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Augmented Reality in Physics Education: A Systematic Review of Its Potential, Challenges, and Future Research Directions

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Abstract

The advancement of digital technology has driven the emergence of various educational innovations, one of which is Augmented Reality (AR), widely recognized for its potential to bridge the gap between abstract concepts and concrete experiences in physics education. Although numerous studies have demonstrated the benefits of AR, comprehensive reviews that critically examine its potential, challenges, and future research directions remain limited. This study employs a Systematic Literature Review (SLR) following the PRISMA framework, utilizing data sourced from ScienceDirect, IEEE Xplore, Google Scholar, and SINTA within the period 2020–2025. Of the 320 articles identified, 25 met the inclusion criteria and were subjected to thematic analysis. The findings reveal three major contributions of AR: enhancing conceptual understanding, strengthening critical thinking skills, and increasing learning motivation. The identified challenges include infrastructure limitations, teachers' pedagogical readiness, and the absence of standardized evaluation frameworks. In practical terms, these findings have implications for physics teachers and curriculum developers. AR integration needs to be designed within an inquiry-based learning framework to support meaningful concept construction, not just visualization. In addition, AR module development must be structured, aligned with competency and assessment standards, and contextual. Further research should focus on the integration of AR with AI and the development of adaptive curricula in authentic learning. This review provides a comprehensive overview of AR's role in supporting the transformation of 21st-century physics education, while also identifying opportunities for more focused and impactful future research.

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INTRODUCTION

Physics is a branch of science that is inherently abstract and conceptual. Understanding physical concepts requires strong mental representation skills, mathematical thinking abilities, and deep analytical reasoning. Many concepts, such as magnetic force, electromagnetic waves, and quantum mechanics, cannot be directly observed; instead, they are studied through models, symbols, and mathematical equations (J et al., 2025; Rachmayani et al., 2024). This condition often creates difficulties for students in connecting theoretical knowledge with real-world phenomena (Azairok & Fathurohman, 2023). As a result, several learning problems emerge, including misconceptions, low motivation, and difficulties in comprehending the physical meaning behind the formulas being studied (Akhsan et al., 2023; Gressianita et al., 2024; Saputro & Setyawan, 2020).

This problem is further exacerbated by learning approaches that remain dominated by conventional methods such as lectures and problem-solving exercises (Johan et al., 2023). Such instructional models do not provide sufficient opportunities for students to experiment, explore concepts, or construct understanding through direct experience (Çetin & Türkan, 2022). The lack of learning media capable of presenting visual and interactive representations is one of the main causes of students' low conceptual understanding in physics (Peikos & Sofianidis, 2024). To address these challenges, technological innovations in education are required to bridge the gap between abstract concepts and empirical phenomena through more immersive and contextual learning experiences (Fathurohman, Oklilas, et al., 2023; Pape et al., 2022).

Over the past two decades, advances in digital technology have opened new opportunities in education, particularly through the emergence of immersive technologies such as Augmented Reality (AR) (Anggraini et al., 2024). Unlike Virtual Reality (VR), which creates a fully digital environment, AR allows the integration of three-dimensional virtual objects into the real world in real time, enabling users to directly interact with digital content (Buchner & Kerres, 2023). AR has become a promising educational technology because it provides realistic visual experiences without removing the context of the actual learning environment. Pedagogically, this technology can integrate macroscopic, microscopic, and symbolic representations of physical phenomena into a unified and interactive visual experience (Jiang et al., 2022). This makes AR a flexible and practical tool to implement in physics learning environments (Supriasih et al., 2022).

A bibliometric analysis conducted by Al-Ansi et al. (2023) revealed that international publications on AR and VR in education increased significantly in recent years between 2011 to 2022, especially after the COVID-19 pandemic, signaling global recognition of AR as a pedagogical innovation. This trend indicates that AR has evolved from an experimental innovation into a globally recognized pedagogical tool that supports the transformation of science education (Volioti et al., 2022). In the context of physics education, AR has been employed to visualize phenomena such as magnetic forces, motion dynamics, and optical systems that are difficult to observe directly in school laboratories (Cai et al., 2021).

However, the implementation of AR in physics education is not without challenges. The main barriers lie in infrastructural limitations and the cost of hardware such as high-performance smartphones, as well as the need for continuously updated software (Mystakidis et al., 2021). Disparities in technological access also contribute to unequal adoption of AR, particularly in schools with limited resources. Moreover, teacher readiness plays a crucial role in determining the success of AR implementation (Perifanou et al., 2023; Seira et al., 2024). Many educators still face obstacles in integrating AR into classroom practice, largely due to limited digital literacy and the absence of standardized pedagogical models for embedding AR into the curriculum, resulting in varied levels of implementation effectiveness (Zaki et al., 2024). Therefore, approaches to AR integration must not only focus on technological development but also take into account teacher preparedness, educational policy, and the socio-economic context of schools (Velázquez & Méndez, 2021).

Furthermore, although numerous studies have investigated the use of AR in education, research on its implementation in physics education is still scattered and has not been systematically synthesized based on context, education level, or research design. Most studies focus on learning outcomes, while a comprehensive analysis of implementation challenges, teacher readiness, and curriculum integration remains limited. In fact, the nature of physics, highly dependent on representation and visualization, makes it one of the most promising disciplines for the application of AR technology (Crogman et al., 2025). Therefore, a systematic literature review is required not only to examine the potential of AR as an instructional medium but also to explore the challenges of its implementation and the directions of future research.

In light of these conditions, this study aims to provide a comprehensive overview of research developments on augmented reality in physics education over the past five years (2020–2025), not methodological innovation. Through mapping and critical analysis of existing evidence, this study attempts to combine scattered findings and provide clearer theoretical and practical directions for the integration of AR in physics education, analyzing its potential and benefits for learning outcomes and student engagement, identifying implementation challenges across different educational levels, and formulating future research directions that are adaptive to curriculum needs and advancements in educational technology. In line with these objectives, this study examines the implementation of AR in physics education (2020–2025), its benefits for conceptual understanding and student engagement, the challenges of integrating it into the classroom, and the direction of future development to align with curriculum needs and developments in educational technology. The findings of this study are expected to serve as both a scientific and practical reference for researchers, educators, and educational media developers in optimizing the use of AR to enhance the effectiveness and relevance of physics education in the digital era.

METHODS

This study employed a Systematic Literature Review (SLR) approach to identify, evaluate, and synthesize previous research related to the implementation of Augmented Reality (AR) in physics education. The SLR method was selected due to its systematic, transparent, and replicable nature in presenting research evidence, thereby providing a comprehensive overview of the potential, challenges, and future directions of AR-based learning research. This approach aligns with widely recognized SLR guidelines and offers benefits not only for researchers by mapping research gaps but also for educational practitioners, as it presents empirical evidence supporting learning innovation.

Data were collected through article searches in ScienceDirect, IEEE Xplore, Google Scholar, and SINTA, covering publications from 2020 to 2025. The search was conducted using the keyword combination "Augmented Reality" AND "Physics Education" OR "Physics Learning." The initial search yielded 320 articles. The subsequent selection process followed the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) flow.

During the identification stage, duplicate and irrelevant articles were removed, resulting in a reduced dataset for screening. In the screening stage, selection was based on titles and abstracts, yielding articles deemed suitable for further review. The eligibility stage involved a full-text examination of each article to assess the relevance of AR in physics learning. Articles that were not accessible in full text, not peer-reviewed, or unrelated to the study context were excluded. Ultimately, 25 articles met the inclusion criteria and were analyzed in this study.

To ensure methodological accuracy, a quality appraisal was conducted on all articles that passed the selection based on clarity of purpose, appropriateness of research design, transparency of data collection, validity of analysis, and relevance of findings to the implementation of AR in physics learning. Each aspect was assessed on a three-point scale (low, medium, high), and only articles with a minimum quality rating of medium were included in the final synthesis. The data were analyzed using thematic analysis through the stages of thorough reading, extraction of key information, coding of findings, grouping of codes into categories, and synthesis into main themes. This process was carried out iteratively to ensure consistency and coherence between themes. These stages are shown in Figure 1. The research stages are as follows.

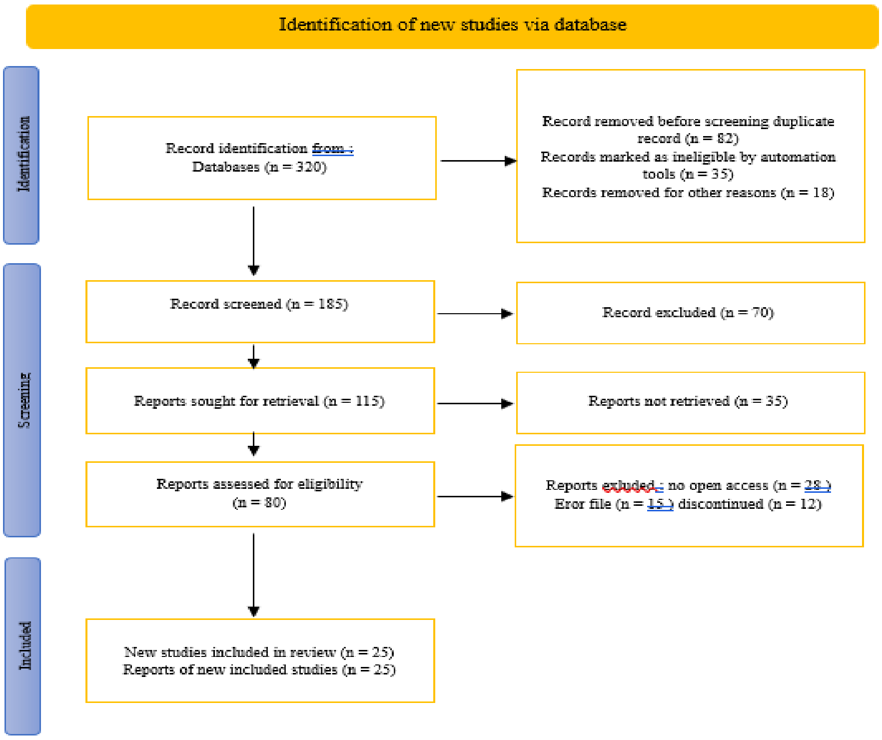

Figure 1 PRISMA flow diagram of the study

In this analysis, new studies were initially identified through database searches, yielding a total of 320 records. Prior to screening, several records were removed based on predefined criteria: 82 duplicates were eliminated, 35 records were flagged as ineligible by automated tools, and 155 records were excluded for other reasons. Following this initial screening, 185 records remained for further processing. Subsequently, 70 records were excluded from the analysis. Of the remaining 115 reports assessed for eligibility, further screening was conducted. During this stage, 28 reports were excluded due to a lack of open access, 15 reports were excluded because of file errors, and 12 reports were removed due to discontinuation. Ultimately, the final dataset comprised 25 newly identified studies that met all inclusion criteria and were included in this review.

RESULTS AND DISCUSSION

Augmented Reality in Physics Education

Augmented Reality (AR) integrates the real world with virtual elements in real time, creating interactive, contextual, and immersive learning experiences. In the context of physics education, AR plays a crucial role in bridging the gap between abstract phenomena and students' concrete experiences (Nurjanah et al., 2024). Through the integration of 3D images, simulations, and direct interaction with virtual objects, AR provides concrete visual representations of complex physical phenomena.

Trends in research over the past five years (2020–2025) indicate a significant increase in the use of AR in science education. Garzón et al., (2020), in a meta-analysis of 62 studies, reported an effect size of 0.71 on learning outcomes, indicating a moderate to high effectiveness of AR. Additionally, studies by Faridi et al. (2021); Lin et al. (2023) demonstrate that AR use can enhance students' critical thinking skills and conceptual understanding. As shown in Figure 2, research trends in augmented reality have increased during the 2020 – 2025 period.

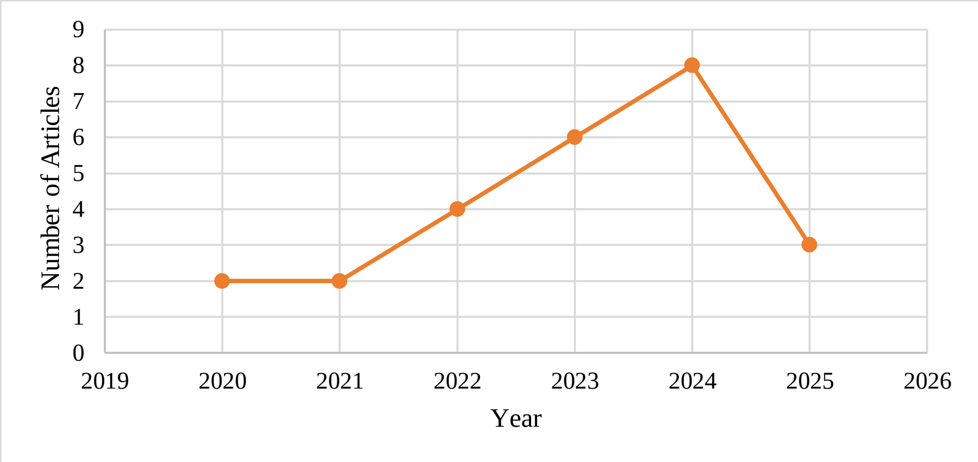

Figure 2 Publication trends of augmented reality in physics education (2020–2025)

Furthermore, several studies have demonstrated the successful application of AR across various physics topics. Yu et al. (2023) developed MagAR to visualize magnetic fields, while Widiasih et al. (2023) implemented AR in the topic of human eye optics, resulting in a significant increase in student participation and learning interest. Similar findings were reported by Arymbekov et al. (2024) in nuclear physics learning and by Novita (2023), who utilized an AR-based e-book to teach the concepts of temperature and heat.

Recent studies, such as that by Hedenqvist et al. (2023), emphasized that AR is particularly effective for teaching torque concepts, as it allows interactive engagement with virtual objects that represent forces and moments. Meanwhile, Cárdenas-Sainz et al. (2023); Zatarain-Cabada et al. (2023) developed Web-XR platforms, enabling AR-based learning without the need for specialized devices. This advancement expands access to AR technology for institutions with limited resources. Table 1 presents a summary of the key characteristics of the studies analyzed in this research.

Table 1 Publication trends of augmented reality (AR) by method, concept, and subject matter

No	Author(s) (year)	Research focus/context	Method & sample	Main findings	Relevance to Physics Education
1	Garzón & Acevedo (2020)	Meta-analysis of AR implementation in education	Analysis of 62 quantitative studies (N ≈ 4,578)	Effect size of 0.71 on learning outcomes	Provides strong empirical evidence for the effectiveness of AR in science education
2	Faridi et al. (2020)	AR application in electromagnetism at high school level	Quasi-experimental design (N = 80)	Improved critical thinking and learning gain	Facilitates interactive visualization of Lorentz force and magnetic induction
3	Saputro (2021)	AR use in high school physics to reduce misconceptions	Experimental design	Reduces misconceptions of abstract concepts	Simplifies understanding of force and field concepts through 3D visualization
4	Arymbekov (2022)	AR application for nuclear physics learning in high school	Solomon Four-Group design	AR more effective than virtual laboratory	Relevant for modern physics and nuclear energy learning

No	Author(s) (year)	Research focus/context	Method & sample	Main findings	Relevance to Physics Education
5	Lin et al. (2022)	Reflective AR in elementary science inquiry	Quasi-experimental design (N = 81)	Enhances higher-order thinking skills	Promotes visual-based scientific inquiry skills
6	Yu et al. (2022)	Development of MagAR for magnetic field topics in junior high school	Quasi-experimental design	Increases motivation and reduces learning anxiety	Provides three-dimensional visualization of magnetic fields
7	Dutta et al. (2023)	Integration of AR in the flipped classroom model	Experimental design (N = 128)	Improves critical thinking and learning motivation	Strengthens project-based learning implementation
8	Hedenqvist et al. (2023)	AR implementation for torque concepts	Experimental design (N = 26)	Enhances conceptual understanding and student participation	Supports mechanics learning through virtual experimentation
9	Widiasih et al. (2023)	AR application in eye optics for university students	Experimental design	Increases learning interest and reduces misconceptions	Visualizes the optical system of the eye in a realistic and interactive way
10	Novita (2023)	AR-based physics e-book development on heat and temperature topics	Research and Development (4D model), N = 135	Improves students' learning interest and engagement	Effective for contextual thermodynamics learning

Overall, among the 25 studies analyzed (as seen in Table 1), the majority employed a quasi-experimental method (60%), followed by research and development (R&D) studies (20%) and true experimental designs (20%). Comparative analysis based on research design also shows significant differences in findings. Experimental and quasi-experimental studies consistently report significant improvements in conceptual understanding and learning motivation, especially in structured classroom interventions. In contrast, development-based research (R&D) places more emphasis on the feasibility, practicality, and validity of media design than on quantitative measurements of learning outcome improvements. In addition, studies that integrate AR into blended learning or flipped classroom models tend to show a stronger impact on higher-order thinking skills than the use of AR alone. This suggests that the effectiveness of AR is highly dependent on the pedagogical integration model used. The most frequently investigated topics include electromagnetism, optics, and mechanics. The findings consistently demonstrate that the use of Augmented Reality (AR) enhances students' cognitive, affective, and psychomotor engagement in physics learning.

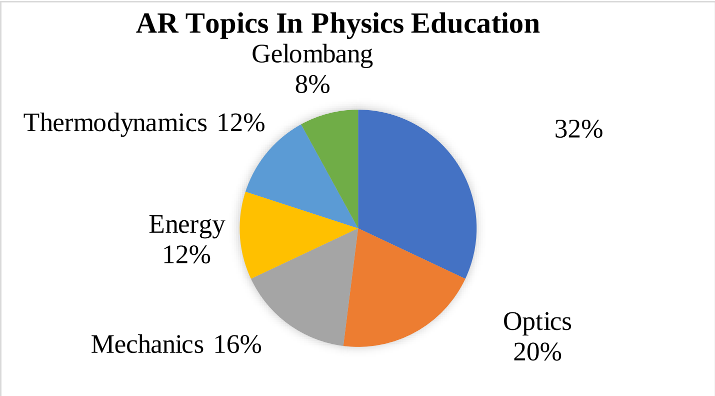

Figure 3Distribution of AR topics in physics

The Potential of Augmented Reality in Physics Education

The synthesis of 25 studies reveals that Augmented Reality (AR) holds three main potentials in physics education: enhancing conceptual understanding, increasing learning motivation and participation, and deepening scientific inquiry experiences. First, from a cognitive perspective, AR has been proven effective in improving students' comprehension of abstract concepts. Sasikumar et al. (2022) reported a significant improvement in understanding the Lorentz force through 3D magnetic field simulations. Similarly, Al-Alwan et al. (2020) found that inquiry-based reflective AR promotes analytical and reflective thinking skills. Furthermore, Asyhari et al. (2024) emphasized that integrating AR in blended learning environments enhances learning outcomes in magnetic topics.

Second, from an affective perspective, AR improves students' motivation and engagement in learning. Novita (2023) demonstrated that AR-based physics e-books make students more enthusiastic about studying concepts such as temperature and heat. Dutta et al. (2023) discovered that implementing AR in a flipped classroom environment strengthens critical thinking and collaboration skills. Likewise, Widiasih et al. (2023) reported similar findings in optics learning, where visualizations of the human eye system made abstract concepts more tangible and comprehensible.

Third, AR shows strong potential in enhancing scientific inquiry experiences. Radu et al. (2023) found that AR enables learners to explore the concepts of force and torque through realistic virtual observations and experiments. Through AR integration, physics learning can transform from passive knowledge acquisition into an active, inquiry-based experience characterized by dynamic visualization and interactive exploration. A comparative analysis based on research design shows that experimental and quasi-experimental studies tend to report significant improvements in concept understanding and learning motivation. Meanwhile, R&D research focuses more on the feasibility and validity of media design than on measuring learning outcomes. In addition, the integration of AR in blended learning or flipped classroom models shows a stronger impact on higher-order thinking skills. These findings confirm that the effectiveness of AR depends on the pedagogical integration model used.

Challenges in Implementing Augmented Reality in Physics Education

Despite its significant potential, research findings indicate three main categories of challenges in implementing Augmented Reality (AR) in physics education: technological, pedagogical, and contextual challenges. Zhang et al. (2024) identified that limitations in devices, connectivity issues, and visual fatigue are among the key barriers in AR-based learning environments. Similarly, studies by Laumann et al. (2024); Ou Yang et al. (2023) highlighted concerns related to device compatibility and the need for high-performance hardware, which often hinder implementation, particularly in schools with limited resources.

From a pedagogical perspective, Putra et al. (2024) found that many teachers still lack sufficient digital literacy to design and develop AR-based learning content. Furthermore, numerous educators tend to perceive AR merely as a supplementary tool rather than an integral component of instructional strategy. Kholiq (2020); Upadhyay et al. (2024) emphasized the importance of teacher training and well-structured instructional design guidelines to ensure the effective integration of AR into the physics curriculum.

Contextual factors such as institutional support, device procurement costs, and program sustainability also serve as major barriers to AR implementation. Studies by Villada Castillo et al. (2025); Zhan et al. (2020) indicate that AR initiatives often stagnate at the project stage due to the lack of long-term policy and financial support. These challenges, however, can be mitigated through collaborative approaches among researchers, educators, and policymakers to strengthen infrastructure readiness and enhance teacher competencies in AR-based education.

Comparative findings also show that AR implementation challenges differ based on institutional context. Schools with limited technological infrastructure generally face hardware and internet connectivity constraints. Conversely, at the university level, challenges are more related to learning design and the integration of AR into existing curricula. Studies conducted in developing regions also report issues of program sustainability and policy support more frequently than studies in regions with more advanced technological readiness. Based on this context, it is important to align AR implementation strategies with institutional readiness and local socio-economic conditions. The challenges of AR implementation are shown in Figure 4.

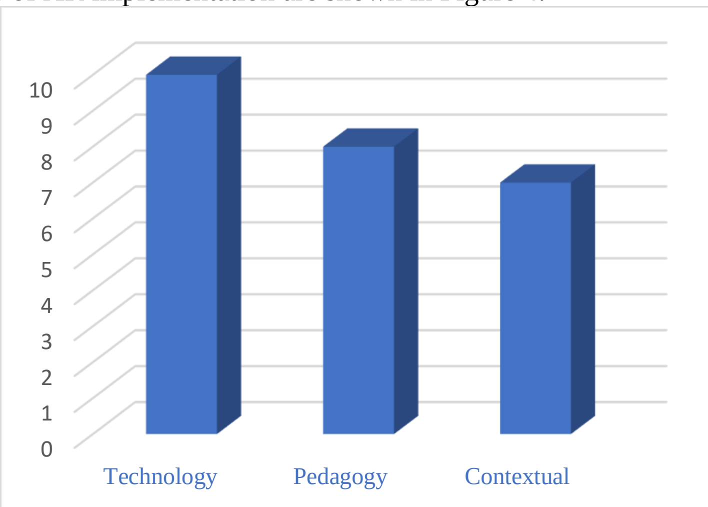

Figure 4 Implementation challenges of AR

Future Research Directions

The findings of this review indicate that future research on Augmented Reality (AR) in physics education is moving toward technological integration, local contextualization, and inclusive approaches. The integration of AR with Artificial Intelligence (AI) and the Internet of Things (IoT) represents a primary research direction. Ateş (2025) developed an AR-based Intelligent Tutoring System capable of providing adaptive feedback to students, signifying a paradigm shift from visualization-based learning to data-driven adaptive learning.

AR also holds great potential for application in local wisdom and industrial contexts, such as renewable energy systems and precision agriculture. For instance, AR can be utilized to demonstrate the law of energy conservation in biogas systems or energy conversion processes in palm oil mills, aligning with the goals of energy literacy and Education for Sustainable Development (ESD). Moreover, recent trends highlight the growing importance of inclusive learning and teacher training through AR. Iatraki & Mikropoulos (2025) found that AR facilitates science learning for students with special needs by providing accessible and interactive visual experiences. Additionally, teacher readiness remains a key factor in ensuring the sustainable implementation of AR in education.

Table 2 Future research focus on AR in physics education and development indicators

Research focus area	Development direction and objectives	Expected indicators
Integration of AR with AI and IoT	Developing adaptive learning systems that provide real-time feedback based on students' learning difficulties	Adaptive AR, automated analytics, personalized learning
Context-based and industry-oriented curriculum	Linking AR applications with themes such as renewable energy, biogas, and palm oil industry contexts	Local relevance, energy literacy, integration of Education for Sustainable Development (ESD)
Inclusive and socially equitable learning	Designing AR environments accessible for students with special needs and disabilities	Inclusive engagement, equitable access to educational technology
AR-based evaluation and assessment	Developing standardized instruments to evaluate the long-term effectiveness of AR implementation	Valid rubrics, longitudinal analysis, measurable learning impact
Teacher training and digital literacy	Enhancing teachers' capacity in AR-based instructional design and digital pedagogy	Digital pedagogical competence, sustainable implementation
Multidisciplinary collaboration	Integrating AR research with engineering, psychology, and the creative industries to foster educational innovation	Cross-disciplinary collaboration, innovative learning models

Research indicates that Augmented Reality (AR) is highly effective in enhancing both learning outcomes and student motivation. However, challenges remain regarding its implementation and teacher training (Rifa'i et al., 2025; Rizki et al., 2025). The integration of AR with Artificial Intelligence (AI) and industry-specific contexts is predicted to be the most promising research direction over the next five years. Consequently, AR is expected to function not only as an instructional aid but also as a core component in developing an intelligent, contextual, and sustainable ecosystem for physics education (Aji et al., 2025).

CONCLUSION

Based on the synthesis of reviewed studies, this review confirms that the implementation of AR has made a significant contribution to transforming physics education in the digital era. AR serves not only as a visualization tool but also as an interactive learning medium that integrates the real and virtual worlds in real time. Through three-dimensional representations, AR helps students comprehend complex physics phenomena, strengthens the connection between theoretical concepts and empirical experiences, and enhances learning outcomes, motivation, and active participation in the learning process. In practical terms, these findings confirm that physics teachers need to integrate AR pedagogically into abstract concepts to encourage interactive and contextual learning. Schools need to ensure the availability of infrastructure and ongoing professional training, while policymakers need to support the integration of immersive technology into the curriculum and digital transformation strategies for education. This systemic support is a prerequisite for the effective, equitable, and sustainable implementation of AR.

However, the effectiveness of AR is not without challenges, particularly regarding teacher readiness, digital literacy, and limitations in educational infrastructure. Insufficient technical support and school policies often hinder the optimal utilization of this technology.

Looking forward, future research directions point to the integration of AR with AI to create adaptive learning systems, especially in local contexts such as energy and environmental industries. This integration opens opportunities for personalized and responsive learning experiences tailored to students' abilities. Moreover, it enhances the relevance of physics education to local contexts in Indonesia, expanding the role of AR beyond a learning tool while reinforcing its connection to energy and environmental sustainability, in alignment with the goals of ESD.

This study has several limitations. Variations in research methodology, the limited scope of publications, and restricted access to paid journals may have affected the completeness and consistency of the data. Therefore, the findings should be interpreted with caution, particularly when generalizing to broader contexts.

Despite these limitations, the findings highlight the significant potential of AR as a contextual and adaptive approach to physics education. Effective implementation requires not only enhanced teacher competence but also adequate digital infrastructure. Future research is encouraged to explore AR in greater depth and to link it with physics concepts that are relevant to local contexts, such as energy and environmental systems, thereby supporting the advancement of innovative and sustainable physics learning.

CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

AUTHOR CONTRIBUTIONS STATEMENT

Author contributions: EAS: conceptualization, writing, original draft. AF: methodology, data curation. HA: supervision, writing, review & editing.

AI DISCLOSURE STATEMENT

The authors declare that this research was prepared, researched, written, and edited without the aid of artificial intelligence (AI) techniques.

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