Vol. 15, No. 04, pp. 2348-2366, 2025 DOI: 10.23960/jpp.v15i4.pp2348-2366

Jurnal Pendidikan Progresif

e-ISSN: 2550-1313 | p-ISSN: 2087-9849
http://jpp.fkip.unila.ac.id/index.php/jpp/

Enhancing High School Physics Learning Through Augmented Reality: A Bibliometric and Systematic Review

Tugirin[1,*], Heru Kuswanto[1], Deo Alfitra Ramazhoni[1], Rahmania Amanah Putri[1], Riyadi Muslim[2], & Jordan Kyle More[3]

[1]Department of Magister Physics Education, Yogyakarta State University, Indonesia
[2]Department of Manufacturing Engineering Technology, Sebelas Maret University, Indonesia
[3]Department of Computer Science, US Air Force Academy, United States of America

*Corresponding email: tugirin0129.2024@student.uny.ac.id

Received: 19 August 2025 Accepted: 06 November 2025 Published: 27 November 2025

Abstract: Enhancing High School Physics Learning Through Augmented Reality: A Bibliometric and Systematic Review. Objective: This study aims to investigate the research trends, opportunities, effectiveness, and challenges of implementing Augmented Reality (AR) technology in physics education through a systematic literature analysis. **Methods:** This research employed a bibliometric and systematic review approach of 45 selected journal articles obtained from the Scopus database. Data were extracted on May 2, 2025, covering publications from 2020 to 2025. The initial search using the keywords "(augmented reality) AND (physics learning)" yielded 167 documents, which were rigorously filtered based on inclusion and exclusion criteria. The analysis was conducted using the Biblioshiny (R) software to generate thematic maps, publication trends, and collaboration networks. **Findings:** The findings reveal that AR technology provides significant opportunities to develop interactive, immersive, and contextual physics learning experiences, particularly in visualizing abstract physics concepts. AR has proven effective in enhancing students' conceptual understanding, scientific literacy, and critical thinking skills. However, its implementation still faces crucial challenges, including a lack of curriculum-aligned content, limited technical infrastructure, and insufficient teacher training. **Conclusion:** Integrating AR technology into the physics curriculum has demonstrated a significant and positive impact on enhancing learning quality. Successful implementation depends on collaborative efforts among curriculum developers, educators, and policymakers to overcome the identified challenges. These findings provide a strategic foundation for developing sustainable, adaptive, and relevant physics education in the digital era.

Keywords: augmented reality, conceptual understanding, physics learning, biblioshiny, systematic literature.

To cite this article:

Tugirin, Kuswanto, H., Ramazhoni, D. A., Putri, R. A., Muslim, R., & More, J. K. (2025). Enhancing High School Physics Learning Through Augmented Reality: A Bibliometric and Systematic Review. *Jurnal Pendidikan Progresif*, *15*(4), 2348-2366. doi: 10.23960/jpp.v15i4.pp2348-2366.

INTRODUCTION

The development of Augmented Reality (AR) technology in the science learning process is very rapid in today's digital era. Augmented reality has great potential to radically change science education by making abstract science concepts visible and interactive. (Jiang et al., 2020). The use of augmented reality creates an environment that fully integrates next-generation AR-assisted notes, virtual laboratories, and interactive learning with real-time, application-centered scenario creation. (Lai & Cheong, 2022). Physics is a branch of science that studies the various properties of energy and matter. Most of the principles of Physics are based on mathematics, mechanics, optics, electricity, magnetism, and thermodynamics. It is often difficult for students to understand concepts because they cannot visualize the phenomena, thus exacerbating the problem and a lack of interest in STEM subjects. (Faridi et al., 2021). AR can be effective in providing better visualization and interaction with real-life three-dimensional virtual objects that can facilitate the learning experience. (Radu & Schneider, 2023) Added that learning physics is often difficult for students because concepts such as electricity and magnetism (Alé-Silva & Huerta-Cancino, 2024) are not easily visible to the naked eye. Sound cannot be seen with the naked eye. Emerging technologies such as AR can transform education by making challenging concepts visible and accessible to beginners.

AR technology represents one of the most recent innovations gaining significant attention in science education. Numerous studies have demonstrated that AR holds great potential to enhance students' engagement, motivation, and conceptual understanding (Koumpouros, 2024). Although AR has been applied in various levels of physics education, its exploration remains limited across specific sub-disciplines and has yet to be fully integrated into the curriculum (Arymbekov et al., 2024). Arymbekov et al. (2024) further emphasized the need to equip both teachers and students with the technical and pedagogical competencies necessary to effectively connect virtual content with real-world learning contexts.

Recent bibliometric findings indicate that students' interest in STEM fields, particularly physics, remains relatively low due to the difficulty of understanding abstract concepts such as electricity, magnetism, and wave phenomena (Faridi et al., 2021; Freese et al., 2023). Based on an analysis of 401 international publications related to "augmented reality" and "physics learning", the majority of studies concluded that AR effectively bridges this gap by enabling immersive and interactive visualization of three-dimensional phenomena. Therefore, AR serves as a strategic technological tool to address students' low interest in STEM while improving learning outcomes and critical thinking skills in physics education (Radu & Schneider, 2023; Rizki et al., 2025).

Based on the conducted literature review, research on the effectiveness of AR in physics education reveals a strong consensus that AR is significantly effective, rather than an ongoing debate. However, upon closer examination, important nuances emerge regarding how AR's effectiveness manifests and the factors influencing it, offering a valuable starting point for further academic discussion. Most studies agree that AR is significantly effective in enhancing various aspects of learning. Studies by Alfianti et al. (2023) and Rizki et al. (2025), for instance, indicate that integrating AR with local wisdom (ethnophysics) not only enhances students' creativity and motivation but also improves their multiple representation and problem-solving skills. These findings are reinforced by Rizki et al. (2025), who concluded that combining AR with cooperative learning models and digital games can enhance critical thinking skills and learning motivation. Similar support is provided by Zafeiropoulou et al. (2021), who emphasize that AR-based game-based learning (ARGBL) offers a promising pathway for teaching and learning development. This is also supported by Nasir & Fakhruddin (2023), who report the positive impact of AR-based multimedia learning on students' academic achievement in physics.

Although this body of evidence supports the effectiveness of AR, the emerging "debate" or research gap lies not in whether AR has a positive impact, but rather in the contexts and mechanisms that shape its effectiveness. A critical question that warrants further exploration is: Are improved learning outcomes primarily caused by the AR technology itself or by the accompanying pedagogical design and learning elements (such as local wisdom integration, cooperative models, or game components)? In other words, AR's effectiveness may not be solely a function of its technology, but rather the result of a synergy between AR's technical capabilities and effective instructional strategies. This necessitates a deeper investigation into the optimal combinations and conditions for its implementation in physics education.

Augmented reality (AR) technology continues to evolve, requiring ongoing research and development to optimize its use in education. As highlighted by Altmeyer et al. (2020), further studies are necessary to examine whether the advantages of AR, particularly its capacity to integrate information from multiple sources that are close in time and space, can be applied broadly across different educational disciplines. Cai et al. (2021) further emphasized that most AR studies in physics education mainly focus on improving students' academic achievement and learning motivation, while only a few explore the cognitive mechanisms underlying these improvements. In addition, Radu & Schneider (2023) noted that AR often produces a novelty effect. Although specific AR visualizations can effectively help students grasp spatial and structural relationships, they may also hinder understanding of kinesthetic or motion-based concepts. Therefore, more comprehensive research is needed to determine how far AR can provide lasting and meaningful benefits in physics learning.

This review distinguishes itself from prior works not merely through the analytical instrument employed, namely Biblioshiny within the R environment, but through the depth and originality of insights that this approach generates. Previous reviews, such as those by Lai & Cheong (2022), Prahani et al. (2022), Sharma et al. (2022), Tene et al. (2024), and Vidak, Movre Šapiæ, & Zahtila (2024), have contributed significantly to understanding the potential of AR in education. However, most of these studies remain descriptive in nature, focusing on technological advancements, opportunities, and pedagogical impacts without systematically mapping the intellectual structure, thematic evolution, and research dynamics within the specific domain of physics education. They tend to overlap in discussing benefits and challenges, yet fail to reveal how research topics interrelate, evolve, and converge toward particular theoretical or methodological directions.

In contrast, this review integrates a bibliometric analysis using Biblioshiny (R) with a critical interpretive synthesis, providing a more comprehensive and data-driven understanding of the field. This approach allows the identification of longitudinal publication trends and citation dynamics between 2020 and 2025, while simultaneously visualizing thematic evolution through centrality density mapping to distinguish between motor themes and emerging or declining topics. Moreover, the co-occurrence analysis uncovers interdisciplinary bridge areas, such as the integration of AR with artificial intelligence, gamification, and local wisdom, that have not been explicitly addressed in earlier reviews. The findings also highlight the limited nature of international collaborations, which are often dominated by regionally confined networks, as well as methodological inconsistencies related to sample size, device comparison, and outcome measurement.

Therefore, the novelty of this study lies not only in the use of a more sophisticated bibliometric tool but in the conceptual synthesis that such analysis enables. By combining quantitative mapping with qualitative interpretation, this paper moves beyond the descriptive tendencies of previous reviews, offering a structured, evidence-based portrayal of how AR research in physics education has developed, where thematic concentrations currently lie, and what research gaps must be addressed. In essence, this review provides a forward-looking framework that situates AR research within its broader intellectual and pedagogical context, revealing both consolidation and fragmentation across global scholarship.

This review paper focuses on the development of augmented reality technology in physics education. This paper will also discuss the trend of research and development of augmented reality technology in physics learning. Finally, this paper will discuss the challenges of using augmented reality in physics education in schools and the future direction of augmented reality technology in physics education. The review article is divided into four parts: Part 1 discusses the introduction of the importance of augmented reality technology in physics learning, Part 2 covers the materials and methods used in the review, Part 3 presents the results and discussion of trends, opportunities, effectiveness, challenges, and future research design of augmented reality technology in physics learning. Finally, part 4 provides a conclusion.

To identify current trends, challenges, and research gaps regarding the implementation of AR in physics learning, a Systematic Literature Review (SLR) was conducted as a preliminary analysis. The review followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) protocol and employed a combination of bibliometric and qualitative content analyses. The main goal of this review was to map the evolution of research on AR in physics education, highlight underexplored areas, and justify the need for more integrative pedagogical frameworks.

■ METHOD

Research Design

This research is a systematic literature review, whose steps include formulating research questions, identifying relevant literature, selecting, and extracting and synthesizing data. This research began with the identification of Scopus-sourced articles, which were carried out in May 2025. The identified articles are those in the field of augmented reality in physics learning, specifically those published between 2020 and 2025. This study adopts a qualitative narrative review, focusing on the thematic synthesis of the literature without conducting statistical meta-analysis. Although primarily qualitative, this review combines descriptive quantitative synthesis (e.g., frequency calculations based on publication trends and citations, most productive journals, wordcloud, and themes) to summarize key patterns in the literature.

Search Strategy

The keywords and filters used were as follows: There were 114 documents with keywords: (TITLE-ABS-KEY (augmented reality) AND TITLE-ABS-KEY (physics learning)) AND PUBYEAR > 2018 AND PUBYEAR < 2026 AND (LIMIT-TO (DOCTYPE, "ar")) AND (LIMIT-TO (LANGUAGE, "English")) AND (LIMIT-TO (OA, "all")) AND (LIMIT-TO (SRCTYPE, "j")). There were 53 documents with keywords: (TITLE-ABS-KEY (augmented reality) AND TITLE-ABS-KEY (physics education)) AND PUBYEAR > 2018 AND PUBYEAR < 2026 AND (LIMIT-TO (DOCTYPE, "ar")) AND (LIMIT-TO (SRCTYPE, "j")) AND (LIMIT-TO (LANGUAGE, "English")) AND (LIMIT-TO (OA, "all"))

A total of 167 documents were then collected in a single database to filter out duplicate articles. The first stage involves filtering duplicate articles to obtain 131 articles, which are then further filtered using an abstract selection process aimed at removing articles that are not relevant to the topic or outside the educational context. Of the 131 articles, 25 were deemed irrelevant to the topic, and 21 were outside the educational context. Therefore, 85 articles were obtained at this stage and will be screened again. The next stage is to filter the articles that are accessible and those that are not, even if they are relevant to the research topic. As a result, up to seven articles could not be accessed, resulting in 78 articles for final screening. The final stage, which involves 78 articles, will then be filtered again to remove articles that are not the result of research (e.g., review articles, content analysis) and exclude articles whose subjects are not school students (e.g., communities, students, and teachers). The results obtained were 45 articles, which will then be analyzed systematically.

Data Analysis

This study adheres to the PRISMA guidelines to ensure a transparent and rigorous methodology, as shown in Figure 1. All reference management is done using Mendeley, while the remaining 45 articles are then read, analyzed, categorized, and coded using the spreadsheet program. In addition, this study aims to reveal the results of increased research, identify opportunities for effective physics learning with augmented reality technology, address challenges in implementing augmented reality technology in the physics learning process, and provide recommendations for further research. To visualize it, the Biblioshiny software is used. Visualization encompasses trend analysis, thematic mapping, collaboration, cluster analysis, and thematic evolution visualization. Thematic maps are used to show the density and centralization of various topics. Density indicates the relevance of a topic based on the number of studies. Centralization is represented on a horizontal axis, distinguishing topics that are the center of attention in that field from less influential topics. The combination of these two factors helps identify key research themes and suggests areas for future investigation.

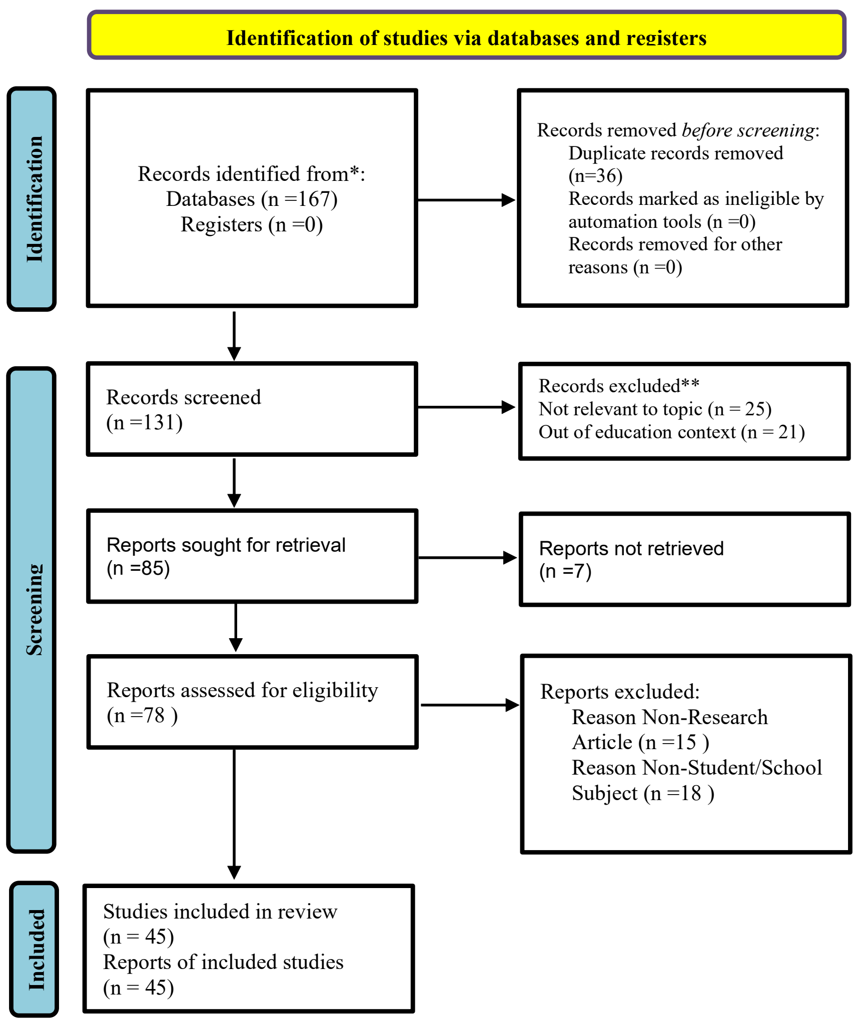

Figure 1. Review design for augmented reality (AR) on the PRISMA protocol

RESULT AND DISCUSSION

Of the 85 articles obtained, 45 articles were then analyzed in depth. Many articles are eliminated because most of them discuss the use of augmented reality at the student level, and do not focus on students. Additionally, numerous articles discuss the broader application of augmented reality, encompassing subjects beyond physics. To btain concrete answers to the research questions posed, the researchers selected articles that specifically focused on the use of augmented reality in physics learning in schools.

Based on Figure 2, the publication and citation trends in AR research related to physics learning exhibit a consistent upward trajectory between 2020 and 2023, followed by a partial decline in 2025 due to the limited data collection period, which ended in May of that year. This upward trend reflects the growing academic recognition of AR as a transformative educational technology that bridges conceptual understanding with experiential learning (Freese et al., 2023; Lai & Cheong, 2022).

The year 2024 saw the highest number of publications (11 documents), indicating a maturation phase in the research field. In contrast, the citation analysis in Table 1 reveals that 2020 contributed the most influential foundational works, with a total of 523 citations and an average of 8.77 citations per document. Seminal studies published in 2020–2021 (Altmeyer et al., 2020; Choi et al., 2021; Thees et al., 2020) established the early theoretical and methodological frameworks, particularly regarding cognitive engagement, immersive visualization, and pedagogical feasibility, that have since underpinned later research directions.

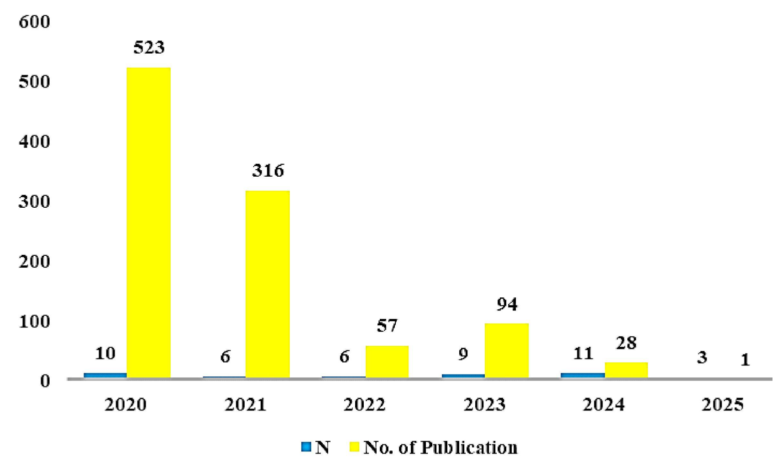

Figure 2. Years-wise publication and citation trend

The continuous annual increase publications (averaging 19%) demonstrates not only the sustained relevance of AR in physics education but also the diversification of research foci from instructional design and student engagement (Arymbekov et al., 2024; Rizki et al., 2024) to AI-driven adaptive systems and mixed-reality integration (Sharma et al., 2022; Vidak al., 2024).

Table 1. Distribution, publication, and citations

Year	N	Total Citation	Mean TC per Document	Mean TC per Year	Citable Years
2020	10	523	8.77	1.12	6
2021	6	316	10.53	1.27	5

2022	6	57	2.38	0.57	4
2023	9	94	3.48	0.62	3
2024	11	28	1.27	0.69	2
2025	3	1	0.33	1.67	1

This trend further suggests a paradigm transition in AR research from exploratory experimentation toward pedagogical normalization, where AR technologies are no longer treated as novel add-ons but as integrated tools within mainstream science education. The emergence of recent works, such as those by Deng et al. (2023), supports this shift, expanding AR's scope into interdisciplinary and context-based applications that enhance scientific reasoning and conceptual visualization in physics learning.

Table 2. Most cited articles about augmented reality

Rank	Title	Author	TC	TC per Year	NTC
1	Effects of learning physics using augmented reality on students' self-efficacy and conceptions of learning	(Cai et al., 2021)	127	25.4	3.06
2	A framework utilizing augmented reality to improve critical thinking ability and learning gain of the students in physics	(Faridi et al., 2021)	99	19.8	2.39
3	The effects of an augmented reality-based magnetic experimental tool on students' knowledge improvement and cognitive load	(Liu et al., 2021)	49	9.8	1.181
4	The effect of using augmented reality and sensing technology to teach magnetism in high school physics	(Abdusselam & Karal, 2020)	40	6.667	0.853
5	Effects of wearable hybrid AR/VR learning material on high school students' situational interest, engagement, and learning performance: the case of a physics laboratory learning environment	(Sun et al., 2023)	35	11.667	2.076
6	Student worksheet with AR videos: physics learning media in the laboratory for senior high school students	(Bakri et al., 2020)	29	4.833	0.619
7	An evaluation of the "Picasa" research project: an augmented reality in physics learning	(Suprapto et al., 2020)	28	4.667	0.597
8	How augmented reality enhances typical classroom experiments: examples from mechanics, electricity, and optics	(Teichrew & Erb, 2020)	22	3.667	0.469
9	Using augmented reality in K-12 education: an indicative platform for teaching physics	(Volioti et al., 2022)	20	5	1.201
10	How Augmented Reality (AR) can help and hinder collaborative learning: a study of AR in electromagnetism education	(Radu & Schneider, 2023)	20	6.667	1.186

The Most Productive Journal

As shown in Table 3, the International Journal of Information and Education Technology (IJIET), published by IACSIT Press, stands out as the most productive outlet for AR research, with seven publications, an h-index of 3, and 31 citations. This indicates that AR in education, particularly in physics learning, has been primarily disseminated through technology-oriented journals, rather than traditional science education platforms, reflecting its strong alignment with the fields of digital innovation and instructional design (Sharma et al., 2022; Vidak et al., 2024).

When evaluating journal productivity and reliability, bibliometric indicators such as h-index, citation impact, and topical relevance serve as robust measures of academic influence (Pianda et al., 2024). The predominance of IJIET and related journals underscores the interdisciplinary nature of AR research, which bridges computer science, educational technology, and engineering education (Lai & Cheong, 2022; Tene et al., 2024). The clustering of AR studies in open-access, high-output journals also suggests a field characterized by rapid publication cycles and technological adaptability features commonly associated with fast-evolving educational innovations (Prahani et al., 2022).

Table 3. The most productive journal on augmented reality technology

Rank	Journal	Publisher	TP	TC	h-indeks
1	International Journal of Information and Education Technology	IACSIT Press	5	31	3
2	Physics Education	IOP Publishing	5	40	3
3	Physics Teacher	AIP Publishing	4	12	2
4	Journal of Technology and Science Education	DOAJ	4	7	2
5	Computer Applications in Engineering Education	Wiley	3	133	4
6	Education and Information Technologies	Springer Nature	2	56	3
7	International Journal of Emerging Technologies in Learning	Scispace	2	54	3
8	International Journal of Interactive Mobile Technologies	Enriched Publication	2	21	5.3
9	Journal of Computer Assisted Learning	Wiley	2	259	2
10	Computers	MDPI	2	22	2

This distribution pattern highlights the emergence of AR-based physics learning as a hybrid domain positioned between technology development and pedagogical practice. Future research should strengthen theoretical linkages between these two domains, ensuring that the integration of AR moves beyond technical novelty toward a sustained pedagogical framework that enhances conceptual understanding and learner engagement in physics education.

WordCloud

Figure 3 presents a word cloud visualization generated from bibliometric keyword analysis, illustrating the relative frequency of terms appearing in the dataset. The term "augmented reality" dominates with 35 occurrences, followed by "students" and "virtual reality" (14 occurrences each), "deep learning" (12 occurrences), and "e-learning" and "learning systems" (6 occurrences each). Other frequently co-occurring terms include "computer-aided instruction," "engineering education," "neural network," "physics education," "simulation," and "thermodynamics" (5 occurrences).

The prominence of "augmented reality" and "students" confirms that research trends in AR remain predominantly learner-centered, emphasizing engagement, motivation, and conceptual understanding (Arymbekov et al., 2024; Lai & Cheong, 2022). The frequent association of "virtual reality" and "deep learning" demonstrates an increasing intersection between immersive environments and artificial intelligence, aligning with global trends toward adaptive and data-driven educational technologies (Sharma et al., 2022; Vidak, 2024). Meanwhile, the recurrent appearance of "physics education," "simulation," and "thermodynamics" suggests that AR is often employed to visualize abstract or experimentally challenging physics phenomena, thereby enhancing students' spatial and conceptual reasoning (Freese et al., 2023; Rahmayani et al., 2024).

This thematic pattern aligns with previous bibliometric insights that position AR as a hybrid domain bridging educational technology and cognitive learning theories, where interactivity and visualization play key pedagogical roles (Prahani et al., 2022; Tene et al., 2024). Thus, the word cloud not only reflects research volume but also reveals the evolving focus of AR-based physics learning toward adaptive, immersive, and student-centered environments.

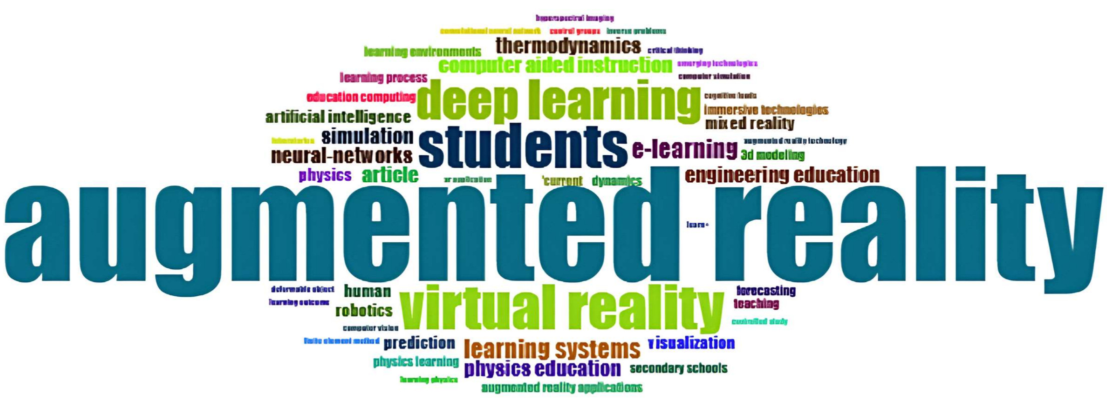

Figure 3. Wordcloud

The linkage between deep learning and virtual reality on the keyword map indicates that educational research is now shifting towards the use of artificial intelligence to create more interactive and adaptive learning experiences. From a theoretical perspective, this supports a constructivist view that emphasizes that students learn better when they actively build knowledge through interaction with the digital learning environment. From a practical perspective, combining deep learning with virtual reality enables the learning system to provide immediate feedback and adjust the level of difficulty according to the student's ability. In physics learning, for example, this technology can be used to create simulations that help students understand complex concepts, such as interference, diffraction, or thermodynamics, in a more realistic way. These findings indicate that research on augmented reality and similar technologies is now not only focused on visualization, but also on how such systems can serve as intelligent learning assistants that enhance students' understanding and independence.

Thematic Map of Keyword

The thematic map in Figure 4 visualizes the conceptual landscape of research on AR in physics learning from 2020 to 2024, generated through co-word analysis using the Biblioshiny package in R. Author keywords (DE) were employed as the analytical field, with a minimum occurrence threshold of five keywords to ensure conceptual relevance. Data normalization was applied using the association strength method, and clustering was performed with the Louvain community detection algorithm. The resulting themes were positioned along two dimensions: centrality (x-axis), indicating overall relevance to the field, and density (y-axis), representing conceptual development and maturity (Pianda et al., 2024).

In the Motor Themes quadrant (upper right), topics such as augmented reality, students, e-learning, virtual reality, and deep learning emerged as core research drivers. This dominance underscores a global emphasis on immersive and intelligent learning environments, where AR and AI converge to promote engagement and personalized instruction (Lai & Cheong, 2022; Sharma et al., 2022; Vidak, 2024). The intersection between AR/VR and deep learning signals an epistemic transition from technology adoption toward cognitive adaptivity, reflecting the field's evolution toward innovative and interactive learning ecosystems.

The Niche Themes (upper left), including education computing, AR application, and student learning outcomes, are theoretically rich but peripheral. They often support methodological advances in learning analytics and AR evaluation frameworks (Tene et al., 2024). Their lower connectivity suggests that they focus on specialized subfields, such as impact measurement and pedagogical refinement, rather than broad theoretical integration**.** The Emerging or Declining Themes (lower left) contain inverse problems and critical thinking. Although these have low centrality and density, their presence indicates an underexplored but promising frontier connecting AR with higher-order cognitive skills, a research gap highlighted by Arymbekov et al. (2024). These themes may represent the next wave of AR-based physics learning studies, focusing on inquiry-based, problem-solving-oriented pedagogies.

In contrast, the Basic Themes (lower right), including physics education, immersive technologies, and the learning process, form the conceptual backbone of the field. They represent fundamental but still maturing topics that underpin AR studies, emphasizing the need for deeper inquiry into cognitive mechanisms, instructional scaffolding, and conceptual transfer (Freese et al., 2023).

Interestingly, a bridging cluster at the intersection of the axes of human, artificial intelligence, and review functions serves as a transitional link between educational practice and computational intelligence, suggesting an increasing alignment between pedagogy and machine-driven adaptivity. Overall, the thematic evolution shown in Figure 4 reveals a paradigm shift in AR-based physics learning from descriptive and feasibility-oriented research toward integrated, intelligent, and adaptive educational ecosystems, consistent with global trajectories reported by Prahani et al. (2022) and Tene et al. (2024).

AR's opportunities also extend to virtual laboratories, allowing for safe experimentation without the need for expensive or inaccessible physical labs (Amelia et al., 2020). Simulations have been shown to reduce experimental risk, particularly in circuits and electronics (Iatraki & Mikropoulos, 2024; Sriadhi et al., 2022; Volioti et al., 2022). When combined with game-based learning, AR enhances motivation, engagement, and creativity (Rizki et al., 2023, 2024), transforming physics from a traditionally abstract discipline into an enjoyable, challenge-driven experience (Raskar & Srivastava, 2025; Ullah et al., 2022).

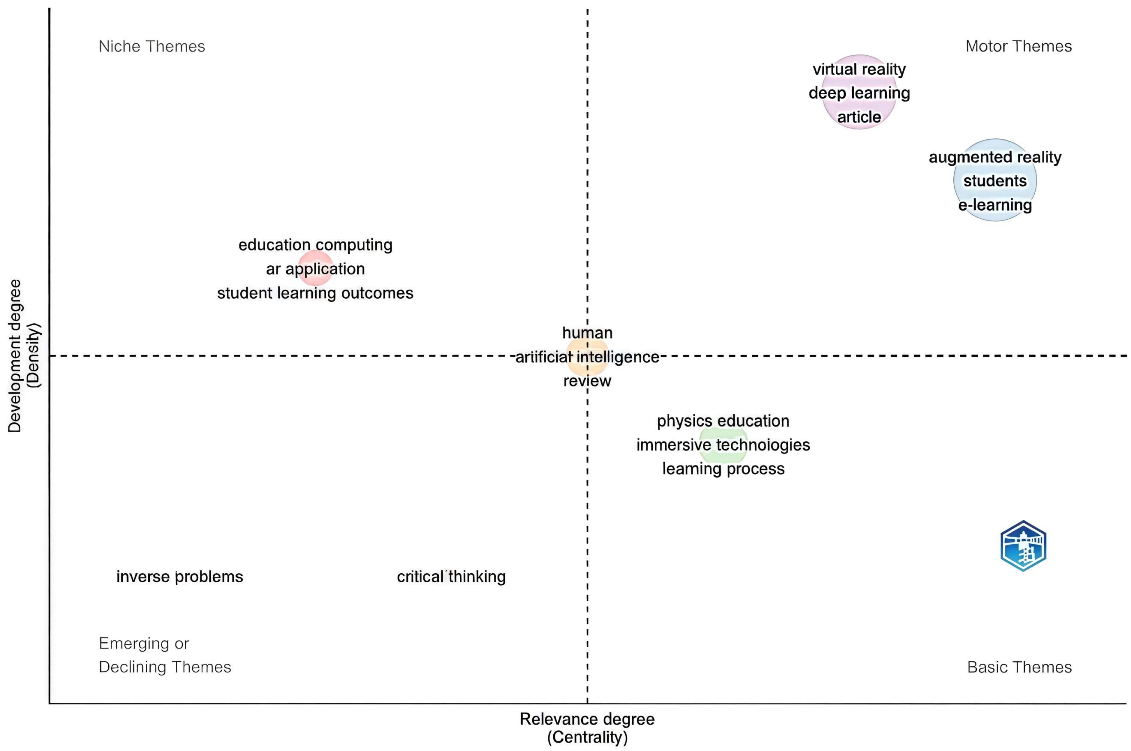

Figure 4. Thematic mapping

Another emerging opportunity lies in integrating AR with local wisdom and cultural contexts (Alfianti et al., 2023). For example, AR-enhanced ethnoscience models contextualize physics concepts through "Wayang" performance and the Pacu Jalur festival, enriching scientific learning with cultural relevance (Rizki et al., 2025; Saprudin et al., 2025). Such cultural AR applications strengthen the link between physics and students' daily realities while promoting national identity in science learning.

Additionally, the combination of AR with artificial intelligence (AI) offers adaptive learning recommendations tailored to student profiles, thereby personalizing learning and enhancing conceptual retention (Abdusselam & Karal, 2020). Studies by Prahani et al. (2022) and Sharma et al. (2022) further demonstrate that AR's interdisciplinary design, which merges deep learning, simulation, and ethnophysics, marks a new frontier for physics education research.

Beyond the bibliometric mapping, the SLR findings reveal that the conceptual clusters identified in the thematic map are underpinned by diverse pedagogical frameworks. Studies incorporating Problem-Based Learning (PBL) (Rahmayani et al., 2024), Contextual Teaching and Learning (CTL) (Rahmayani et al., 2024; Rizki et al., 2024), and STEM-based approaches demonstrate that AR's educational impact relies heavily on instructional design rather than the technology alone. Several papers further highlight the potential of AR for formative assessment through real-time simulations and embedded feedback mechanisms (Alé-Silva & Huerta-Cancino, 2024). Moreover, the emphasis on cognitive load theory across multiple studies (Altmeyer et al., 2020; Liu et al., 2021) aligns with the Basic Themes quadrant, underscoring the importance of optimizing interactivity to avoid cognitive overload. Finally, research linking AR with ethnophysics and local wisdom (Alfianti et al., 2023; Rizki et al., 2025; Saprudin et al., 2025) enriches the Emerging Themes, indicating that contextual and culturally embedded AR models could represent the next frontier of innovation in physics education.

The thematic structure shown in Figure 4 reveals that research on AR in physics learning has evolved from a separate application of technology to a theoretical and pedagogically integrated field. The coexistence between motor, niche, basic, and emerging themes reflects a multidimensional ecosystem where AR connects aspects of visualization, cognition, and culture. The convergence between AR and deep learning suggests an epistemic shift towards intelligent adaptivity. At the same time, the integration of contextual and cultural dimensions marks the emergence of ethnophysics as an inclusive approach in science learning.

Theoretically, this synthesis confirms that AR-based learning is aligned with the framework of constructivism and cognitive load theory, which supports the development of high-level thinking skills through interactive engagement and hands-on experience. In practical terms, this emphasizes the importance of AR design that combines AI-based adaptivity with local cultural contexts to create a learning environment that is not only intelligent but also human-centered and contextually relevant. Thus, this thematic evolution signals a paradigm shift towards an AR-based physics learning model that is adaptive, interdisciplinary, and responsive to cultural diversity.

Network Visualization

Figure 5 presents the co-occurrence network of author keywords derived from bibliometric analysis, illustrating the thematic relationships among studies on AR in physics and educational contexts. The network is structured into three main clusters: blue, green, and red, each representing distinct yet interrelated research trajectories.

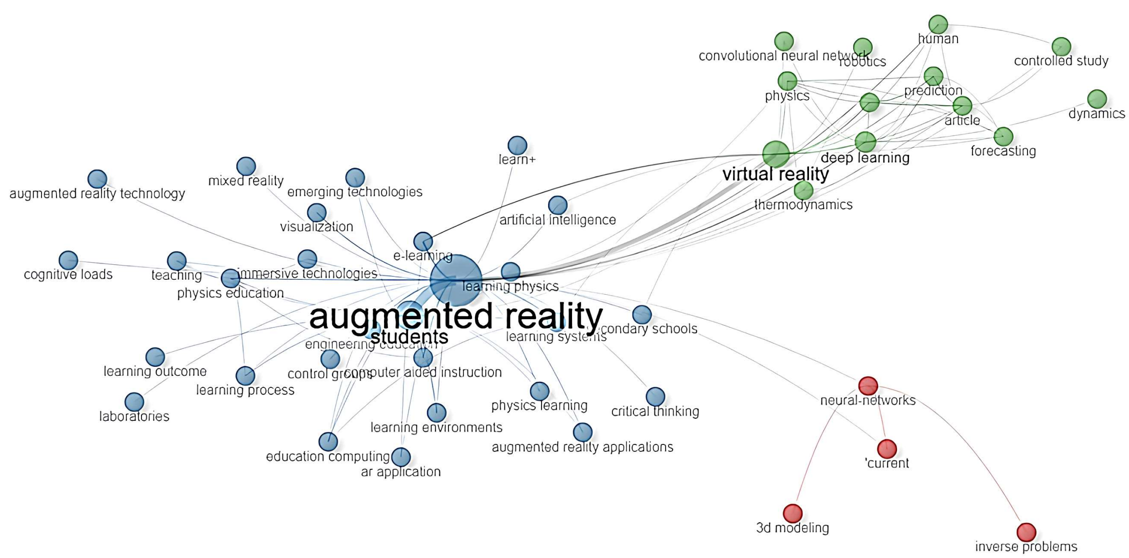

Figure 5. Network visualization

The blue cluster, dominated by augmented reality and students, represents the pedagogical foundation of AR-based learning. Research in this group emphasizes learner-centered design, motivation, and conceptual understanding (Lai & Cheong, 2022; Nasir & Fakhruddin, 2023; Rizki et al., 2024; Utami et al., 2024). Several SLR sources (Cai et al., 2021; Daineko et al., 2020; Faridi et al., 2021) highlight how AR fosters visualization and engagement in physics topics such as mechanics, optics, and thermodynamics. These findings confirm that AR's primary educational contribution lies in transforming abstract phenomena into tangible, interactive experiences (Freese et al., 2023; Rahmayani et al., 2024).

The green cluster links virtual reality, deep learning, and robotics, signifying a technological evolution of AR research. Studies in this group (Giancaspro et al., 2024; Sharma et al., 2022; Vidak, 2024) demonstrate the convergence of AR with artificial intelligence to develop adaptive learning systems and predictive simulations. This aligns with trends toward intelligent tutoring systems, where cognitive adaptivity and real-time feedback enhance personalized learning. Several papers (Amelia et al., 2020; Sriadhi et al., 2022; Volioti et al., 2022) further demonstrate the application of AR/VR in laboratory simulations, which minimizes costs and risks while enabling authentic experimentation.

Meanwhile, the red cluster, which encompasses neural networks, 3D modeling, and inverse problems, represents an emerging research frontier. Studies such as Tene et al. (2024) and Prahani et al. (2022) propose AR-driven modeling frameworks that combine computational simulation with cognitive scaffolding. This area remains underexplored but promises to extend AR's function beyond visualization toward intelligent modeling of physical systems.

The network visualization shown in Figure 5 shows the epistemic maturity in AR research in the field of physics education, where the boundaries between pedagogical and computational aspects are increasingly converging. The coexistence between human-centered clusters (blue) and machine-driven clusters (green and red) reflects the paradigm of symbiotic cognition, in which human learning processes are amplified by artificial intelligence. Theoretically, this connectedness reinforces the perspectives of connectivism and socioconstructivism, which assert that knowledge construction now occurs in collaborative networks between humans and machines, rather than solely in individual cognition.

In practical terms, this integration opens up the opportunity to design intelligent AR environments that can adapt to learners' cognitive states, provide predictive feedback, and automate complex physics simulations. This innovation has the potential to revolutionize lab-based learning into a dynamic ecosystem that is data-oriented, secure, personalized, and context-rich. Thus, the ever-evolving structure of AR research reflects the transformation of education towards hybrid intelligence, where pedagogy and computing combine to cultivate adaptive, exploratory, and independent learners in the digital age.

Collaboration Network

Figure 6 presents the visualization of the author collaboration network generated through bibliometric mapping in Biblioshiny. The purpose of this analysis is to illustrate the structure and intensity of co-authorship relationships in AR research related to physics and educational technology. The network consists of eleven collaboration clusters, each representing distinct research communities with varying degrees of interaction and productivity.

The red cluster, dominated by Indonesian researchers Suprapto, Saphira, and Ramadani, with collaborators such as Mubarak, Wibowo, and Alfarizi, reflects a strong local collaboration pattern primarily centered on AR applications in physics learning. This finding is consistent with previous studies, which report Indonesia as one of the most active contributors to AR education research within Southeast Asia (Rizki et al., 2025; Tene et al., 2024). Despite its productivity, the cluster remains regionally bounded, highlighting the need for broader international engagement.

The green cluster, involving Kuswanto and Rahmad, represents a smaller, emerging research

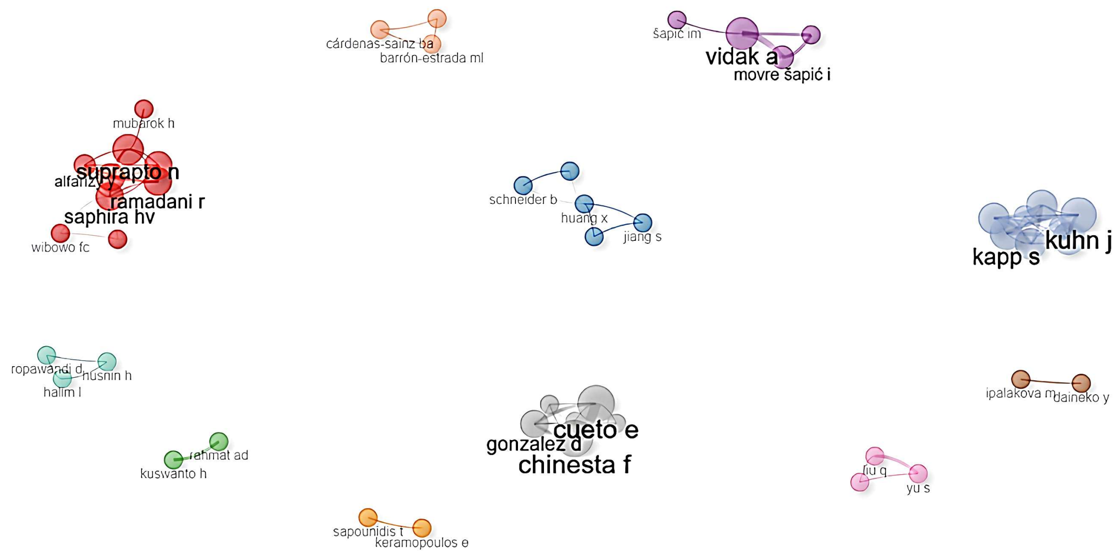

Figure 6. Collaboration network

group with developing connections, often focusing on experimental AR implementation in classroom settings. The purple cluster, led by Vidak and Movre Šapiæ, shows a stable and well-structured collaboration network, likely representing European contributions to the discourse on AR opportunities and challenges (Vidak, 2024).

Meanwhile, the blue cluster comprising Schneider, Huang, and Radu demonstrates a balanced network of cross-regional collaboration, linking Western and Asian research efforts. The gray cluster, led by Chinesta and Gonzalez, forms a dense and cohesive subnetwork associated with engineering education and simulation-based AR studies, aligning with findings from Prahani et al. (2022) regarding the technological orientation of AR research clusters.

The orange cluster, centered on Keramopoulos, and the brown cluster, featuring Ipalakova and Daineko, both indicate limited but focused collaborations, likely representing niche studies in computational and robotics-based AR applications. Similarly, the light-orange cluster, a smaller, dyadic collaboration between Chavez-Echeagaray and Barron-Estrada, suggests the presence of isolated research partnerships that have not yet connected to the broader network.

The co-authorship structure also shows an increasing interdisciplinary nature, connecting educational technologists, physicists, and computer scientists. This interaction enriched the diversity of methodologies and strengthened the development of a hybrid model that combines pedagogical design with intelligent simulation systems. This increasing global collaboration not only has an impact on the quantity of publications but also on the unification of visions towards intelligent, adaptive, and culturally rooted AR learning. In line with the findings (Freese et al., 2023; Tene et al., 2024), this type of collaborative network accelerates innovation by leveraging regional excellence in pedagogical creativity from Southeast Asia, combined with computational precision from Europe and East Asia.

Overall, the visualization reveals that AR research in physics learning is dominated by localized and discipline-specific collaborations rather than global networks. Indonesia stands out as the most active country, yet its collaborations remain primarily domestic. This indicates both a strength and a developmental gap: strong national productivity but limited cross-country integration. Future efforts should therefore encourage international and interdisciplinary collaborations, connecting Asian research communities with European and North American networks to advance the global maturity of AR-based physics learning research (Prahani et al., 2022; Sharma et al., 2022).

The collaboration analysis in Figure 6 highlights that interdisciplinary and international partnerships are increasingly essential for sustaining the advancement of AR-based physics education. The network structure shows that Southeast Asian scholars, particularly from Indonesia and Malaysia, play a central role in integrating cultural and pedagogical perspectives. In contrast, collaborations with European and East Asian researchers contribute technological and computational depth.

Theoretically, this pattern reflects a shift toward knowledge co-construction across regions, where global expertise converges to design culturally relevant yet technologically sophisticated AR models. Practically, it highlights the importance of establishing research consortia and shared platforms to expand access, resource exchange, and data integration. Ultimately, such global collaborations accelerate innovation, enabling the creation of AR ecosystems that are inclusive, adaptive, and responsive to diverse educational contexts.

CONCLUSION

This study provides comprehensive insights into the opportunities, effectiveness, and challenges of implementing Augmented Reality (AR) technology in physics learning. The findings confirm that AR offers substantial opportunities to enhance students' conceptual understanding, foster interactive and flexible experiment-based learning, and increase motivation and engagement through immersive, game-based, and contextually relevant learning experiences. Moreover, AR integration has been proven effective in enhancing scientific literacy, critical thinking, creativity, and multiple representation skills, thereby contributing to deeper cognitive processing and improved academic achievement. However, the study also identifies several challenges that hinder the optimal adoption of AR in schools, including limited technological infrastructure, insufficient teacher readiness, technical difficulties, cognitive load issues, and the need for more pedagogically aligned content design. These constraints underscore the importance of capacity building, professional development, and collaborative efforts among educators, policymakers, and developers to ensure the sustainability of AR-based learning environments.

The findings of this review provide empirical evidence and strategic direction for advancing the development of AR in physics education, emphasizing its potential role in shaping innovative and future-oriented learning ecosystems. This study thus serves as valuable input for stakeholders, including governments, educational institutions, industry, and curriculum designers, to align physics education with emerging technologies. In the broader vision, Augmented Reality has the potential to reshape the paradigm of physics education, transforming it from abstract, theory-centered instruction into a dynamic, experiential, and technology-integrated learning model that prepares students for the demands of the 21st century.

REFERENCES

Abdusselam, M. S., & Karal, H. (2020). The effect of using augmented reality and sensing technology to teach magnetism in high school physics. *Technology, Pedagogy and Education*, *29*(4), 407–424. https://doi.org/10.1080/1475939X.2020.1766550

Alé-Silva, J., & Huerta-Cancino, L. (2024). The sun in augmented reality: an interactive resource for physics learning. *The Physics Teacher*, *62*(3), 223–225. https://doi.org/10.1119/5.0095415

Alfianti, A., Kuswanto, H., Rahmat, A. D., & Nurdiyanto, R. (2023). Development of

DICTY-AR integrated local wisdom to improve multiple representation and problem-solving skills. *International Journal of Information and Education Technology*, *13*(9), 1383–1390. https://doi.org/10.18178/ijiet.2023.13.9.1941

Altmeyer, K., Kapp, S., Thees, M., Malone, S., Kuhn, J., & Brünken, R. (2020). The use of augmented reality to foster conceptual knowledge acquisition in STEM laboratory courses theoretical background and empirical results. *British Journal of Educational Technology*, *51*(3), 611–628. https://doi.org/https://doi.org/10.1111/bjet.12900

Amelia, R., Azizah, R. S. N., Suwandi, A. R., Amalia, I. F., & Ismail, A. (2020). Application of augmented reality to physics practicum to enhance students' understanding of concepts. *International Journal of Scientific and Technology Research*, *9*(3), 1128–1131.

Arymbekov, B., Turekhanova, K., & Turdalyuly, M. (2024). The effect of augmented reality (AR) supported teaching activities on academic success and motivation to learn nuclear physics among high school pupils. *International Journal of Information and Education Technology*, *14*(5), 743–760. https://doi.org/10.18178/ijiet.2024.14.5.2099

Bakri, F., Permana, H., Wulandari, S., & Muliyati, D. (2020). Student worksheet with AR videos: physics learning media in laboratory for senior high school students. *Journal of Technology and Science Education*, *10*(2), 231–240. https://doi.org/https://doi.org/10.3926/jotse.891

Cai, S., Liu, C., Wang, T., Liu, E., & Liang, J.-C. (2021). Effects of learning physics using Augmented Reality on students' self-efficacy and conceptions of learning. *British Journal of Educational Technology*, *52*(1), 235–251. https://doi.org/https://doi.org/10.1111/bjet.13020

Choi, S., Gopakumar, M., Peng, Y., Kim, J., & Wetzstein, G. (2021). Neural 3D holography: learning accurate wave propagation models for 3D holographic virtual and augmented reality displays. *ACM Trans. Graph.*, *40*(6). https://doi.org/10.1145/3478513.3480542

Daineko, Y., Ipalakova, M., Tsoy, D., Bolatov, Z., Baurzhan, Z., & Yelgondy, Y. (2020). Augmented and virtual reality for physics: Experience of Kazakhstan secondary educational institutions. *Computer Applications in Engineering Education*, *28*(5), 1220–1231. https://doi.org/https://doi.org/10.1002/cae.22297

Deng, Y., Du, S., Wang, D., Shao, Y., & Huang, D. (2023). A calibration-based hybrid transfer learning framework for RUL prediction of rolling bearing across different machines. *IEEE Transactions on Instrumentation and Measurement*, *72*, 1–15. https://doi.org/10.1109/TIM.2023.3260283

Faridi, H., Tuli, N., Mantri, A., Singh, G., & Gargrish, S. (2021). A framework utilizing augmented reality to improve critical thinking ability and learning gain of the students in Physics. *Computer Applications in Engineering Education*, *29*(1), 258–273. https://doi.org/https://doi.org/10.1002/cae.22342

Freese, M., Teichrew, A., Winkelmann, J., Erb, R., Ullrich, M., & Tremmel, M. (2023). Measuring teachers' competencies for a purposeful use of augmented reality experiments in physics lessons. *Frontiers in Education*, *8*(June), 1–11. https://doi.org/10.3389/feduc.2023.1180266

Giancaspro, J. W., Arboleda, D., Kim, N. J., Chin, S. J., Britton, J. C., & Secada, W. G. (2024). An active learning approach to teach distributed forces using augmented reality with guided inquiry. *Computer*

Applications in Engineering Education, *32*(2), e22703. https://doi.org/https://doi.org/10.1002/cae.22703
Iatraki, G., & Mikropoulos, A. A. (2024). *Immersive AR Interventions to include Students with Intellectual Disabilities: Systematic Instruction or Inquiry Learning?* 97–104. https://doi.org/10.1145/3696593.3696638
Jiang, S., Huang, X., Xie, C., Sung, S., & Yalcinkaya, R. (2020). Augmented scientific investigation: Support the exploration of invisible fine details in science via augmented reality. *Proceedings of the Interaction Design and Children Conference, IDC 2020*, 349–354. https://doi.org/10.1145/3392063.3394406
Koumpouros, Y. (2024). Revealing the true potential and prospects of augmented reality in education. *Smart Learning Environments*, *11*(1), 1–62. https://doi.org/10.1186/s40561-023-00288-0
Lai, J. W., & Cheong, K. H. (2022). Educational opportunities and challenges in augmented reality: featuring implementations in physics education. *IEEE Access*, *10*, 43143–43158. https://doi.org/10.1109/ACCESS.2022.3166478
Liu, Q., Yu, S., Chen, W., Wang, Q., & Xu, S. (2021). The effects of an augmented reality based magnetic experimental tool on students' knowledge improvement and cognitive load. *Journal of Computer Assisted Learning*, *37*(3), 645–656. https://doi.org/https://doi.org/10.1111/jcal.12513
Nasir, M., & Fakhruddin, Z. (2023). Design and analysis of multimedia mobile learning based on augmented reality to improve achievement in physics learning. *International Journal of Information and Education Technology*, *13*(6), 993–1000. https://doi.org/10.18178/ijiet.2023.13.6.1897
Pianda, D., Hilmiana, H., Widianto, S., & Sartika, D. (2024). The impact of internship experience on the employability of vocational students: a bibliometric and systematic review. *Cogent Business \& Management*, *11*(1), 2386465. https://doi.org/10.1080/23311975.2024.2386465
Prahani, B. K., Rizki, I. A., Nisa, K., Citra, N. F., Alhusni, H. Z., & Wibowo, F. C. (2022). Implementation of online problem-based learning assisted by digital book with 3D animations to improve student's physics problem-solving skills in magnetic field subject. *Journal of Technology and Science Education*, *12*(2), 379–396. https://doi.org/10.3926/jotse.1590
Radu, I., & Schneider, B. (2023). How augmented reality (AR) can help and hinder collaborative learning: a study of AR in electromagnetism education. *IEEE Transactions on Visualization and Computer Graphics*, *29*(9), 3734–3745. https://doi.org/10.1109/TVCG.2022.3169980
Rahmayani, F., Kuswanto, H., & Rahmat, A. D. (2024). Development of e-book integrated augmented reality based on STEM approaches to improve critical thinking and multiple representation skills in learning physics. *International Journal of Information and Education Technology*, *14*(4), 632–641. https://doi.org/10.18178/ijiet.2024.14.4.2087
Raskar, S. S., & Srivastava, D. (2025). Develop AR-based Virtual Labs to Provide a Safe and Accessible Learning Environment for Students. *Journal of Information Systems Engineering and Management*, *10*(2), 49–73. https://doi.org/10.52783/jisem.v10i2.1356
Rizki, I. A., Mirsa, F. R., Islamiyah, A. N., Saputri,

A. D., Ramadani, R., & Habibbulloh, M. (2025). Ethnoscience-enhanced physics virtual simulation and augmented reality with inquiry learning: Impact on students' creativity and motivation. *Thinking Skills and Creativity*, *57*(September 2024), 101846. https://doi.org/10.1016/j.tsc.2025.101846

Rizki, I. A., Saphira, H. V., Alfarizy, Y., Saputri, A. D., Ramadani, R., & Suprapto, N. (2023). Integration of adventure game and augmented reality based on android in physics learning. *International Journal of Interactive Mobile Technologies*, *17*(1), 4–21. https://doi.org/10.3991/ijim.v17i01.35211

Rizki, I. A., Suprapto, N., Saphira, H. V., Alfarizy, Y., Ramadani, R., Saputri, A. D., & Suryani, D. (2024). Cooperative model, digital game, and augmented reality-based learning to enhance students' critical thinking skills and learning motivation. *Journal of Pedagogical Research*, *8*(1), 339–355. https://doi.org/10.33902/JPR.202423825

Saprudin, S., Lutfi, S., Hamid, F., Ismail, A., Hayat, M. S., & Gumilar, S. (2025). Utilizing augmented reality media in science laboratory activities: enhancing students' competence in explaining phenomena scientifically. *Journal of Engineering Science and Technology*, *20*(3), 41–48.

Sharma, S., Tuli, N., & Mantri, A. (2022). Augmented reality in educational environments: a systematic review. *Journal of Engineering Education Transformations*, *36*(2), 7–19. https://doi.org/10.16920/jeet/2022/v36i2/22149

Sriadhi, S., Hamid, A., Sitompul, H., & Restu, R. (2022). Effectiveness of augmented reality-based learning media for engineering physics teaching. *International Journal of Emerging Technologies in Learning*, *17*(5), 281–293. https://doi.org/10.3991/ijet.v17i05.28613

Sun, J. C.-Y., Ye, S.-L., Yu, S.-J., & Chiu, T. K. F. (2023). Effects of wearable hybrid AR/VR learning material on high school students' situational interest, engagement, and learning performance: the case of a physics laboratory learning environment. *Journal of Science Education and Technology*, *32*(1), 1–12. https://doi.org/10.1007/s10956-022-10001-4

Suprapto, N., Nandyansah, W., & Mubarok, H. (2020). An evaluation of the "PicsAR" research project: An augmented reality in physics learning. *International Journal of Emerging Technologies in Learning*, *15*(10), 113–125. https://doi.org/10.3991/ijet.v15i10.12703

Teichrew, A., & Erb, R. (2020). How augmented reality enhances typical classroom experiments/ : examples from mechanics. *Physics Education*, *55*, 1–7.

Tene, T., Bonilla García, N., Coello-Fiallos, D., Borja, M., & Vacacela Gómez, C. (2024). A systematic review of immersive educational technologies in medical physics and radiation physics. *Frontiers in Medicine*, *11*, 1384799. https://doi.org/10.3389/fmed.2024.1384799

Thees, M., Kapp, S., Strzys, M. P., Beil, F., Lukowicz, P., & Kuhn, J. (2020). Effects of augmented reality on learning and cognitive load in university physics laboratory courses. *Computers in Human Behavior*, *108*, 106316. https://doi.org/https://doi.org/10.1016/j.chb.2020.106316

Ullah, M., Amin, S. U., Munsif, M., Yamin, M. M., Safaev, U., Khan, H., Khan, S., & Ullah, H. (2022). Serious games in science education: a systematic literature. *Virtual Reality & Intelligent Hardware*, *4*(3), 189–209. https://doi.org/https://doi.org/10.1016/j.vrih.2022.02.001

Utami, P. L., Hariyono, E., Hidaayatullaah, H.

N., & Suprapto, N. (2024). Optimizing the Ferris wheel physics e-book with a video tracking method to enhance student learning motivation. *Journal of Physics: Conference Series* (Vol. 2900, Issue 1). Institute of Physics. https://doi.org/10.1088/1742-6596/2900/1/012033

Vidak, A. (2024). Augmented reality technology in teaching about physics: a systematic review of opportunities and challenges. *European Journal of Physics*, *45*(2), 23002. https://doi.org/10.1088/1361-6404/ad0e84

Vidak, A., Movre Šapiæ, I., & Zahtila, K. (2024). A user experience survey of an augmented reality android application for learning Coulomb's law. *Physics Education*, *59*, 45033. https://doi.org/10.1088/1361-6552/ad5248

Volioti, C., Keramopoulos, E., Sapounidis, T., Melisidis, K., Zafeiropoulou, M., Sotiriou, C., & Spiridis, V. (2022). Using augmented reality in K-12 education: an indicative platform for teaching physics. *Information (Switzerland)*, *13*(7). https://doi.org/10.3390/info13070336

Zafeiropoulou, M., Volioti, C., Keramopoulos, E., & Sapounidis, T. (2021). Game-based learning approach/ : a pilot study in primary. *Computers*, *10*(126), 1–14. https://files.eric.ed.gov/fulltext/EJ1298077.pdf