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Augmented Reality-Based Digital Learning Modules for Critical Thinking in Physics Education: Trends, Mechanisms, and Future Directions

Algiranto[1*], Martha Loupatty[1], and Isnawati[2]
[1]Physics Education Study Program, Universitas Musamus, Merauke, Indonesia
[2]Science Education Study Program, Universitas Negeri Yogyakarta, Yogyakarta, Indonesia

*algiranto@unmus.ac.id

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ABSTRACT
Critical thinking is an essential competency in physics education, yet its development remains challenging due to the abstract nature of physics concepts and the limitations of conventional instruction. Augmented Reality (AR)-based digital learning modules have emerged as a promising approach for creating interactive and immersive learning experiences. However, evidence regarding their role in fostering critical thinking remains fragmented across educational levels, physics topics, instructional approaches, and learning outcomes. This study systematically reviews research on AR-based digital learning modules for critical thinking in physics education. Following the PRISMA 2020 guidelines, 26 Scopus-indexed articles published between 2020 and 2025 were analyzed using descriptive and thematic synthesis. The review examined publication trends, research characteristics, instructional features, educational outcomes, mechanisms supporting critical thinking, and future research directions. The findings indicate a growing research interest in AR-based digital learning modules, with most studies employing Android-based applications, quasi-experimental designs, and inquiry-oriented pedagogies. While the reviewed studies consistently reported improvements in conceptual understanding, learning motivation, engagement, and scientific inquiry, only a limited number directly assessed critical thinking. The thematic synthesis identified five mechanisms through which AR supports critical thinking: conceptual visualization, scientific inquiry, authentic problem solving, collaborative reflection, and learning motivation as a mediating factor. The review also highlights research gaps related to higher-order thinking assessment, intelligent learning environments, long-term implementation, and methodological diversity. These findings provide a comprehensive evidence base and future research roadmap for designing more effective AR-enhanced physics learning environments.
Keywords: augmented reality, critical thinking, digital learning module, physics education, systematic literature review

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INTRODUCTION

The rapid advancement of science and digital technology has transformed the competencies required of learners in the twenty-first century. Beyond acquiring disciplinary knowledge, students are expected to develop higher-order thinking skills that enable them to analyze information, evaluate evidence, solve complex problems, and make informed decisions in increasingly complex environments (OECD, 2023; UNESCO, 2020). Among these competencies, critical thinking has become one of the primary goals of science education because it supports scientific reasoning, evidence-based argumentation, problem solving, and informed decision-making. Within physics education, critical thinking is particularly important since students are expected to interpret abstract scientific phenomena, evaluate empirical evidence, explain causal relationships, and apply scientific principles to authentic situations(Abdusselam & Karal, 2020; Cai et al., 2021; Demircioglu et al., 2023; Dewi & Kuswanto, 2023; Faridi et al., 2021; Wibowo, 2023).

Despite its importance, fostering students' critical thinking remains a persistent challenge in physics education. Physics learning requires students to understand abstract concepts, visualize invisible phenomena, interpret multiple representations, and solve complex scientific problems. However, many learning environments continue to rely on teacher-centered instruction, procedural problem solving, and formula memorization, limiting opportunities for students to engage in scientific inquiry and higher-order thinking. Several studies have reported that students frequently experience difficulties connecting theoretical concepts with real-world phenomena, resulting in limited conceptual understanding and weak critical thinking performance (Dewi & Kuswanto, 2023; Faridi et al., 2021; Rahmat et al., 2023; Rizki et al., 2023; Ropawandi et al., 2022; Wibowo, 2023). Furthermore, conventional instructional approaches often fail to provide meaningful visualization, interactive exploration, and authentic problem-solving experiences that are essential for developing critical thinking in physics learning (Jesionkowska & Wild, 2020; Radu et al., 2023; Vidak & Šapi, 2021).

To overcome these challenges, researchers have increasingly integrated digital technologies into physics instruction through the development of AR-based digital learning modules. Compared with conventional printed materials, digital learning modules provide greater flexibility by integrating multimedia resources, interactive simulations, immediate feedback, and self-directed learning activities. Among these innovations, Augmented Reality (AR) has attracted considerable attention because it enables students to visualize abstract and invisible physical phenomena through interactive three-dimensional representations integrated with real-world environments. Numerous studies have demonstrated that AR-based digital learning modules enhance conceptual understanding, learning motivation, scientific visualization, inquiry skills, and classroom engagement by providing more immersive and interactive learning experiences (Faridi et al., 2021; Rahmat et al., 2023; Rahmayani et al., 2024; Rizki et al., 2023; Ropawandi et al., 2022). AR has also been successfully implemented across various physics topics, including electricity, mechanics, optics, astronomy, marine physics, renewable energy, and virtual laboratory activities, demonstrating its broad applicability within physics education (Cai et al., 2021; Jesionkowska & Wild, 2020; Volioti et al., 2022; Wibowo, 2023).

Although the reported educational outcomes are generally positive, the existing evidence remains highly heterogeneous. Many empirical studies have demonstrated improvements in students' conceptual understanding, learning achievement, motivation, engagement, inquiry skills, and scientific visualization (Cai et al., 2021; Laumann et al., 2024; Radu et al., 2023; Rahmat et al., 2023; Volioti et al., 2022). However, only a relatively small number of studies have explicitly investigated students' critical thinking skills using dedicated assessment instruments (Demircioglu et al., 2023; Dewi & Kuswanto, 2023; Faridi et al., 2021; Rahmayani et al., 2024; Rizki et al., 2023). Consequently, while AR has been widely recognized as an effective educational technology, its contribution to fostering critical thinking remains fragmented across different educational levels, physics topics, instructional approaches, and technological implementations.

Despite the growing body of research, several important gaps remain. First, existing studies predominantly emphasize conceptual understanding, motivation, engagement, and learning achievement, whereas comparatively few directly examine critical thinking as the primary learning outcome. Second, previous investigations are distributed across diverse educational contexts, physics topics, pedagogical approaches, research designs, and AR technologies, making it difficult to identify consistent patterns regarding the conditions under which AR-based digital learning modules effectively foster critical thinking. Third, although previous review studies have discussed AR in education from broader technological perspectives, there remains a lack of a systematic literature review that comprehensively synthesizes publication trends, research characteristics, instructional features, pedagogical approaches, educational outcomes, underlying mechanisms, and future research directions specifically related to AR-based digital learning modules for improving critical thinking in physics education. This lack of comprehensive synthesis limits the development of evidence-based recommendations for researchers, educators, curriculum developers, and instructional designers.

To address these gaps, this study conducts a systematic literature review of research on AR-based digital learning modules for improving critical thinking skills in physics education. Unlike previous studies that primarily reported individual empirical findings or reviewed AR within broader educational contexts, this review integrates evidence from selected studies to examine publication trends, research characteristics, instructional features, pedagogical approaches, educational outcomes, and the mechanisms through which AR supports critical thinking. In addition, this review identifies current research gaps and proposes a future research roadmap to guide subsequent investigations. By synthesizing these dimensions within a unified analytical framework, this study provides a comprehensive understanding of the current state of the field while offering evidence-based recommendations for advancing AR-supported physics education. Accordingly, this study aims to systematically review and synthesize the existing literature on the use of Augmented Reality (AR)-based digital learning modules for improving critical thinking skills in physics education. Specifically, this review seeks to:

1. examine publication trends and research characteristics of AR-based digital learning modules in physics education;
2. identify the instructional features, pedagogical approaches, physics topics, educational levels, and research methodologies employed in previous studies;
3. synthesize the mechanisms through which AR-based digital learning modules foster students' critical thinking skills; and
4. identify current research gaps and propose a future research roadmap for AR-based digital learning modules in physics education.

Through these objectives, this review is expected to provide a comprehensive evidence base that supports researchers, educators, curriculum developers, and instructional designers in designing more effective AR-enhanced physics learning environments.

METHODS

This study employed a Systematic Literature Review (SLR) to comprehensively synthesize research on Augmented Reality (AR)-based digital learning modules for improving critical thinking skills in physics education. The review followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) guidelines to ensure a transparent, systematic, and reproducible review process. SLR was selected because it enables the identification, evaluation, and synthesis of empirical evidence from previous studies while minimizing potential bias in the review process.

The literature search was conducted using the Scopus database because of its extensive coverage of high-quality peer-reviewed journals. The search included articles published between 2020 and 2025 using combinations of keywords related to Augmented Reality, digital learning module, physics education, and critical thinking, connected through Boolean operators (AND/OR). Only journal articles written in English and published in final form were considered for further screening. The process of identifying, screening, assessing eligibility, and selecting the final studies followed the PRISMA 2020 guidelines, as illustrated in Figure 1.

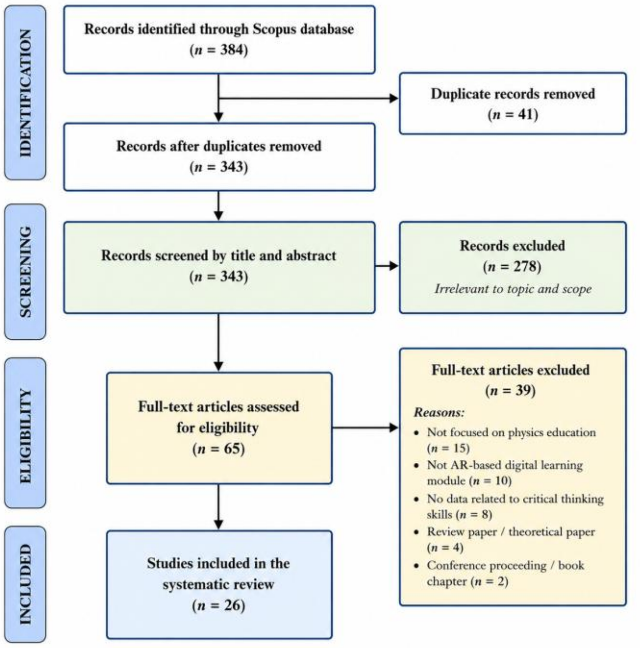

Figure 1 PRISMA flow diagram

The study selection followed the four PRISMA stages: identification, screening, eligibility, and inclusion. Articles were screened based on predefined inclusion and exclusion criteria. Eligible studies focused on the implementation of AR-based digital learning modules in physics education and reported empirical findings related to students' learning outcomes, particularly critical thinking skills. Studies published as conference proceedings, book chapters, reviews, editorials, or articles unrelated to physics education were excluded. The eligibility of the retrieved studies was determined using predefined inclusion and exclusion criteria to ensure that only relevant and high-quality studies were included in the review. The criteria are summarized in Table 1.

Table 1 Inclusion and Exclusion Criteria

Inclusion Criteria	Exclusion Criteria
Journal articles indexed in the Scopus database	Publications not indexed in Scopus
Articles published between 2020 and 2025	Articles published before 2020
Written in English	Non-English publications
Peer-reviewed journal articles	Conference proceedings, book chapters, editorials, reviews, notes, and theses/dissertations
Studies focusing on Augmented Reality (AR)-based digital learning modules	Studies that do not involve AR or digital learning modules
Research conducted in physics education	Studies conducted outside physics education
Empirical studies reporting learning outcomes	Conceptual, theoretical, or opinion papers without empirical data
Studies investigating critical thinking skills as a primary or secondary learning outcome	Studies that do not report critical thinking outcomes

Data from the selected studies were extracted using a standardized review protocol, including publication year, country, educational level, research design, physics topic, AR application, instructional characteristics, and reported learning outcomes. The extracted data were synthesized descriptively and thematically to identify publication trends, implementation patterns, research characteristics, and the effectiveness of AR-based digital learning modules in enhancing students' critical thinking skills.

RESULT AND DISCUSSION

Publication Trends of AR-Based Digital Learning Modules

To address the first research objective, this section examines publication trends in studies investigating AR-based digital learning modules in physics education. The review included 26 studies published between 2020 and 2025, providing an overview of the evolution of research activity during the review period.

The number of publications increased from three studies in 2020 to five in 2021, declined slightly to four in 2022, and reached a peak of seven publications in 2023. Subsequently, the number of publications decreased to five studies in 2024 and two studies in 2025. Despite these year-to-year fluctuations, the overall publication pattern demonstrates sustained scholarly interest in the application of AR for physics education.

The increasing number of publications between 2020 and 2023 suggests that research has progressed from the initial adoption of AR technologies toward broader investigations of their pedagogical applications. Although fewer studies were identified in 2024 and 2025, this pattern is likely influenced by publication and indexing cycles rather than indicating declining research interest. Overall, the consistent publication of studies throughout the review period suggests that AR-based digital learning modules have become an established and continuously evolving research area, providing a foundation for examining research characteristics, instructional mechanisms, and future research directions.

Research Characteristics

To provide an overview of the research landscape, the characteristics of the included studies were analyzed from four perspectives: country distribution, educational level, physics topics, and research design. These characteristics illustrate the geographical distribution, educational contexts, subject coverage, and methodological approaches of research on AR-based digital learning modules in physics education. The distributions are presented in Figure 2.

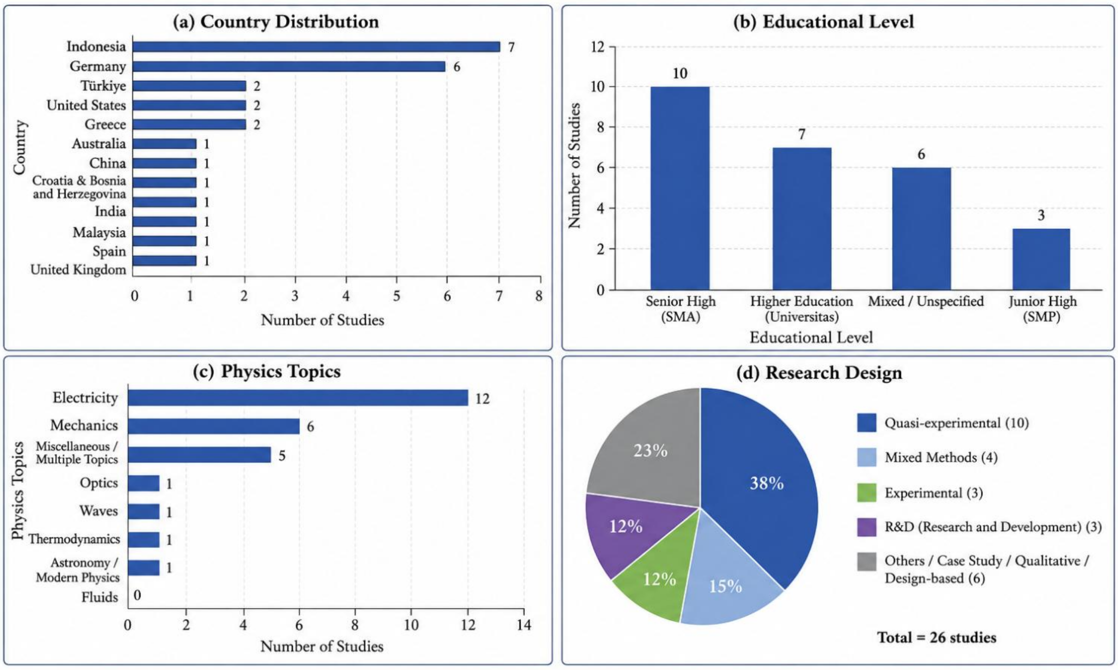

Figure 2. Research characteristics of the included studies. (a) Country distribution; (b) Educational level; (c) Physics topics; (d) Research design.

Figure 2(a) shows that the reviewed studies were conducted across twelve countries, indicating growing international interest in AR-supported physics education. Indonesia contributed the largest number of publications, followed by Germany, whereas Türkiye, the United States, and Greece each contributed two studies. The remaining countries were represented by a single publication. This distribution suggests that although AR research has expanded internationally, broader geographical representation is still needed to strengthen cross-cultural evidence and generalizability.

As shown in Figure 2(b), senior high school was the most common educational setting, followed by higher education. Only a limited number of studies were conducted at the junior high school level, while several studies involved mixed educational contexts or did not explicitly specify participants' educational levels. This pattern indicates that current AR research has primarily focused on educational contexts where physics concepts become increasingly abstract and conceptually demanding.

Figure 2(c) indicates that electricity and electromagnetism were the most frequently investigated physics topics, followed by mechanics. Other topics, including optics, waves, thermodynamics, and interdisciplinary physics, received comparatively less attention. This distribution suggests that AR implementation has been concentrated on topics requiring visualization of abstract phenomena, while several areas of physics remain relatively underexplored.

Figure 2(d) shows that quasi-experimental research was the dominant methodological approach, followed by mixed-methods, experimental, and research-and-development studies. The predominance of quasi-experimental designs reflects their suitability for evaluating instructional interventions in authentic classroom settings. However, the limited number of qualitative and longitudinal studies indicates opportunities for future research to provide deeper insights into learning processes and long-term educational outcomes.

Characteristics of AR-Based Digital Learning Modules

To characterize the current landscape of AR-based digital learning modules in physics education, the reviewed studies were synthesized across five dimensions: learning platforms, physics topics, pedagogical approaches, assessment methods, and educational outcomes. Rather than describing individual studies, this cross-study synthesis identifies the dominant characteristics and recurring patterns across the literature. The results are summarized in Table 2.

Table 2. Cross-study synthesis of AR-based digital learning modules in physics education

Aspect	Category	n (%)
Learning Platform	Android-based Mobile AR	12 (46.2)
	AR Laboratory / Experimental Platform	7 (26.9)
	Other AR Platforms	6 (23.1)
Physics Topics	Electricity & Electromagnetism	10 (38.5)
	Mechanics	7 (26.9)
	Other Physics Topics	9 (34.6)
Pedagogical Approaches	Inquiry-Based Learning	8 (30.8)
	Constructivist Learning	6 (23.1)
	Active / Experiential Learning	5 (19.2)
	Other Learning Approaches	8 (30.8)
Assessment Methods	Achievement & Conceptual Understanding Tests	8 (30.8)
	Motivation, Perception & Usability Questionnaires	7 (26.9)
	Critical Thinking Assessment	6 (23.1)
	Other Assessment Methods*	19 (73.1)
Educational Outcomes	Improved Motivation & Engagement	12 (46.2)
	Improved Conceptual Understanding	11 (42.3)
	Improved Scientific Inquiry, Problem Solving & Practical Skills	8 (30.8)
	Improved Critical Thinking Skills	7 (23.1)

Note. Other assessment methods include observation, interviews, product evaluation, and studies without empirical assessment.

The synthesis reveals several consistent patterns in the implementation of AR-based digital learning modules across the reviewed studies. Android-based mobile applications were the most frequently adopted learning platform (n = 12), as reported by Dewi & Kuswanto (2023), Faridi et al. (2021), Rahmayani et al. (2024), Rizki et al. (2023), Ropawandi et al. (2022), and Wibowo (2023). In comparison, AR laboratory or experimental platforms were implemented in fewer studies, including those by Stolzenberger et al. (2022),Teichrew & Erb (2020), Thees et al. (2020), Vidak & Šapi (2021), and Yau et al. (2020). Other implementations, such as remote tutoring, field-based learning, workshop-based activities, lesson-plan integration, and multi-application platforms, were explored by Demircioglu et al. (2023), Jesionkowska & Wild (2020) Moreno-guerrero et al. (2020), Radu et al. (2023), and Volioti et al. (2022). These findings indicate that mobile devices have become the predominant platform for integrating AR into physics instruction because of their accessibility, portability, and compatibility with classroom learning environments.

Regarding instructional content, electricity and electromagnetism emerged as the most frequently investigated physics topics (n = 10), represented by studies such as Faridi et al. (2020), Ropawandi et al. (2022), Stolzenberger et al. (2022), Radu et al. (2023), and Amiraslanov et al. (2020) . Mechanics was the second most common topic (n = 7), including research by Abdusselam & Karal (2020), Vidak et al. (2021), Dewi and Kuswanto (2023), and Rizki et al. (2023). Other topics including optics, astronomy, renewable energy, marine physics, and integrated physics were addressed by Cai et al. (2021), Rahmat et al. (2023), Jesionkowska & Wild (2020), Volioti et al. (2022), Wibowo (2023), Rahmayani et al. (2024), and Yau et al. (2020). This distribution suggests that AR applications have primarily focused on conceptually challenging topics that benefit from visualization, while many areas of physics remain relatively underexplored.

From a pedagogical perspective, inquiry-based learning was the most frequently adopted instructional approach (n = 8), as demonstrated by Abdusselam and Karal (2020), Cai et al. (2021), Yau et al. (2020), Radu et al. (2023), and Ainur et al. (2025). Constructivist learning approaches were also widely implemented through the studies of Faridi et al. (2020), Ropawandi et al. (2022), Vidak et al. (2021), and Rizki et al. (2024), whereas active or experiential learning was reported by Moreno-Guerrero et al. (2020), Jesionkowska et al. (2020), Zafeiropoulou et al. (2021), and Stolzenberger et al. (2022). Additional pedagogical approaches, including STEM education, argument-driven inquiry (ADI), game-based learning, self-directed learning, and technology-enhanced learning, were also integrated into several studies (Demircioglu et al., 2023; Rahmat et al., 2023; Rahmayani et al., 2024; Volioti et al., 2022; Wibowo, 2023). Collectively, these findings indicate that AR is predominantly embedded within student-centered pedagogies rather than functioning merely as a visualization technology.

Assessment practices showed considerable diversity across the reviewed studies. The most common assessments focused on conceptual understanding and learning achievement (n = 8), as reported by Abdusselam and Karal (2020), Thees et al. (2020), Ropawandi et al. (2022), Rahmat et al. (2023), and Laumann et al. (2024). Other studies evaluated learners' motivation, perceptions, self-efficacy, and usability through questionnaires (Cai et al., 2021; Moreno-guerrero et al., 2020; Teichrew et al., 2023; Volioti et al., 2022; Zafeiropoulou et al., 2021). Only six studies explicitly employed dedicated critical thinking assessments, namely those by Faridi et al. (2021), Dewi and Kuswanto (2023), Demircioglu et al. (2023), Rahmayani et al. (2024), Wibowo (2023), and Rizki et al. (2024). Meanwhile, several studies relied on observations, interviews, product evaluations, or design-oriented evaluations without formal learning assessments. These findings demonstrate that research has largely emphasized cognitive achievement and learner perceptions, whereas rigorous assessment of higher-order thinking remains comparatively limited.

A similar trend was observed in the reported educational outcomes. Improvements in motivation and engagement (n = 12) and conceptual understanding (n = 11) were the most consistently reported outcomes across the reviewed studies, followed by enhancements in scientific inquiry, problem-solving, and practical skills (n = 8). Representative evidence was provided by Cai et al. (2021), Faridi et al. (2020), Abdusselam and Karal (2020), Volioti et al.

(2022), Rahmat et al. (2023), Radu et al. (2023), and Laumann et al. (2024). In contrast, only seven studies reported direct improvements in students' critical thinking skills using explicit assessment instruments (Amiraslanov et al., 2020; Demircioglu et al., 2023; Dewi & Kuswanto, 2023; Faridi et al., 2021; Rahmayani et al., 2024; Rizki et al., 2024; Wibowo, 2023). This imbalance suggests that, although AR-based digital learning modules have consistently demonstrated positive educational impacts, empirical evidence specifically explaining how these modules foster critical thinking remains comparatively limited. Therefore, the following section synthesizes the underlying instructional mechanisms through which AR-based digital learning modules support the development of critical thinking in physics education.

Mechanisms Through Which AR-Based Digital Learning Modules Foster Critical Thinking

Although only six of the twenty-six reviewed studies explicitly assessed students' critical thinking using dedicated assessment instruments, the overall body of evidence suggests that AR-based digital learning modules facilitate several learning processes closely associated with higher-order thinking. Rather than fostering critical thinking through a single instructional feature, AR appears to support a set of interconnected cognitive and pedagogical mechanisms that collectively strengthen students' conceptual reasoning, scientific inquiry, analytical problem solving, evaluation, and reflective thinking. Based on the thematic synthesis of the reviewed studies, these mechanisms are synthesized into the conceptual framework presented in Figure 3. As illustrated in Figure 3, AR-based digital learning modules serve as the primary instructional environment that supports five interconnected learning mechanisms: interactive visualization, scientific inquiry, authentic problem solving, collaborative reflection, and learning motivation. Rather than operating independently, these mechanisms complement one another and collectively contribute to the development of students' critical thinking skills.

The first mechanism is interactive visualization, which represents the most fundamental contribution of AR to physics learning. Across topics such as electricity, electromagnetism, optics, gravitation, astronomy, and integrated physics, AR enabled students to visualize abstract and invisible physical phenomena through interactive three-dimensional representations (Cai et al., 2021; Faridi et al., 2021; Rahmat et al., 2023; Ropawandi et al., 2022; Stolzenberger et al., 2022; Teichrew et al., 2023; Teichrew & Erb, 2020; Vidak & Šapi, 2021). By making abstract concepts observable and manipulable, AR helped students reduce misconceptions, strengthen conceptual understanding, and recognize causal relationships among physical variables. These experiences established the conceptual reasoning necessary for interpreting scientific evidence and constructing well-supported explanations.

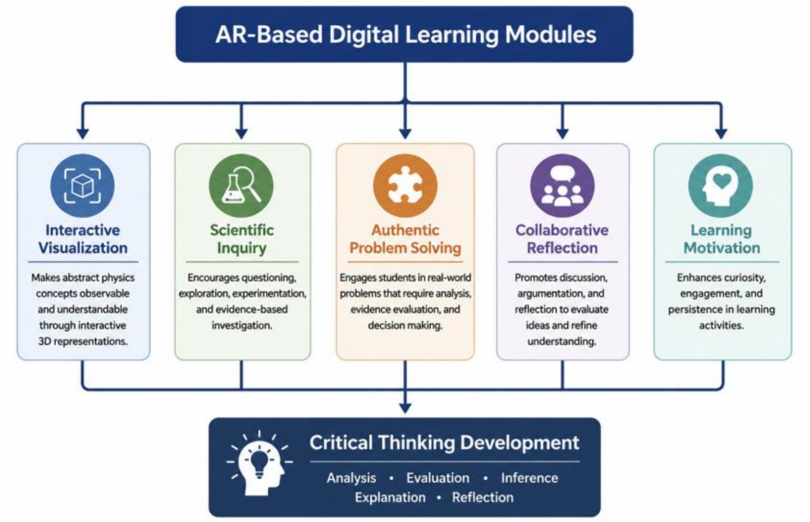

Figure 3. Conceptual mechanisms through which AR-based digital learning modules foster critical thinking in physics education.

Conceptual understanding was consistently reinforced through scientific inquiry, the second mechanism identified in the thematic synthesis. Several studies integrated AR into inquiry-oriented learning activities in which students formulated research questions, manipulated experimental variables, tested hypotheses, and interpreted evidence generated through virtual experiments or interactive simulations (Abdusselam & Karal, 2020; Yau et al., 2020; Cai et al., 2021; Vidak et al., 2021; Radu et al., 2023). These inquiry experiences shifted students from passive recipients of information toward active scientific investigators, encouraging analytical reasoning, evidence-based explanation, and reflective judgment.

The third mechanism involves authentic problem solving, in which AR-supported learning is situated within meaningful real-world contexts. Rather than presenting isolated scientific concepts, several studies required students to analyze authentic situations, evaluate alternative solutions, compare scientific evidence, and make informed decisions based on physics principles (Demircioglu et al., 2023; Wibowo, 2023; Rahmayani et al., 2024; Rizki et al., 2024). These authentic learning experiences encouraged students to apply conceptual knowledge beyond the classroom while strengthening analytical reasoning and evidence-based decision making.

The reviewed literature also demonstrates that the educational value of AR is strengthened through collaborative reflection. AR-supported instruction frequently incorporated collaborative investigation, peer discussion, scientific argumentation, and reflective dialogue as integral components of the learning process (Jesionkowska et al., 2020; Moreno-Guerrero et al., 2020; Cai et al., 2021; Zafeiropoulou et al., 2021; Radu et al., 2023). Through these collaborative activities, students communicated scientific ideas, justified claims with evidence, evaluated alternative explanations, reconsidered assumptions, and refined their understanding through social interaction. Such evaluative and reflective processes represent essential dimensions of critical thinking.

The fifth mechanism identified in the synthesis is learning motivation, which functions as an enabling rather than a direct cognitive mechanism. Across multiple studies, AR-based learning environments consistently increased students' curiosity, engagement, motivation, and persistence during learning activities (Moreno-Guerrero et al., 2020; Volioti et al., 2022; Rahmat et al., 2023; Rizki et al., 2023; Laumann et al., 2024). Increased motivation encouraged students to devote more time to exploring scientific phenomena, persist in solving challenging problems, participate actively in collaborative learning, and engage more deeply in inquiry processes. Consequently, motivation strengthens each stage of the learning process, indirectly supporting the development of critical thinking.

Taken together, the reviewed evidence indicates that critical thinking is not fostered by visualization alone but emerges from the interaction of multiple complementary mechanisms. As synthesized in Figure 4, interactive visualization provides the conceptual foundation for scientific inquiry, which is subsequently strengthened through authentic problem solving and collaborative reflection, while learning motivation sustains students' engagement throughout these processes. The convergence of these mechanisms ultimately supports the development of higher-order thinking skills, including analysis, evaluation, inference, explanation, and reflection. This conceptual framework extends the existing literature by explaining how AR-based digital learning modules foster critical thinking in physics education and provides a theoretical basis for the future research directions presented in the following section.

Research Gaps and Future Research Roadmap

Although AR-based digital learning modules have demonstrated considerable educational potential in physics education, the reviewed studies reveal several recurring research gaps. Existing research remains concentrated on specific technologies, instructional contexts, research designs, and learning outcomes, leaving important questions regarding long-term learning, higher-order thinking, intelligent learning environments, and broader educational implementation unanswered. The major research gaps identified through this review are summarized in Table 3.

Table 3. Research gaps and future directions in AR-based digital learning modules for physics education

Research Area	Identified Gap	Future Research Direction
AR Technology	Mobile AR dominates; limited WebAR, cross-platform, mixed reality, and AI-supported AR.	Develop intelligent, adaptive, and cross-platform AR learning ecosystems.
Physics Content	Research focuses mainly on electricity, electromagnetism, and mechanics.	Expand AR implementation to modern physics, thermodynamics, quantum physics, nuclear physics, and interdisciplinary STEM topics.
Research Design	Studies are predominantly short-term, quasi-experimental, and conducted with small samples.	Conduct longitudinal, mixed-methods, design-based, and multi-context investigations.
Assessment	Assessment primarily targets conceptual understanding, achievement, motivation, and usability.	Develop comprehensive frameworks assessing critical thinking, scientific reasoning, problem solving, and higher-order thinking skills.
Educational Context	Limited evidence across diverse educational settings, teachers, and learner populations.	Explore multi-school, cross-cultural, inclusive, and teacher-focused AR implementation.
Learning Environment	Most AR modules function as stand-alone learning media.	Integrate AR with Artificial Intelligence, learning analytics, adaptive feedback, and collaborative learning environments.

The synthesis highlights two overarching research gaps. First, existing studies remain largely technology-oriented, with most investigations focusing on Android-based mobile AR applications implemented through short-term classroom interventions. Emerging technologies, including WebAR, mixed reality, adaptive learning, and AI-supported learning environments, remain comparatively underexplored (Faridi et al., 2020; Rahmat et al., 2023; Moreno-Guerrero et al., 2020; Demircioglu et al., 2023). Second, current research provides limited evidence regarding long-term learning processes and higher-order thinking development. Although improvements in conceptual understanding and learning motivation were consistently reported (Cai et al., 2021; Abdusselam & Karal, 2020; Rahmat et al., 2023; Volioti et al., 2022), relatively few studies directly assessed students' critical thinking using dedicated assessment instruments (Faridi et al., 2020; Dewi & Kuswanto, 2023; Rahmayani et al., 2024; Demircioglu et al., 2023; Rizki et al., 2024). These findings highlight the need for more comprehensive assessment frameworks and longitudinal research capable of explaining how AR supports the development of critical thinking.

Future Research Roadmap

Building upon the identified research gaps, this review proposes a future research roadmap that emphasizes the development of intelligent, pedagogically integrated, and evidence-based AR learning environments. The proposed research priorities are summarized in Table 4**.**

Table 4. Future Research Roadmap for AR-Based Digital Learning Modules in Physics Education

Priority	Research Agenda	Expected Contribution
High	AI-integrated AR learning environments	Personalized feedback, adaptive scaffolding, and intelligent support for critical thinking development.
High	Longitudinal investigations	Stronger evidence of long-term retention, transfer learning, and sustainable higher-

Priority	Research Agenda	Expected Contribution
		order thinking development.
High	Comprehensive higher-order thinking assessment	Valid and reliable measurement of critical thinking, scientific reasoning, and problem-solving skills.
Medium	Learning analytics and collaborative AR	Deeper understanding of students' cognitive processes, inquiry patterns, and collaborative learning.
Medium	Expansion to underrepresented physics topics	Broader curriculum coverage and increased contextual relevance of AR-supported learning.
Emerging	AR ecosystems supporting Education for Sustainable Development (ESD)	Integration of AR with contextual learning, sustainability, disaster resilience, and environmental literacy.

Overall, the proposed roadmap reflects a shift from developing stand-alone AR applications toward designing intelligent, adaptive, and pedagogically integrated learning ecosystems. Future studies should move beyond evaluating whether AR improves learning outcomes and instead investigate how technological features, instructional design, and learning contexts interact to foster critical thinking. Integrating Artificial Intelligence, learning analytics, adaptive feedback, and comprehensive higher-order thinking assessment will provide stronger evidence for designing the next generation of AR-supported physics learning.

CONCLUSION

This systematic literature review provides a comprehensive synthesis of recent research on AR-based digital learning modules in physics education and offers a conceptual understanding of how these learning environments foster students' critical thinking. By integrating evidence from the reviewed studies, this review extends the current literature beyond describing research trends to explaining the interconnected mechanisms through which AR supports higher-order thinking in physics learning. The proposed conceptual framework and future research roadmap provide practical guidance for researchers, educators, and instructional designers in developing more pedagogically integrated and evidence-based AR learning environments. Future studies should prioritize intelligent AR ecosystems, comprehensive assessment of higher-order thinking, and rigorous research designs that provide stronger evidence for the long-term educational impact of AR-supported learning. This review is limited to Scopus-indexed studies published between 2020 and 2025. Future reviews may expand the scope by incorporating additional databases, broader publication periods, and quantitative meta-analytic approaches to strengthen the evidence base for AR-supported physics education.

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