Studies in Bibliometrics of Education and Technology
Homepage: https://scie-journal.net/index.php/SiBET
Email:

p-ISSN:XXXXX; e-ISSN: XXXXX
SiBET, Vol. 1, No. 2, April 2026
Page 1-13
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Mapping Augmented Reality in Physics Education for Enhancing Students' Critical Thinking Skills: A Bibliometric Analysis (2015–2026)

***Wildan Khusni Mubarok[1], Sherlynggar Anugrah[1], Nina Fajriyah Citra[2]**
[1]Department of Physics Education, Faculty of Mathematics and Natural Science, Universitas Negeri Surabaya, Indonesia
[2]Master of Education in Digital Learning, Faculty of Education, Monash University, Australia

Article Info

Article history:

Received: 27 February 2026
Revised: 12 March 2026
Accepted: 26 March 2026
Available Online: 30 April 2026

Keywords:

Augmented Reality
Bibliometric Analysis
Critical Thinking
Physics Education
Science Mapping

ABSTRACT

This study addresses the growing need to understand the development of augmented reality (AR) research in physics education, particularly to enhance students' critical thinking skills in 21st-century learning. The study aims to map global research trends, identify thematic developments, examine collaboration networks, and explore emerging directions of AR integration in physics education during 2015–2026. A quantitative bibliometric approach was employed, using publications indexed in the Scopus database, to understand the development of augmented reality (AR) research in physics education, with the PRISMA framework for systematic article selection. Data were analyzed through performance analysis and science mapping using VOSviewer and the Bibliometrix package to identify publication trends, citation patterns, keyword relationships, and research collaborations. The results indicate a significant increase in research output after 2020, reflecting growing global interest in AR integration within physics learning. Keyword co-occurrence analysis reveals that augmented reality, critical thinking, and students are the dominant research themes, supported by topics related to learning systems, teaching materials, and 21st-century competencies. The findings also show a shift from technology-oriented studies toward pedagogically grounded approaches that position AR as a strategic tool for developing higher-order thinking skills. In addition, the emerging integration of artificial intelligence and adaptive learning demonstrates the evolution of more innovative learning environments. The novelty of this study lies in its comprehensive bibliometric mapping that integrates AR, physics education, and critical thinking within a unified analytical framework. These findings provide important implications for future research and the development of more innovative and effective physics learning strategies.

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INTRODUCTION

Quality education is recognized as a fundamental basis for developing competitive, high-quality human resources in the 21st century (Karoso et al., 2024; Dwikoranto et al., 2025). In line with the transformation of modern education, the mastery of 6C competencies, collaboration, communication, creativity, critical thinking, compassion, and computation has become an essential objective of learning processes in schools (Shaturaev, 2021; Kembara et al., 2022; Khahro & Javed, 2022). Among these competencies, critical thinking is particularly important because it enables students to analyze information, evaluate evidence, and make logical decisions grounded in scientific reasoning (Puspawati et al., 2021; Lintangesukmanjaya et al., 2024). Therefore, strengthening critical thinking skills has become one of the primary indicators of successful learning in contemporary education.

Physics education plays a significant role in fostering students' critical thinking skills because learning physics requires not only conceptual understanding but also the ability to relate theoretical knowledge to real-world phenomena through systematic scientific reasoning (Ma et al., 2023; Nugroho & Dewi, 2025; Tuveri et al., 2026). The learning process involves analyzing data, interpreting evidence, and logically evaluating information to construct a meaningful understanding (Putra et al., 2023; Sutiani et al., 2021). Ideally, physics instruction should therefore encourage inquiry-based learning and actively engage students in scientific

reasoning activities (Supena et al., 2021). However, previous studies indicate that students' critical thinking skills in physics remain at moderate to low levels due to instructional practices that still emphasize information transmission rather than exploration and analytical reasoning (Sarwanto et al., 2021; Hou & Xue, 2023; Zulfikar, 2024).

To address these challenges, integrating digital technology into education has become an important strategy for improving learning quality (Alenezi et al., 2023; Sentriyo et al., 2023). One promising innovation is augmented reality (AR), which enables the visualization of abstract physics concepts through interactive three-dimensional virtual objects integrated into real-world environments (Alhejri et al., 2022; Adryansyah et al., 2023). AR has been shown to increase student engagement, support active exploration, and create immersive learning experiences that contribute to improved conceptual understanding and the development of critical thinking (Afifi et al., 2021; Kalsum et al., 2023; Mubarok & Anugrah, 2025). Consequently, AR is increasingly considered an effective technological approach for enhancing physics learning outcomes.

Although studies on AR in physics education have grown significantly and generally report positive impacts on learning achievement, motivation, and engagement (Fauziyah et al., 2024; Apriliyanto, 2025), existing research remains fragmented and limited to specific instructional contexts and topics (Lin & Yu, 2024). As a result, there remains a limited understanding of the global development of AR research in physics education, particularly regarding critical thinking skills. Furthermore, collaboration patterns, thematic evolution, and emerging research trends in this field have not yet been comprehensively explored (Fu et al., 2022; Klarin, 2024). This condition indicates the need for a systematic mapping study that integrates augmented reality, physics education, and critical thinking within a unified analytical framework (Faridi et al., 2021; Rizki et al., 2024; Tugirin et al., 2025).

Therefore, this study aims to systematically map the global research landscape on augmented reality in physics education to enhance students' critical thinking skills during the period 2015–2026. This study employs bibliometric analysis combined with the PRISMA framework to identify publication trends, influential authors, collaboration networks, and thematic developments in the field (Zhang et al., 2023; Xu et al., 2021). By analyzing publication data, citation patterns, and keyword relationships, this study is expected to provide a comprehensive overview of the development of AR research in physics education and to serve as a reference for future studies and the development of more innovative and effective physics learning strategies.

RESEARCH METHOD

This study employs a quantitative bibliometric design to analyze the global development of research on augmented reality (AR) in physics education aimed at enhancing students' critical thinking skills from 2015 to early 2026. The selected time span was determined based on scientific and methodological considerations. The year 2015 represents the initial phase of substantial growth in the integration of AR technologies into educational practices, supported by advances in mobile technology, interactive learning applications, and the increasing accessibility of AR-based instructional media in science education. Furthermore, publications on AR in physics education began to show more consistent and measurable growth after 2015, making this period appropriate for identifying research trends, thematic evolution, and collaboration patterns within the field. Meanwhile, the inclusion of publications up to early 2026 enables this study to capture the most recent developments and emerging research directions in AR-assisted physics learning. Bibliometric analysis enables the systematic evaluation of scientific publications using metadata such as authorship, citations, affiliations, and keywords, allowing the identification of publication trends, research productivity, collaboration networks, and the intellectual structure of the field.

This study integrates performance analysis and science mapping to provide a comprehensive perspective: performance analysis assesses research productivity and impact (including annual trends, leading authors, countries, institutions, and journals), while science mapping visualizes relationships among research elements and reveals conceptual structures. This combined approach supports an objective, in-depth understanding of the evolution of AR research in physics education, particularly regarding the development of critical thinking (Singh et al., 2021; Lyu et al., 2024). Bibliographic data were obtained from the Scopus database due to its extensive coverage and high indexing standards. Data collection used the query TITLE-ABS-KEY (augmented AND reality AND physics AND education AND critical AND thinking), and all records were exported in CSV format for further analysis.

To ensure transparency and methodological rigor in the selection process, this study followed the PRISMA 2020 guidelines. The PRISMA framework was used because it provides a structured, systematic

procedure for identifying, screening, and selecting relevant studies while minimizing bias in the literature selection process (Anugrah et al, 2026). The selection process consisted of four stages:

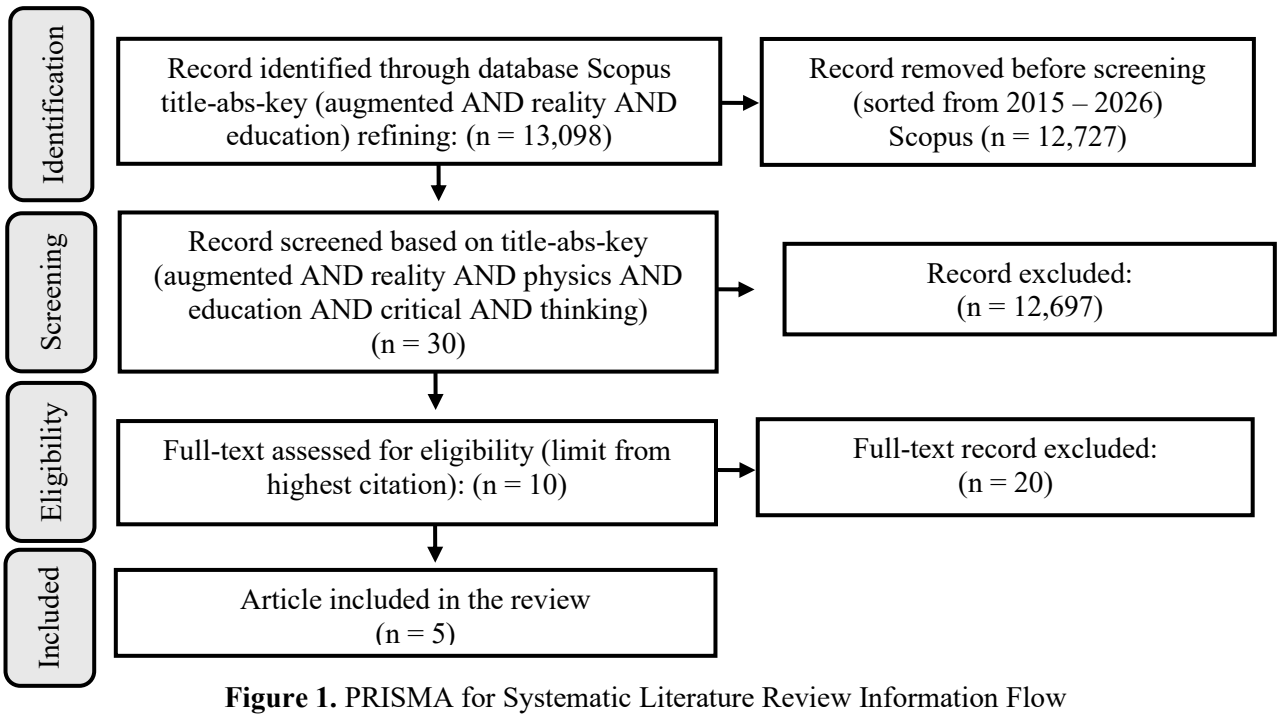


Figure 1. PRISMA for Systematic Literature Review Information Flow

The inclusion criteria in this study were publications indexed in Scopus, peer-reviewed journal articles, documents written in English, and publications from 2015 to 2026, while conference papers, book chapters, editorials, and studies not directly related to augmented reality, physics education, or critical thinking were excluded. The final dataset obtained through the PRISMA filtering process served as the unit of analysis for mapping publication patterns, collaboration networks, and thematic developments. Bibliometric tools were used as the main analytical instruments, with VOS viewer applied to visualize co-authorship networks, institutional collaborations, country-level partnerships, citation relationships, and keyword co-occurrence clusters (Dewi & Rahayu, 2023; Lyu et al., 2025), while the Bibliometric package was used for descriptive analyses, including annual publication trends, source impact, author productivity, and thematic evolution (Khanra et al., 2022). Data analysis was conducted in several stages: first, descriptive indicators were generated to examine publication growth and productivity trends; second, network analysis identified collaboration patterns among authors, institutions, and countries; third, keyword co-occurrence analysis revealed dominant themes and emerging trends reflecting the field's conceptual structure; and finally, the findings were interpreted to provide insights into the development of augmented reality research in physics education and its contribution to enhancing students' critical thinking skills.

RESULTS AND DISCUSSION

Results

The bibliometric analysis based on the Scopus database reveals the temporal distribution of publications on augmented reality (AR) in physics education for enhancing students' critical thinking skills during the period 2015–2026. To provide a clearer overview of research development, the annual publication data are presented graphically.

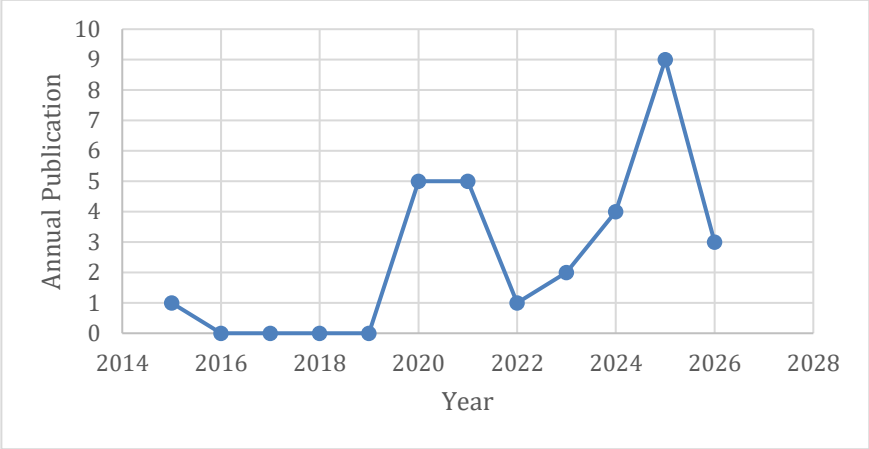


Figure 2. Annual Publication Trends on AR in Physics Education (2015–2026)

The results show that research activity was initially very limited, with only one publication in 2015 and none from 2016 to 2019, indicating that augmented reality in physics education—particularly for critical thinking was still in an early stage; a notable increase began in 2020 with five publications and remained stable in 2021, marking the initial expansion driven by digital and immersive technologies, followed by a brief decline in 2022, before rising again to two publications in 2023 and four in 2024, and peaking at nine in 2025 the highest in the study period reflecting growing global attention, and although it decreased to three in 2026, the overall trend remains higher than in the early years, with document type distribution further illustrating dissemination patterns, as shown in Figure 3.

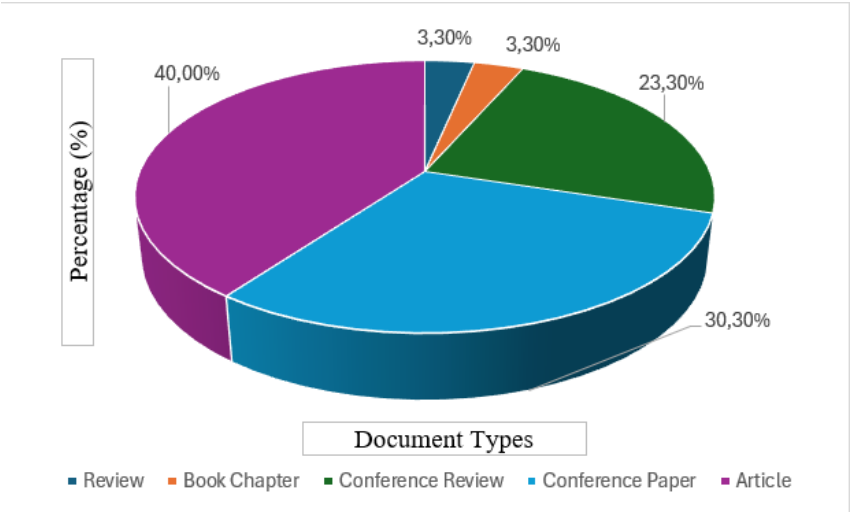


Figure 3. Distribution of Document Types

The results show that journal articles dominate publications (40.0%), followed by conference papers (30.0%) and conference reviews (23.3%), while book chapters and review articles contribute minimally (3.3% each); this pattern indicates increasing research maturity through peer-reviewed work alongside a dynamic research environment where conferences facilitate emerging ideas, and the low share of review articles highlights opportunities for more comprehensive synthesis studies, so overall the field appears developing yet increasingly structured, balancing exploratory and established contributions, with further analysis of country contributions revealing the global distribution of research, as shown in Figure 4.

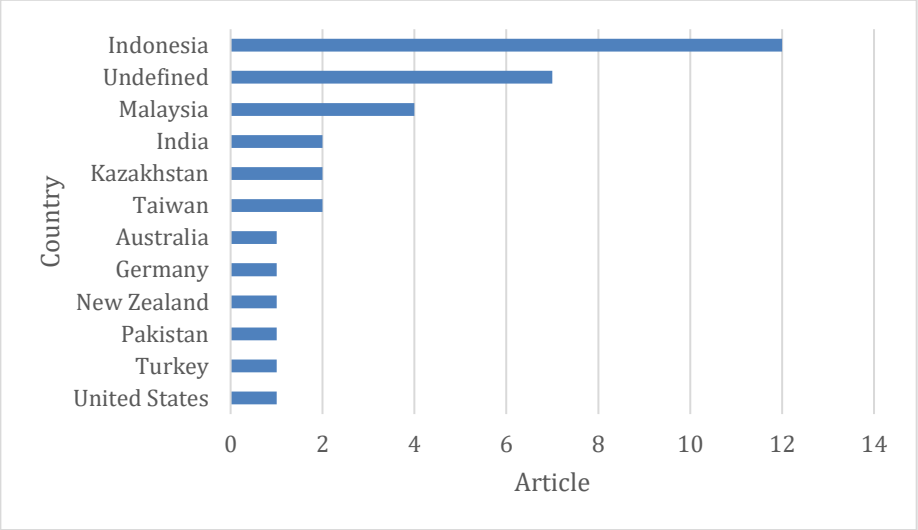


Figure 4. Top Contributing Countries

The results indicate that Indonesia is the most productive country in this field, reflecting strong national interest in integrating augmented reality into physics education to develop higher-order thinking skills, followed by the "undefined" category representing publications without clear country affiliations due to metadata or indexing limitations, while among identified countries Malaysia emerges as a leading contributor, followed by India, Kazakhstan, and Taiwan with moderate output, and Australia, Germany, New Zealand, and Pakistan showing relatively limited but growing engagement; further analysis of publication sources highlights the key journals and conference proceedings shaping this research area, with the distribution of documents over time (Figure 5) illustrating both the diversity of outlets and their temporal contributions.

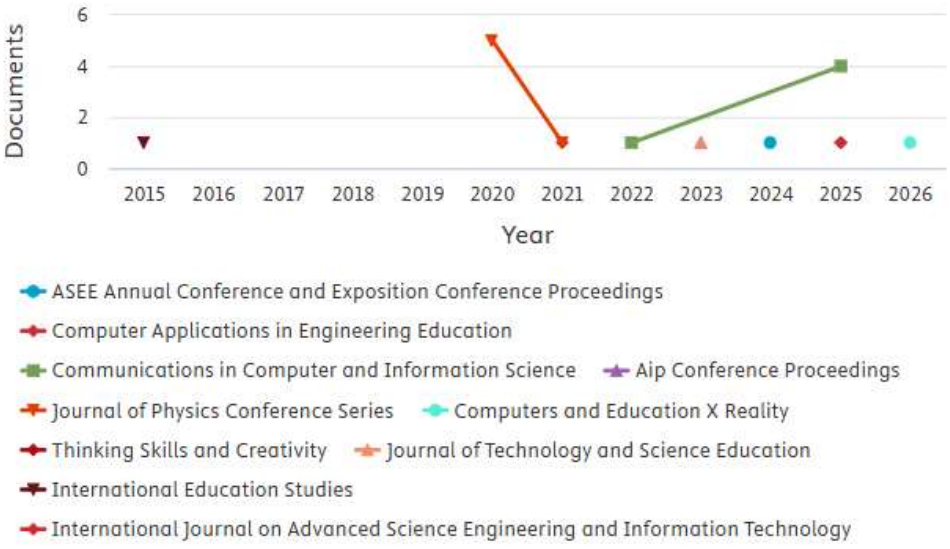


Figure 5. Document per Year by Source

The results indicate that publication sources contribute intermittently, reflecting the emerging and specialized nature of the field; the *Journal of Physics: Conference Series* shows the highest contribution, peaking at five publications in 2020 before declining in 2021, highlighting the role of conference proceedings in early dissemination, while *Communications in Computer and Information Science* demonstrates a rising trend from 2022 to 2025, indicating growing interest, and other sources contribute only one publication each across different years, resulting in a diverse but scattered landscape; similarly, several journals show modest contributions, suggesting that the topic spans multiple disciplines such as education, engineering, and educational technology, as further supported by the subject area distribution in Figure 6.

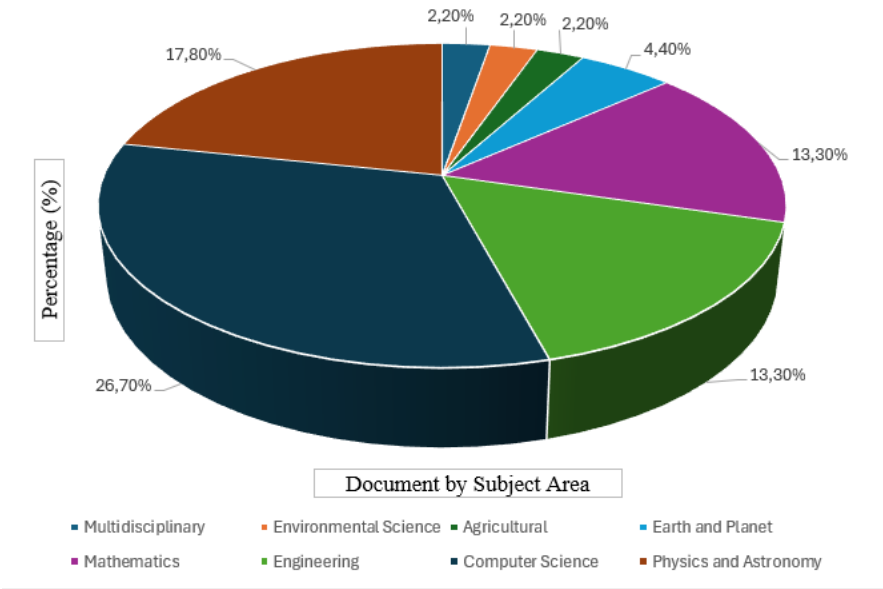


Figure 6. Distribution of Document by Subject Area

The results indicate that Computer Science dominates publications (26.7%), reflecting the technological foundation of augmented reality, followed by Physics and Astronomy (17.8%) highlighting its role in visualizing abstract concepts in physics education; Social Sciences contribute around 16–17%, emphasizing pedagogical aspects, while Engineering (13.3%) supports technical development, and although fields such as Mathematics and Decision Sciences contribute less than 10%, they play complementary roles in data analysis and modeling, which then leads to the analysis of keyword co-occurrence through network visualization, as shown in Figure 7.

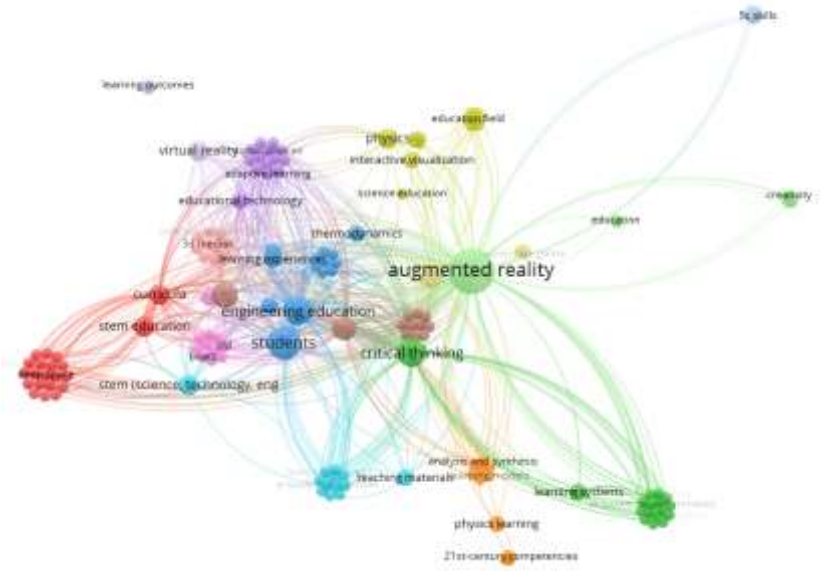


Figure 7. Keyword Co-Occurrence Network Visualization

The network visualization reveals five coherent clusters that define the intellectual structure of research on augmented reality (AR) in physics education with a focus on critical thinking, where Cluster 1 (deep space and STEM) represents peripheral yet relevant applications in complex physics contexts, Cluster 2 (teaching materials, learning models, and e-student worksheets) emphasizes the development of AR-based instructional tools, Cluster 3 as the largest and most central cluster (learning systems, physics, education, and experiments) reflects the core implementation of AR in physics learning environments, Cluster 4 (analysis and synthesis, physics learning, and 21st-century competencies) directly represents higher-order thinking skills, particularly

critical thinking, and Cluster 5 (learning media and related terms) acts as an integrative bridge connecting instructional design and implementation; structurally, learning systems emerges as the most dominant keyword with the highest centrality and co-occurrence links, followed by teaching materials, analysis and synthesis, and physics learning, with the prominence of analysis and synthesis indicating a strong orientation toward outcome-based research on critical thinking, so overall the network reflects a mature field transitioning from technology-driven exploration to pedagogically grounded implementation, where enhancing critical thinking becomes the central focus, with the top five keywords further detailed in Table 1.

Table 1. Top 5 Keyword by Author

Keyword	Total Link Strength
Augmented Reality	176
Students	144
Engineering Education	107
Teaching	100
Critical Thinking	89

The most significant keywords are identified based on their total link strength, reflecting the central themes and the intensity of relationships within the research network, where augmented reality (176) emerges as the most dominant keyword, indicating its central role as the primary technological focus, followed by students (144) which highlights a strong learner-centered orientation in examining engagement and learning outcomes; furthermore, engineering education (107) and teaching (100) demonstrate the close relationship between technological integration and pedagogical practices, suggesting that the implementation of augmented reality is closely tied to instructional design and educational strategies, while critical thinking (89) remains a key focus confirming that the development of higher-order thinking skills is a major objective, so overall these interconnected keywords indicate that current research not only emphasizes augmented reality as a technological tool but also its pedagogical impact, reflecting a well-defined direction integrating technology, pedagogy, and student-centered outcomes in engineering and physics education, which is then followed by the analysis of keyword branches in Figure 8 related to this research domain.

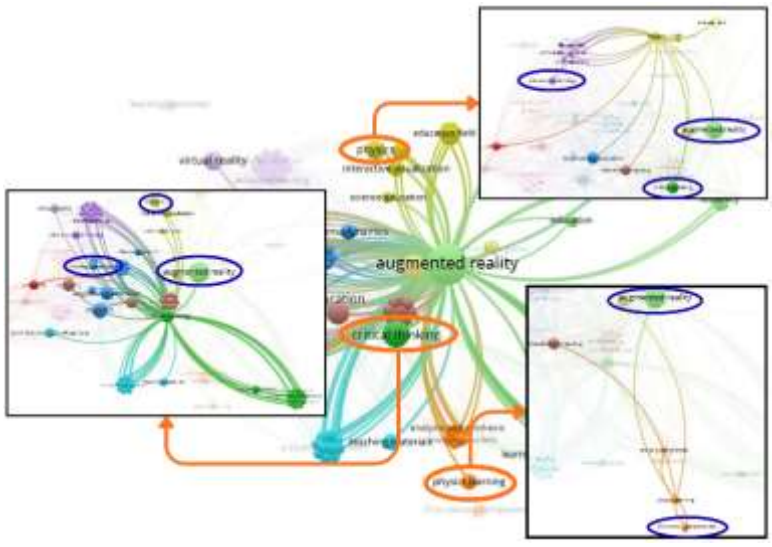


Figure 8. Branches Keywords

The keyword mapping shows that augmented reality is the most dominant and interconnected node, closely linked to critical thinking, students, engineering education, and education computing, reflecting a strong focus on integrating AR into student-centered physics learning to enhance higher-order thinking skills; the prominence of critical thinking connected with analysis and synthesis and 21st-century competencies indicates that AR is increasingly viewed as a cognitive tool for complex reasoning rather than merely for visualization, while its links to teaching materials, learning models, and learning systems highlight its integration within structured pedagogical frameworks, and its connections with physics, science education, thermodynamics, and interactive visualization emphasize its role in addressing abstract concepts;

additionally, emerging links with educational technology, artificial intelligence, adaptive learning, virtual reality, and digital devices suggest a convergence of immersive and intelligent technologies, collectively indicating a shift toward an integrative paradigm that combines technological innovation, pedagogy, and cognitive skill development, positioning AR as a key enabler for enhancing critical thinking in physics education.

Table 2. Overview of Most Cited Papers

Author (s)	Citation; SJR	Research Findings and Recommendations
Saidin et al (2015)	262; 0,228 (Q3)	This study shows that augmented reality (AR) has strong potential to enhance learning by improving understanding of abstract concepts, increasing engagement, and supporting active, meaningful experiences that foster critical thinking; however, its implementation remains limited by technical constraints, accessibility, and low research adoption, therefore it is recommended to develop more user-friendly, scalable, and mobile-based AR systems while expanding empirical studies—especially in physics education—to strengthen its pedagogical effectiveness and optimize overall learning quality.
Faridi et al (2021)	127; 0,831 (Q1)	This study shows that augmented reality (AR)-based learning significantly enhances students' critical thinking and learning gains in physics by improving the visualization of abstract concepts—such as electromagnetic phenomena—while experimental comparisons confirm increased conceptual understanding and engagement compared to traditional methods; therefore, it is recommended to integrate AR as an interactive, visualization-oriented tool supported by structured learning frameworks and broader adoption in STEM education to strengthen higher-order thinking skills and optimize learning effectiveness in complex domains.
Wibowo (2023)	16; 0,392 (Q2)	This study shows that augmented reality (AR) learning media developed using the ADDIE model is feasible and effective in physics education by enhancing understanding of abstract concepts through interactive 3D visualization, while also improving learning outcomes and critical thinking through active, exploratory experiences; however, its scope is limited by a small sample and specific context, therefore broader implementation and large-scale studies are recommended, along with further refinement of AR-based instructional design to maximize its impact on higher-order thinking skills.
Rizki et al (2024)	11; 0,363 (Q3)	This study shows that augmented reality (AR) enhances students' conceptual understanding and supports critical thinking by providing interactive, visual learning experiences that make abstract physics concepts more engaging than conventional methods; however, its implementation is still limited by scope, technological readiness, and insufficient empirical evidence, therefore it is recommended to expand AR integration through well-designed instructional frameworks, improved accessibility, and broader experimental studies to strengthen its effectiveness and optimize its role in fostering higher-order thinking skills.
Arymbekov et al (2024)	10; 0,474 (Q2)	This study shows that augmented reality (AR)-supported teaching improves students' academic achievement, motivation, and critical thinking in physics especially in complex topics like nuclear physics and is more effective than conventional methods and virtual labs due to its immersive, interactive nature; however, its use is still limited to specific topics and controlled settings, therefore it is recommended to expand its integration across curricula, compare its effectiveness across topics, and conduct larger-scale studies to strengthen its role in enhancing both cognitive and motivational aspects of learning.

The analysis of the most cited publications provides important insight into the intellectual structure and scientific impact of research in this field, as citation counts reflect the scholarly influence of studies through their frequency of use by other researchers; by examining the top five most cited papers, this section identifies key works that have shaped the development of augmented reality in physics education, particularly in enhancing students' critical thinking skills, while also revealing dominant themes, methodological approaches, and technological innovations that guide the field, thereby enabling a clearer understanding of its evolution, major breakthroughs, and existing research gaps, and offering a concise yet critical foundation for future research directions.

Discussion

The findings of this bibliometric analysis reveal a clear evolution of research on augmented reality (AR) in physics education toward a more coherent, pedagogically grounded direction, in which AR, students, and critical thinking form a tightly interconnected core. This indicates a shift from technology-centered approaches toward outcome-oriented research that positions AR as a tool for fostering higher-order cognitive processes rather than merely supporting visualization, reflecting a more mature and purposeful development of the field. According to Saidin et al. (2015), AR has strong potential to enhance learning by improving understanding of abstract concepts and increasing student engagement, particularly in physics education. Similarly, Faridi et al. (2021) emphasized that AR-based learning significantly improves conceptual understanding and learning gains by visualizing complex and abstract scientific phenomena. These findings are also consistent with previous studies reporting that AR supports active and meaningful learning experiences in science education (Ibáñez & Delgado-Kloos, 2018; Akçayır & Akçayır, 2017).

Furthermore, critical thinking has emerged as a central research objective closely linked with instructional elements such as teaching, learning systems, and engineering education, suggesting that AR is increasingly embedded within structured pedagogical frameworks. Supported by keywords such as analysis, synthesis, and 21st-century competencies, this pattern highlights a transition from simple technology adoption to pedagogical transformation, with a focus on how AR actively shapes students' thinking processes. Wibowo (2023) demonstrated that AR learning media developed using the ADDIE model effectively improve students' visualization abilities, learning outcomes, and critical thinking through active exploratory learning experiences. In addition, Rizki et al. (2024) found that AR enhances conceptual understanding and supports critical thinking by providing interactive and visual learning environments that make abstract physics concepts more accessible. These findings support constructivist learning theory, in which interactive environments encourage learners to actively construct knowledge and engage in higher-order thinking.

The study also identifies a growing technological convergence in which AR is increasingly integrated with artificial intelligence, adaptive learning, and virtual reality, indicating the emergence of more advanced, immersive, and data-driven learning environments. Alongside this, the strong linkage between physics topics, particularly thermodynamics and interactive visualization, confirms that AR is especially effective in addressing abstract and complex concepts, functioning as a bridge between theoretical understanding and experiential learning. Arumbekov et al. (2024) further reported that AR-supported instruction improves students' academic achievement and critical thinking in physics, especially for complex topics requiring high levels of visualization and interaction. This trend aligns with recent studies highlighting the role of immersive technologies in developing analytical and problem-solving skills in STEM education (Radianti et al., 2020; Wu et al., 2013).

Evidence from highly cited studies confirms that AR improves conceptual understanding, critical thinking, learning outcomes, and student motivation, although challenges such as limited sample sizes, short intervention durations, and scalability issues persist. Saidin et al. (2015) and Rizki et al. (2024) both emphasized the need for broader empirical studies and stronger instructional frameworks to optimize AR implementation in educational settings. Therefore, future research should focus on large-scale, longitudinal studies; deeper integration with intelligent technologies; and the development of standardized pedagogical frameworks to maximize AR's educational impact. Overall, this study highlights a transition toward an integrated, interdisciplinary, and cognitively oriented research paradigm in physics education.

CONCLUSION

Fundamental Finding: This study reveals that research on augmented reality (AR) in physics education has evolved into a more coherent and mature field, with a strong shift toward pedagogically grounded approaches that emphasize developing students' critical thinking skills. The keyword structure and network patterns indicate that AR is not only a technological tool but also a cognitive and instructional medium, increasingly integrated into teaching practices, learning systems, and emerging technologies such as artificial intelligence and adaptive learning, highlighting a transition toward an outcome-oriented, interdisciplinary research paradigm. **Implications:** These findings imply that (1) educators should integrate AR within structured and student-centered instructional frameworks to enhance higher-order thinking skills; (2) researchers are encouraged to move beyond exploratory studies toward more theory-driven and pedagogically aligned implementations; and (3) the broader academic and educational community can position AR as a strategic tool for improving the quality of physics education, particularly in addressing abstract and complex concepts through immersive and interactive learning environments. **Future Research:** Future research should focus on large-scale and longitudinal empirical studies to validate the effectiveness of AR across

diverse contexts, the development of standardized and theory-based AR instructional models, and deeper integration with intelligent technologies such as AI and adaptive learning systems, in order to enhance personalization, scalability, and long-term impact on critical thinking and overall learning outcomes in physics education.

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Author (s):

*Wildan Khusni Mubarok (Corresponding Author)
Department of Physics Education, Faculty of Mathematics and Natural Science,
Universitas Negeri Surabaya, Indonesia
Email: wildan.22052@mhs.unesa.ac.id

Sherlynggar Anugrah
Department of Physics Education, Faculty of Mathematics and Natural Science,
Universitas Negeri Surabaya, Indonesia
Email: sherlynggar.23063@mhs.unesa.ac.id

Nina Fajriyah Citra
Master of Education in Digital Learning, Faculty of Education,
Monash University, Australia
Email: ncit0004@student.monash.edu