualitative thematic analysis approach. The results show that AR integration in IBL can improve learning motivation, conceptual understanding, and 21st-century skills of elementary school students, especially critical thinking, creativity, collaboration, and communication. In addition, AR has been proven to support every stage of inquiry learning, from orientation and conceptualization to investigation and discussion, culminating in a conclusion, through interactive visualization and a more immersive learning experience. However, the implementation of AR still faces various challenges, such as limited infrastructure, device readiness, teacher competency, and the potential to increase students' cognitive load if instructional design is not appropriate. This study confirms that the success of AR integration in inquiry-based science learning is determined not only by technological sophistication but also by the suitability of the pedagogical design to the characteristics of elementary school students. Therefore, continuous teacher training, the development of more intuitive AR applications, and adequate infrastructure support are needed to optimize the implementation of AR in elementary education.

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■ INTRODUCTION

The digital transformation in education demands pedagogical innovation that positions students as active subjects in independently constructing knowledge. In this context, the Inquiry-Based Learning (IBL) approach remains the gold standard for fostering students' independent learning and critical thinking skills (Aditomo & Klieme, 2021; Pedaste et al., 2024). However, the implementation of inquiry in science materials is often hampered by the abstract nature of the material. The integration of immersive technologies, such as Augmented Reality (AR), has emerged as a crucial means of visualizing these concepts in elementary schools through a 21st-century interactive digital medium (Apostoleas et al., 2022; Wen, Lai, et al., 2023).

This pedagogical barrier is particularly evident in the Solar System, where students are required to understand the mechanisms of celestial body motion, the cosmic distance scale, and eclipse phenomena, which are impossible to physically demonstrate in the classroom (Parmadi et al., 2023; Sukma et al., 2024). Cognitively, elementary school students are still at the concrete operational stage, requiring concrete visual representations to construct understanding (Aolia et al., 2025; Imanulhaq & Ichsan, 2022; Syafawani & Safari, 2024). This gap between the "invisible" nature of matter and the need for concrete visualization often leads to poor conceptual understanding and underdeveloped students' abilities in scientific exploration (Chen et al., 2025; Sati et al., 2024).

Augmented Reality (AR) technology emerged as a means to overlay three-dimensional virtual objects onto real-world environments in real time. (Bicen & Ozer, 2023; Mystakidis, 2022) . AR does not merely function as a digital teaching aid but as an instrument that bridges the gap between theoretical concepts and real-world sensory experiences (Afrina et al., 2021; Ibáñez & Delgado-Kloos, 2021). AR's potential is highly relevant to the spirit of Indonesia's *Merdeka* Curriculum, which emphasizes digital literacy and student-centered learning. Through AR, macroscopic phenomena such as the movement of planets in the Solar System can be presented precisely in the classroom, making them more concrete and easier for elementary school students to internalize.

In line with technological innovation, the Inquiry-Based Learning (IBL) approach remains the gold standard in science education because it positions students as active agents in scientific inquiry. The integration of AR within an IBL framework theoretically offers powerful synergy by providing rich visual scaffolding. This allows students to engage in safe yet challenging virtual explorations of materials that are difficult to observe directly. Thus, AR not only enhances visualization but also deepens scientific discovery and facilitates the construction of more meaningful knowledge in the digital age (Apostoleas et al., 2022; Su et al., 2024).

Recent developments in science education research indicate that immersive learning technologies are increasingly important in supporting meaningful learning experiences for elementary school students. The integration of digital media into inquiry-based learning enables students to engage with scientific concepts more actively and in context. (Hinostroza et al., 2024) stated that digital technology integrated into inquiry-based learning environments can facilitate exploratory activities, increase student engagement, and support collaborative problem-solving processes. Similarly, Su et al. (2024) explained that Augmented Reality-assisted inquiry learning creates virtual exploration experiences that encourage students to build scientific understanding through direct interaction with three-dimensional representations. These findings indicate that immersive technology no longer functions merely as a supplementary learning medium but has evolved into a strategic pedagogical instrument in science learning in elementary schools.

Despite its great educational potential, the implementation of Augmented Reality in elementary school environments still faces significant pedagogical and infrastructural challenges. Okoye et al. (2023) emphasized that unequal access to digital infrastructure, limited technological resources, and low teacher preparedness remain major obstacles to implementing educational technology in various developing educational contexts. Furthermore, Apostoleas et al. (2022) highlighted that effective AR implementation requires appropriate scaffolding strategies to maintain students' cognitive focus during the inquiry process. Without a well-thought-out learning design, immersive technology can increase students' cognitive load and reduce learning effectiveness. Therefore, a more comprehensive study is needed to examine how AR can be systematically integrated into inquiry-based science learning while accounting for the technical and pedagogical limitations in the elementary school context.

Despite the exponential increase in publications on immersive technology, the existing literature remains fragmented. Previous studies have been dominated by partial assessments of AR's effectiveness at the secondary and tertiary levels (Li et al., 2025; Zhang et al., 2022) and have focused primarily on product development, without delving into its comprehensive pedagogical implications. To date, systematic reviews specifically examining AR integration within an IBL framework at the elementary school level remain limited, particularly those mapping its impact on specific, abstract materials in the post-pandemic era.

Given the limitations and fragmentation of the holistic literature, this study aims to fill this significant gap by presenting a comprehensive *Systematic Literature Review* (SLR). The novelty of this study lies in its in-depth analysis, which not only maps trends in AR integration in inquiry-based science learning at the elementary school level over the past five years (2021-2025), but also specifically dissects the functionality of AR technology based on each stage in the syntax of the inquiry learning model. Furthermore, this SLR will synthesize the literature to identify and connect systemic barriers, such as teacher readiness and infrastructure, with strategic opportunities for AR in supporting the inquiry process. This review is expected to provide theoretical contributions and an evidence-based strategic foundation for practitioners and developers of innovative science learning in the digital era.

Based on the research gaps and literature fragmentation that have been identified, this Systematic Literature Review research is focused on answering the following research questions (RQ):

RQ1. What are the trends and characteristics of research on the integration of Augmented Reality in inquiry-based science learning in elementary schools in the 2021–2025 period?

RQ2. What are the technical and pedagogical challenges reported in implementing Augmented Reality integrated inquiry-based learning in science learning in elementary schools?

RQ3. What strategic opportunities and recommendations can be identified from the literature related to optimizing the use of Augmented Reality in inquiry-based science learning on abstract science material in elementary schools?

■ METHOD

This employed the *Systematic Literature Review* (SLR) method to ensure transparent, unbiased identification, evaluation, and extraction of the literature (Haddaway et al., 2022; Paul et al., 2021). All manuscript selection procedures were carried out in accordance with the updated PRISMA 2020 protocol to maintain reporting quality and ensure high replicability for future researchers (Haddaway et al., 2022; Zhufeng & Sitthiworachart, 2024).

Data obtained from selected articles were analyzed using a qualitative thematic analysis approach. Prior to the analysis, researchers compiled a synthesis matrix in Microsoft Excel to systematically organize key variables from each article, including year of publication, research methodology, stages of inquiry learning, type of Augmented Reality technology, learning outcomes, technical challenges, and pedagogical implications. The thematic analysis process was carried out through repeated reading of selected articles, identifying and coding relevant findings, grouping similar codes into broader themes, and compiling a narrative synthesis to answer the formulated research questions (Byrne, 2022).

Literature Search Strategy

Data were collected through a systematic search of two major electronic databases: Scopus and Google Scholar. Scopus was selected to capture high-quality global literature that had undergone rigorous peer review. Google Scholar was used as a supplementary database to broaden the scope of the literature, including the latest research and national publications relevant to primary education.

The search strategy was designed using a combination of Boolean keywords to optimize the relevance and coverage of results (Paul et al., 2021). In the Scopus database, the search string applied was as follows: ("augmented reality" OR "AR") AND ("inquiry" OR "inquiry-based learning" OR "inquiry learning") AND ("elementary school" OR "primary school" OR "grade school") AND ("science education" OR "science" OR "IPA"). ("inquiry" OR "inquiry learning") AND ("elementary school" OR "primary school") AND ("science" OR "IPA"). It should be noted that Boolean operators in Google Scholar operate slightly differently and are often implicit, but the use of key phrases remains crucial for relevance.

The literature search was conducted in April 2026 through both databases. Although the search was conducted until April 2026, the inclusion period was limited to publications from 2021 to 2025 to ensure the analysis was based on a full, indexed, and complete five-year search, thus providing a more stable and comprehensive picture of trends. In the Scopus database, the search was limited to journal articles published between 2021 and 2025. Given the Google Scholar algorithm's tendency to generate very large volumes of metadata, the researchers limited the analysis to the first 300 articles, sorted by relevance. This restriction aims to ensure a focus on high-quality literature and to avoid less relevant gray literature, in line with the methodological standards of Systematic Literature Reviews (SLR) (Haddaway et al., 2022).

Publications from early 2026 were excluded from the analysis to avoid partial-year bias, as studies published in the first months of the year may not yet represent a complete or stable body of research. Limiting the inclusion period to 2021–2025 ensures that all selected studies have undergone a full publication cycle and are more likely to have consistent indexing, citation, and accessibility status. This approach improves the comparability and stability of the dataset within a Systematic Literature Review.

To address potential concerns regarding the use of Google Scholar, several steps were taken to enhance the transparency and reliability of the search process. The literature search was conducted using standardized keywords, without logging into a personal account, and in incognito mode to minimize the influence of personalization factors such as search history, geographic location, and user-specific algorithms. In addition, the selection of the first 300 articles was used as an initial filtering strategy rather than a definitive dataset. The subsequent screening process was strictly guided by predefined inclusion and exclusion criteria, ensuring that only relevant and eligible studies were included in the final analysis. Therefore, although the exact search results may vary across users and time, the overall methodological procedure remains transparent, consistent, and reproducible in principle.

Article Selection Criteria

To ensure the focus and methodological rigor of the literature analyzed, strict selection criteria were applied throughout the review process. The inclusion criteria required that: (1) the publication type consisted of peer-reviewed scientific articles published in reputable indexed journals or conference proceedings; (2) the main topic explicitly discussed the integration of Augmented Reality (AR) in learning; (3) the learning context focused on Natural Sciences (IPA), Science, or STEM fields with a strong science component; (4) the pedagogical approach employed inquiry-based learning or experiential learning that emphasized students' active involvement in the discovery process; (5) the participants primarily consisted of elementary school students (SD/Primary School/K–6). However, studies involving broader educational levels (e.g., K–12) were also included, provided that the research context was relevant to elementary education or that the findings could be meaningfully applied to primary school learning environments; (6) the methodological quality of the studies was primarily assessed using the Mixed Methods Appraisal Tool (MMAT) developed by Hong et al. (2018), which is designed for evaluating qualitative, quantitative, and mixed-method studies. For studies employing Research and Development (R&D) designs, additional evaluation criteria were applied, focusing on the clarity of the development model, the validation process, and the feasibility of the developed product. This complementary approach ensured that all included studies met acceptable methodological quality standards despite differences in research design; and (7) the publications were published between 2021 and 2025 and written in English or Indonesian.

Furthermore, the quality appraisal process was conducted to ensure the methodological rigor and relevance of the selected studies. The MMAT was considered appropriate because the included articles employed diverse research designs, including quantitative, qualitative, mixed-methods, and research and development approaches. Only studies that met acceptable methodological quality standards were included in the final analysis.

On the other hand, exclusion criteria were applied to: (1) publication types in the form of non-systematic reviews, editorials, opinion papers, books, book chapters, theses/ dissertations that had not been published in indexed journals or proceedings, research reports, or posters; (2) studies that did not clearly discuss the integration of AR and inquiry-based learning simultaneously or were not relevant to science learning in elementary schools; (3) studies conducted outside the elementary school context; (4) articles that did not meet the minimum methodological quality criteria based on the MMAT assessment, including unclear research procedures, insufficient data validity, or weak alignment between findings and conclusions; and (5) publications that did not meet the specified time span and language requirements.

Article Selection Process

This study employed the Systematic Literature Review (SLR) method following the PRISMA 2020 protocol to ensure transparency in the literature selection process. The manuscript selection process began with an identification process that yielded a total of 424 articles from the Scopus databases (n=124) and Google Scholar (n=300). During the pre-screening stage, 84 articles were removed before the main screening process due to duplication (n=64) and metadata errors (n=20).

The next stage was the screening process, where the remaining 340 articles were selected based on their titles and abstracts. Of these, 295 articles were excluded because they did not align with the research focus. Next, in the eligibility stage, 45 full manuscripts were further analyzed. From this stage, 35 articles were excluded because the research subjects were outside the elementary school level (n=15), did not implement an inquiry-based learning model (n=10), and had inadequate research results reports (n=10). In the final stage, 10 articles met all criteria and were included in the synthesis.

The article screening process was conducted independently by two researchers to minimize potential selection bias. The screening process involved examining the titles, abstracts, and full texts of the articles against established inclusion and exclusion criteria. If there were differences of opinion regarding an article's eligibility, the two researchers discussed the matter until a mutual agreement was reached. This process was implemented to improve the consistency and reliability of article selection in systematic

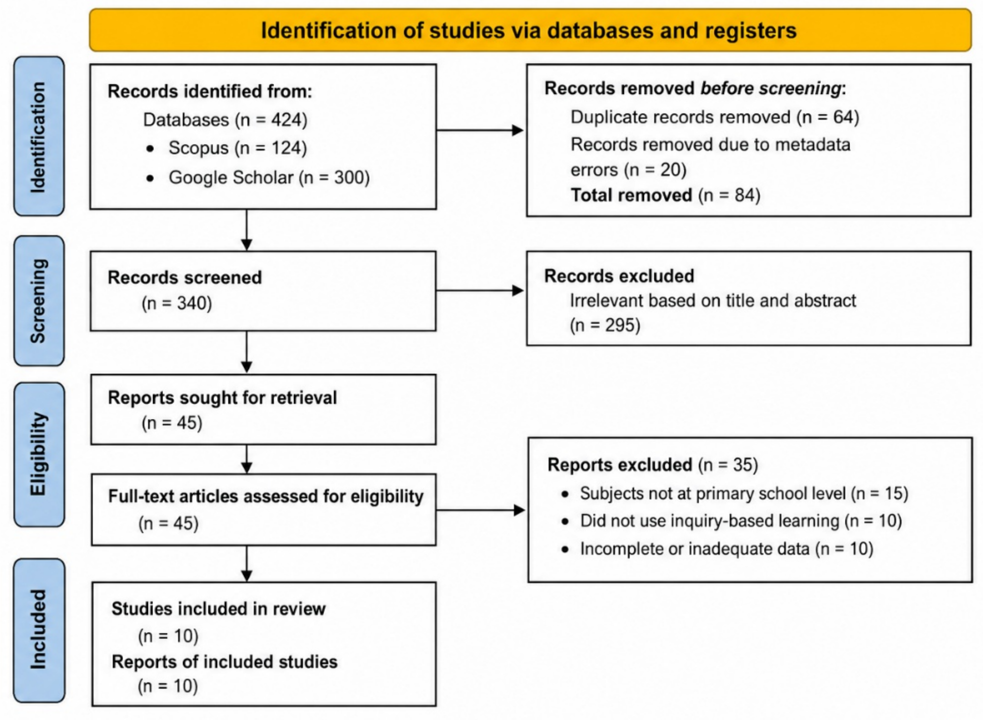


Figure 1. Stages of the article selection process in systematic literature review

literature reviews.

Although the final number of articles included in this study was only 10, this number is considered representative because the research topic has a very specific focus: the integration of Augmented Reality in inquiry-based science learning at the elementary school level. In addition, the selection process was conducted strictly using focused inclusion and exclusion criteria, ensuring that only articles that are truly relevant and meet methodological quality standards are retained in the final synthesis. In Systematic Literature Review research, the quality and relevance of the studies analyzed are prioritized over the number of articles retrieved.

Data Analysis

The extracted data were analyzed using a qualitative thematic analysis approach. This approach was used to identify patterns, themes, and relationships among findings from the selected articles. During data extraction, researchers identified and recorded several key variables from each selected article. These variables included the year of publication, the country of study, the research design, the type of *Augmented Reality technology* used, the stages of *Inquiry-Based Learning* implemented, the science learning materials, the learning outcomes obtained, the technical challenges in implementation, and the pedagogical implications reported in the study. All data were then organized into a synthesis matrix to facilitate grouping themes and thematic analysis.

1. Data Familiarization: Repeatedly reading all extracted data to gain a thorough understanding.
2. Initial Coding: Identifying and coding data segments that are interesting or relevant to the research objectives.
3. Theme Search: Grouping similar or related codes into potential themes.
4. Theme Review: Review themes to ensure internal and external consistency, and relevance to the rest of the data.
5. Defining and Naming Themes: Provide a clear definition and representative name for each theme.
6. Report Preparation: Narrate the findings of each theme with supporting evidence from the included literature.

This thematic analysis will specifically be directed to answer the three research objectives formulated in the introduction, namely: (1) identifying research trends and characteristics, (2) analyzing the main challenges in implementing AR integration in IBL in elementary schools, and (3) exploring opportunities and providing strategic recommendations. In addition, the analysis will explore how AR functions and supports each stage of the inquiry learning model's syntax. Narrative synthesis will be used to integrate findings from various studies, identify consistencies, differences, and remaining knowledge gaps, and provide comprehensive theoretical and practical contributions.

■ RESULT AND DISCUSSION

The results of a literature search related to the research topic in the Google Scholar database provide a more comprehensive understanding of the research findings, presented in tables, graphs, charts, and diagrams. The publication of articles relevant to this topic shows annual developments from 2021 to 2025.

After presenting the publication trends from 2021 to 2025, this study further analyzed the selected articles in line with the research objectives and thematic patterns identified in the literature. Based on the inclusion and exclusion criteria, 10 articles met the methodological quality and relevance standards and were included in the final review process (see Table 1).

Table 1. Research design, participants, AR implementation context, and major findings of the selected studies

No	Author & Year	Methodology	Participants	AR Integration Focus	Main Findings
1	Wen, Lai, et al., 2023 .	Quantitative (Quasi-Experimental)	Elementary school students	AR-based inquiry learning	AR significantly influenced stud epistemic beliefs and encour dynamic views of scier knowledge.
2	Jiang et al., 2025 .	Bibliometric Analysis & Systematic Review	K–12 students	VR/AR-supported STEM learning	AR usage in K–12 incre significantly, although challe related to devices and tea readiness remained prominent.
3	Wen, Wu, et al., 2023 .	Mixed Methods	Fifth-grade elementary students	AR-integrated inquiry framework (QIMS)	AR integration improved stud self-directed learning and cre thinking skills.
4	Cai et al., 2022 .	Exploratory Case Study	Elementary school students	AR learning environment for sound concepts	AR facilitated students' understan of abstract scientific concepts increased their motivation to learn
5	Lo et al., 2021 .	Quantitative (Survey & Test)	Elementary school students	AR-based natural science inquiry activities	AR increased students' interest participation in inquiry-based sci learning.
6	Ismail & Isrokatun, 2025	Quantitative (Pre-test & Post-test)	Elementary school students	AR-enhanced inquiry learning	AR integration effectively devel students' 4C skills in science inc learning.
7	G. Chen et al., 2025	Mixed Methods	Elementary school students	AR-based experiential learning	AR transformed students from pas observers into active participants improved learning behaviors.
8	Arkan et al., 2023	Research and Development (R&D)	Elementary school students	AR for human anatomy learning	AR-supported visualization anatomical concepts that are diff to understand through textbooks al
9	Wen & He, 2025	Qualitative Instructional Design	Elementary school context	AR learning and motivational design	Teacher facilitation and instructi design were important factors in successful implementation of AR.
10	Muhabib et al., 2025	Research and Development (ADDIE Model)	Sixth-grade elementary students	AR-based solar system learning media	AR media proved highly effectiv improving students' understandin solar system concepts.

To provide a more systematic synthesis, the findings are organized into three main themes: (1) the effectiveness of AR integration in inquiry-based science learning at the elementary school level, (2) challenges and limitations in AR implementation, and (3) pedagogical and technological characteristics of AR-supported inquiry learning environments. Table 1 presents an overview of the characteristics of the selected studies, including research design, participants, AR implementation context, and major findings.

To enhance the interpretation of the synthesized data, several visualizations were developed based on the included studies (Figure 2). The bar chart illustrates the distribution of research methodologies, showing a dominance of quantitative approaches. The Sankey diagram shows the distribution of studies by grade level, indicating that most research focuses on upper elementary grades.

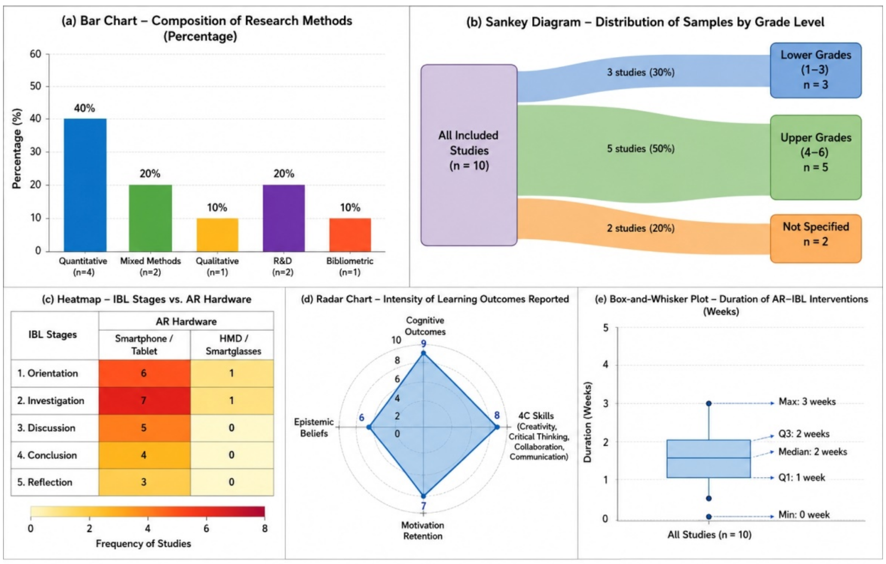
The heatmap highlights the relationship between inquiry-based learning stages and AR hardware usage, with smartphones and tablets being the most commonly used devices. The radar chart emphasizes cognitive outcomes and 4C skills, while epistemic beliefs and motivational aspects are reported only to a moderate extent. Finally, the box-and-whisker plot shows that most interventions are conducted within a relatively short duration, typically ranging from one to three weeks.

This study aims to analyze the trends, challenges, opportunities, and functionality of Augmented Reality (AR) integration in inquiry-based science learning in elementary schools through a systematic literature review. The synthesis of the 10 included articles provides a comprehensive overview of the research landscape in this field and identifies crucial areas for future development.

RQ1. Research Trends and Characteristics

In the initial version of this study, publication trends were described based on the total number of records identified during the preliminary search stage. However, this approach does not align with the principles of Systematic Literature Review (SLR), in which trend analysis must be based on the final set of studies that meet all inclusion and eligibility criteria. Therefore, in this revised version, the analysis of research trends has been refined to focus exclusively on the 10 articles included in the final synthesis. This ensures that the interpretation of trends reflects only validated and relevant studies, thereby strengthening the methodological rigor and validity of the findings. Based on the included studies, several patterns can be identified in research focus, methodological approaches, and the integration of Augmented Reality into inquiry-based science learning at the elementary level.

The results of the publication trend analysis indicate a high and fluctuating research interest in AR integration in inquiry-based science learning in elementary schools during the 2021-2025 period. The peak in publications occurred in 2024, indicating that this topic is increasingly relevant as digital transformation accelerates in post-pandemic education (Balalle, 2024; Okoye et al., 2023). The included articles covered various aspects of AR-IBL implementation, ranging from its impact on students' epistemic beliefs (Wen, Lai,



Note: Some primary studies did not report the duration or grade level explicitly. "Not reported" data were coded as 0 weeks in the box plot and classified as "Not Specified" in the Sankey diagram.

Figure 2. Visual representation of research characteristics and findings from the included studies

et al., 2023) to the development of 21st-century skills (Ismail & Isrokatun, 2025), to its influence on the understanding of abstract science concepts such as sound waves (Cai et al., 2022) and anatomy (Arkan et al., 2023). The majority of studies were published in highly reputable journals (Scopus Q1-Q3), demonstrating a high standard of research quality in this field, although there were also contributions from national publications (Sinta 2). These studies mostly focused on evaluating effectiveness, developing media, and exploring students' perceptions, reflecting efforts to measure the impact of AR-IBL and provide innovative tools. These characteristics align with the pedagogical needs of elementary school students at the concrete operational stage, where real visualization is essential for constructing understanding (Huang et al., 2022; Wang et al., 2025).

Analysis of AR Role in Supporting Each Cycle of Digital Inquiry

Based on the latest inquiry learning framework (Yegorina et al., 2021), AR integration was found to support several main stages, namely orientation, conceptualization, investigation, conclusion, and discussion.

In several articles analyzed, the orientation and conceptualization stages were not explicitly separated. Study findings indicate that AR is used in the early stages of learning to foster students' curiosity and initial understanding of abstract science concepts. In the context of elementary school science learning, early-stage AR integration generally provides visualizations of scientific phenomena that stimulate exploration and shape students' initial conceptualizations. Therefore, several studies tend to integrate these two stages into AR-based early exploration activities rather than rigidly separating them as in the theoretical framework of inquiry learning.

In the investigation phase, AR provides a safe and interactive learning environment for virtual exploration. Students can manipulate virtual objects, observe changes in phenomena, and gather more contextual information through AR-based simulations. Findings from Chen et al. (2025) indicate that an AR-based experiential learning approach can transform students from passive observers to active participants in the learning process. In addition to increasing learning engagement, using AR during the investigation phase helps students understand abstract scientific concepts that are difficult to observe directly.

Furthermore, at the conclusion stage, interactive AR visualizations help students analyze the results of their investigations and draw more accurate conclusions. AR helps students confirm and revise their initial conceptual understanding based on the results of their explorations. Meanwhile, during the discussion stage, AR serves as an effective medium for presentation and learning communication. AR-based visualizations enable students to explain concepts and experimental results more clearly to teachers and peers, thereby supporting the development of communication and collaboration skills (Ismail & Isrokatun, 2025).

Thus, the integration of AR into Inquiry-Based Learning not only enriches students' learning experiences but also helps bridge the gap between abstract science material and the need for concrete representation in elementary school. Furthermore, these findings are supported by prior literature emphasizing that AR integration can facilitate the development of 21st-century skills and digital literacy in elementary education (Huang et al., 2025; Cetin, 2022).

RQ 2. Challenges in AR-IBL Implementation

Despite its great potential, implementing AR-IBL integration in elementary schools faces various technical and pedagogical challenges. On the technical side, several studies have highlighted the cognitive load issues that students may experience when AR designs are too complex or unintuitive (Setiawan et al., 2023). Furthermore, developing high-quality, curriculum-relevant, and accessible AR content is a significant barrier, requiring investment and specialized expertise (Jiang et al., 2025). Equally important, the cost of adequate hardware and the availability of stable internet access are often infrastructure constraints, especially in areas with less advanced technological infrastructure.

From a pedagogical perspective, teacher competency in effectively integrating AR into an Inquiry-Based Learning framework remains a key issue (Jiang et al., 2025; Wen & He, 2025). Many teachers lack adequate training, not only in operating AR technology but also in designing inquiry activities that make optimal use of AR's potential. Furthermore, several studies report that the use of Augmented Reality can increase students' cognitive load if not pedagogically well designed. (Wen, Wu, et al., 2023) found that the complexity of AR interactions can cause students to focus more on exploring the technology than on understanding the scientific concepts being learned. Similar findings were reported by Jiang et al. (2025), who highlighted that the use of mobile-based AR requires a simple instructional design to avoid overloading elementary school students' information-processing capacity. Meanwhile, Cai et al. (2022) noted that overly complex AR visualizations can lead to learning distractions if not accompanied by adequate teacher guidance. Instructional designs that are not aligned with the characteristics of AR and Inquiry-Based Learning can also reduce learning effectiveness, as Wen & He (2025) emphasize the importance of teacher facilitation and ARCS elements in motivational design. This gap indicates that the success of technology adoption depends not only on the availability of devices but also on the teacher's pedagogical capacity to manage AR-based learning effectively.

RQ3. Strategic Opportunities and Recommendations

Despite the challenges, integrating AR into inquiry-based science learning in elementary schools offers significant opportunities to improve the quality of education in the digital era. These opportunities include increased student motivation to learn, deeper conceptual understanding, and the development of 21st-century skills. In addition to the findings derived from the selected studies, several supporting references from broader literature are incorporated to strengthen the discussion and provide contextual insights. These references are used to complement, rather than replace, the core findings obtained from the ten studies included in this systematic literature review.

First, increased student motivation and engagement are key impacts. The interactive and immersive nature of AR can significantly increase student interest, transforming them from passive observers to active participants in the learning process (Cai et al., 2022). The intrinsic motivation generated by these engaging AR experiences can support deeper engagement in inquiry activities. Second, AR plays a significant role in strengthening conceptual understanding. This technology can concretely visualize abstract scientific material, such as concepts that are difficult to visualize, thereby helping students build a stronger and more intuitive understanding (Lo et al., 2021; Jafari et al., 2023). Real-time 3D visualizations allow students to interact directly with models or phenomena that could previously only be imagined. Third, the integration of AR and Inquiry-Based Learning effectively supports the development of 21st-century skills, particularly the 4Cs: critical thinking, creativity, collaboration, and communication (Ismail & Isrokatun, 2025). Through inquiry-based exploration and problem-solving activities enriched with AR technology, students are trained to think critically, collaborate, express ideas, and develop creativity in solving learning problems.

Various studies also report that the evaluation of 21st-century skills in AR-based learning is conducted through various assessment instruments tailored to the characteristics of elementary school students (Ismail & Isrokatun, 2025). For example, using a combination of pre-tests and post-tests and student activity observation sheets to evaluate 4C skills during AR-based science learning. Meanwhile, Wen, Wu et al. (2023) utilized a self-directed learning questionnaire and a student creativity assessment rubric to measure the impact of AR integration on creative thinking skills and learning independence. Several other studies also used observations of learning behavior, interviews, and task performance assessments to identify the development of 21st-century skills during the inquiry learning process. These findings indicate that the evaluation of 21st-century skills in AR-based learning focuses not only on academic outcomes but also on the development of elementary school students' thinking processes, social interactions, and problem-solving abilities.

Based on the identified opportunities and challenges, several strategic recommendations can be considered to optimize AR integration in inquiry-based science learning in elementary schools. First, ongoing teacher training programs that strengthen digital literacy and inquiry pedagogy are needed (Wang et al., 2025; Wahyu et al., 2021). Second, the development of intuitive, relevant AR applications for the elementary school science curriculum is necessary to minimize students' cognitive load (Hinostroza et al., 2024; Wen, Lai, et al., 2023). Third, infrastructure support, including adequate devices and internet connectivity, is crucial to the successful implementation of AR in elementary schools. Furthermore, instructional design that holistically integrates AR with the syntax of inquiry learning is also needed to ensure the learning process remains oriented towards active student engagement and motivation (Ozturk & Akcay, 2023; Wen & He, 2025).

Critical Synthesis of Findings

A deeper synthesis of the reviewed studies suggests that the effectiveness of AR integration in inquiry-based science learning is influenced by the compatibility between the type of AR technology and the inquiry learning phase. Marker-based AR was frequently associated with greater instructional structure

Table 2. Comparative Matrix of AR Types Across Inquiry Learning Stages

Inquiry Learning Stage	Suitable AR Type	Pedagogical Function	Reported Benefits
Orientation	Marker-based AR	Initial visualization of scientific phenomena	Increase curiosity and engagement
Conceptualization	Marker-based AR	Support conceptual understanding of abstract concepts	Improve conceptual understanding
Investigation	Markerless AR	Interactive exploration and experimentation	Promote active inquiry and critical thinking
Discussion	Markerless AR	Facilitate collaborative explanation and presentation of findings	Enhance communication and collaboration skills
Conclusion	Markerless AR	Support reflection and contextual reinforcement of concepts	Strengthen knowledge retention and conceptual understanding

during the orientation and conceptual introduction stages, helping elementary students maintain attention and reduce cognitive overload, particularly for younger learners. In contrast, markerless AR was more commonly used during investigative and exploratory activities because it provides greater flexibility and immersive interaction, enabling students to manipulate virtual objects more independently and to actively construct scientific understanding.

Furthermore, studies emphasizing guided inquiry generally employed marker-based AR to support teacher facilitation and procedural learning, whereas studies focusing on student autonomy and experiential inquiry more frequently utilized markerless AR environments. This pattern suggests that the pedagogical suitability of AR does not depend solely on technological sophistication but rather on its alignment with inquiry objectives, students' cognitive readiness, and classroom infrastructure.

Overall, the synthesis of the included studies highlights consistent patterns regarding the effectiveness, challenges, and pedagogical implications of AR integration in inquiry-based science learning at the elementary level. These findings provide a comprehensive basis for drawing the following conclusions.

■ CONCLUSION

Based on a Systematic Literature Review of global studies published between 2021 and 2025, the integration of Augmented Reality (AR) within the Inquiry-Based Learning (IBL) framework significantly enhances science learning in elementary education. AR effectively transforms abstract scientific concepts into concrete and immersive experiences, supporting all stages of inquiry learning, including orientation, conceptualization, investigation, discussion, and conclusion. Furthermore, AR integration contributes to improved motivation to learn, deeper conceptual understanding, and the development of 21st-century skills, particularly critical thinking, creativity, collaboration, and communication, among elementary school students. (Ismail & Isrokatun, 2025; Wen, Wu, et al., 2023) .

However, implementing AR in inquiry-based learning still faces various challenges, both technically and pedagogically. Infrastructure limitations, device availability, internet connection stability, and teacher competency in designing AR-based inquiry learning activities are key factors influencing the effectiveness of this technology. Furthermore, several studies have shown that overly complex AR applications can potentially increase students' cognitive load if not supported by instructional design tailored to the characteristics of elementary school students.

Based on these findings, this study confirms that the success of AR integration in science learning depends not only on technological sophistication but also on the alignment between pedagogical design, inquiry learning stages, and the learning needs of elementary school students. Therefore, ongoing teacher training, the development of more intuitive AR applications, and adequate infrastructure support are needed to optimize AR implementation in elementary education. Future research is expected to explore the effectiveness of various types of AR, such as marker-based and markerless AR, and examine the long-term impact of AR integration on the development of critical thinking skills, creativity, and learning independence in elementary school students.

■ DECLARATION OF GENERATIVE AI USAGE IN THE WRITING PROCESS

During the writing of this manuscript, the author(s) employed ChatGPT (OpenAI) to assist with language refinement and structuring of the manuscript. The author(s) have carefully reviewed and edited all generated content and take full responsibility for the accuracy and integrity of the final version of the manuscript.

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