

REVIEW

The Use of Technology Augmented Reality in Engineering Education: A Bibliometric Review

El uso de la tecnología de realidad aumentada en la educación en ingeniería: una revisión bibliométrica

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ABSTRACT

Augmented Reality (AR) is a transformative technology within the context of Education 4.0, offering immersive and interactive learning experiences that enhance the visualization of complex engineering concepts. This study aims to conduct a bibliometric analysis of research on the application of AR in engineering education from 2021 to 2025, using Scopus-indexed journal articles as the data source. Data were collected through a targeted search strategy using the keywords “Augmented Reality” and “Engineering Education,” limited to English-language journal articles in the engineering field that were in their final publication stage. The selection process followed the PRISMA flow, resulting in 57 relevant studies from an initial pool of 326 articles. The analysis included publication trends, source journals, keyword co-occurrence mapping, most-cited articles, and international collaboration networks. The results show a steady increase in publications, peaking in 2023, with the most significant contributions coming from China, Germany, and the United States, along with growing participation from developing countries. Keyword mapping revealed three major thematic clusters: AR and VR technology development, AI integration for adaptive learning, and simulation-based technical training. Identified challenges include hardware limitations, gaps in curriculum integration, and the need for low-cost and scalable AR solutions. These findings underscore the importance of strategic research directions that integrate both technical and pedagogical perspectives to optimize the impact of AR in engineering education globally.

Keywords: Augmented Reality; Engineering Education; Bibliometric Analysis; PRISMA.

RESUMEN

La Realidad Aumentada (RA) es una tecnología transformadora en el contexto de la Educación 4.0, ya que ofrece experiencias de aprendizaje inmersivas e interactivas que mejoran la visualización de conceptos complejos en la ingeniería. Este estudio tiene como objetivo realizar un análisis bibliométrico de las investigaciones sobre la aplicación de la RA en la educación en ingeniería durante el periodo de 2021 a 2025, utilizando como fuente de datos artículos publicados en revistas indexadas en Scopus. Los datos se recopilaron mediante una estrategia de búsqueda específica con las palabras clave “Realidad Aumentada” y “Educación en Ingeniería”, limitando los resultados a artículos en inglés del área de ingeniería que estuvieran en su etapa final de publicación. El proceso de selección siguió el diagrama de flujo PRISMA, lo que permitió identificar 57 estudios relevantes a

partir de un total inicial de 326 artículos. El análisis incluyó tendencias de publicación, revistas fuente, mapeo de coocurrencia de palabras clave, artículos más citados y redes de colaboración internacional. Los resultados muestran un crecimiento constante en las publicaciones, con un pico en el año 2023, siendo China, Alemania y Estados Unidos los principales contribuyentes, además de una creciente participación de países en desarrollo. El mapeo de palabras clave reveló tres principales clústeres temáticos: desarrollo de tecnologías RA y RV, integración de inteligencia artificial para el aprendizaje adaptativo y formación técnica basada en simulaciones. Los desafíos identificados incluyen limitaciones de hardware, dificultades en la integración curricular y la necesidad de soluciones de RA escalables y de bajo costo. Estos hallazgos subrayan la importancia de orientar la investigación hacia direcciones estratégicas que integren aspectos técnicos y pedagógicos para optimizar el impacto de la RA en la educación en ingeniería a nivel mundial.

Palabras clave: Realidad Aumentada; Educación en Ingeniería; Análisis Bibliométrico; PRISMA.

INTRODUCTION

The Fourth Industrial Revolution fundamentally reshapes various sectors, particularly education, through the integration of advanced technologies such as artificial intelligence (AI), cloud computing, and virtual and augmented reality.⁽¹⁾ This transformation is encapsulated within the concept of Education 4.0, which leverages these digital tools to foster more interactive and contextually relevant learning environments.⁽²⁾ By incorporating AI, educators are able to personalize learning experiences, while cloud computing enhances accessibility to resources and facilitates collaboration among students and instructors.⁽³⁾ Furthermore, VR/AR technologies offer immersive experiences that significantly increase student engagement and knowledge retention.⁽⁴⁾ As educational institutions adapt to these innovations, they become better equipped to meet the demands of the modern workforce, ultimately preparing students to confront the challenges posed by the evolving landscape of the Fourth Industrial Revolution.

Augmented Reality (AR) serves as a pivotal technology bridging the gap between the Fourth Industrial Revolution and Education 4.0 by enriching the learning experience through real-time, immersive interactions with digital content. This integration is particularly critical in technical education, where AR facilitates hands-on learning and visualization of complex concepts, thereby enhancing student engagement and comprehension.^(5,6) The rapid technological advancements characteristic of the Fourth Industrial Revolution, including AR, are transforming traditional educational methodologies to meet the evolving demands of industry.⁽⁷⁾ Education 4.0 emphasizes the cultivation of critical skills such as creativity and problem-solving, which are essential in today's digital landscape.^(8,9) By fostering an interactive learning environment, AR not only enriches educational content but also prepares students to navigate the technology-driven workforce challenges. As such, AR emerges as a transformative tool in aligning educational practices with the requirements of modern industry.

Augmented Reality (AR) is revolutionizing engineering education by integrating digital information directly into the physical environment, thereby enhancing the learning experience. This technology relies on image processing and computer vision to recognize and interpret visual data, enabling seamless overlay of virtual objects through device cameras.⁽¹⁰⁾ AR can be broadly categorized into two primary types: marker-based AR, which uses visual markers such as 2D images or QR codes to display content, and markerless AR, which does not require markers but instead utilizes user location or preferences for content presentation.^(11,12) The application of AR within engineering curricula allows students to visualize complex concepts and interact with virtual models, thereby improving learning outcomes and accommodating diverse learning styles.^(13,14) This innovative approach not only fosters engagement but also supports kinesthetic learning, positioning AR as a valuable tool in contemporary education.

The deployment of AR in engineering education has yielded numerous positive effects, including enhanced learning outcomes, increased motivation, greater enjoyment in the learning process, heightened interest in engineering subjects, as well as active participation and improved retention of educational content.^(15,16) Despite these promising results, challenges such as technical limitations and the need for better curriculum integration remain.⁽¹⁷⁾ These barriers must be addressed to fully realize AR's potential across all engineering disciplines. Moreover, issues like initial training and device constraints can hinder effective implementation, underscoring the necessity for strategic planning and resource allocation.⁽¹⁸⁾ Given the complexity of engineering fields which often involve abstract concepts and spatial visualization AR proves to be a highly relevant medium to bridge the gap in understanding materials that are difficult to explain through traditional methods.

Empirical studies corroborate the significant impact of AR on enhancing comprehension of complex engineering concepts that are challenging to convey verbally or through two-dimensional media. Koumpourous⁽¹⁹⁾ demonstrated that AR use in engineering education substantially increases student engagement and understanding by enabling direct interaction with visual representations of engineering objects that are typically taught theoretically.

Similarly, Alam and Mohanty⁽²⁰⁾ found that AR effectively promotes practice-based learning and accelerates spatial understanding in disciplines such as mechanical, civil, and electrical engineering. Furthermore, Kaur et al.⁽²¹⁾ reported that AR not only improves academic performance but also boosts student motivation and concentration during engineering instruction. By providing immersive learning experiences, AR bridges the gap between theory and practice and assists students in comprehending technical risks through simulation, thereby contributing to the development of technical skills and workplace safety.

Accordingly, this study aims to review scientific publications addressing the application of Augmented Reality (AR) technology in engineering education. The primary objectives are to describe the characteristics of published research and to identify trends and directions in AR research within this field over the past five years (2021-2025).

Data for this review were sourced from the Scopus database, one of the largest and most reputable repositories of scientific literature. As the adoption of augmented reality (AR) continues to expand as an interactive learning medium, it is essential to understand the extent of its application and its role in enhancing the quality of engineering education. In particular, AR offers significant potential in supporting the visualization of complex and abstract engineering concepts, thereby improving students' comprehension and engagement. By examining relevant literature from Scopus, this review aims to provide a comprehensive overview of current research trends, focus areas, and emerging directions in the integration of AR within engineering education.

METHOD

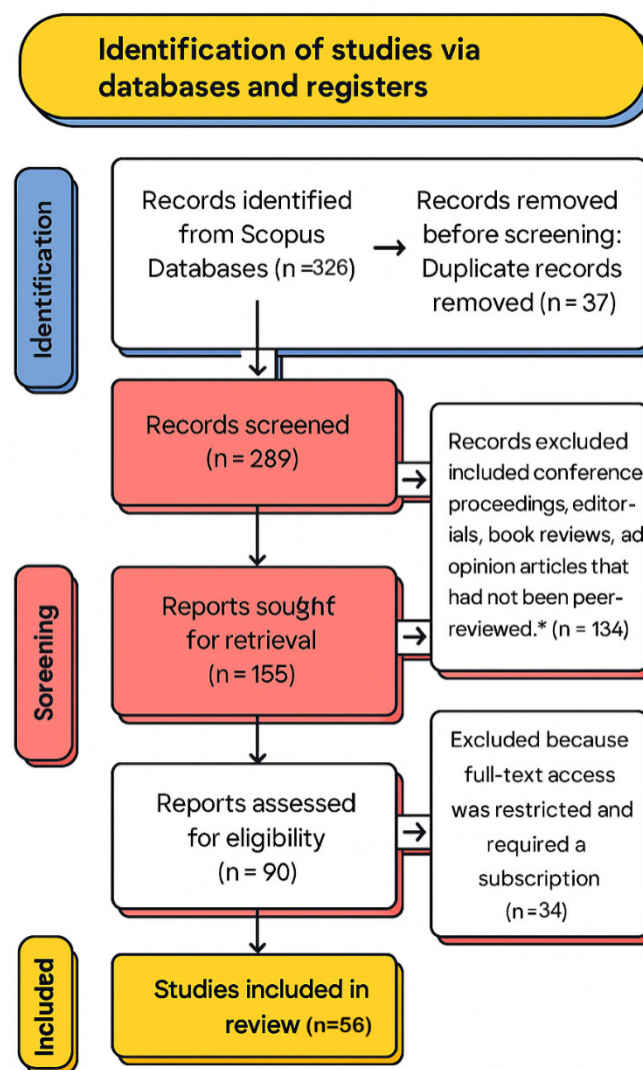


Figure 1. Steps in the PRISMA Literature Search Process

Data Collection

The methodology employed in this study adopts a systematic bibliometric analysis approach to examine the

evolution and application of Augmented Reality (AR) within engineering education over the period from 2021 to 2025. This timeframe was deliberately selected to capture recent trends and cutting-edge developments in the implementation of AR technologies in technical and engineering education contexts.

The primary data source utilized in this study was a comprehensive abstract and citation database managed by a leading academic publisher, renowned for its extensive coverage of scholarly publications, particularly in the fields of engineering and educational technology. A search strategy was carefully designed to retrieve publications that are directly relevant to the research scope. The search string applied was as follows:

(KEY (Augmented Reality) AND KEY (Engineering Education)) AND (LIMIT-TO (PUBYEAR , 2021) OR LIMIT-TO (PUBYEAR , 2022) OR LIMIT-TO (PUBYEAR , 2023) OR LIMIT-TO (PUBYEAR , 2024) OR LIMIT-TO (PUBYEAR , 2025)) AND (LIMIT-TO (SUBJAREA , "ENGI")) AND (LIMIT-TO (DOCTYPE , "ar")) AND (LIMIT-TO (EXACTKEYWORD , "Augmented Reality") OR LIMIT-TO (EXACTKEYWORD , "Engineering Education")) AND (LIMIT-TO (SRCTYPE , "j")) AND (LIMIT-TO (LANGUAGE , "English")) AND (LIMIT-TO (OA , "all"))

The inclusion criteria were strictly defined to filter the results to only those documents categorized as journal articles (document type: "article") that had reached the final publication stage, were written in English, and fell within the subject area of engineering. Moreover, each document was required to include the specific keywords "Engineering Education" or "Augmented Reality" to ensure a strong relevance to the primary topic of investigation.

Search Procedure

The search procedure began by conducting a keyword-based search in the Scopus database using the aforementioned string. The initial search yielded a total of 326 articles. These records were then subjected to an abstract-level screening to assess their compliance with the inclusion criteria. Articles that did not align with the study's objectives or lacked sufficient relevance were progressively excluded through a multi-stage filtering process.

RESULTS

Visualization of Publication Productivity Trends

The trend in scholarly publications related to the use of Augmented Reality (AR) in engineering education demonstrates a consistent growth trajectory over the period from 2021 to 2025. In 2021, the number of publications was relatively modest, with only 8 documents identified. However, this figure doubled to 16 documents in 2022, indicating a sharp increase in academic interest and an initial phase of exploration into the integration of AR technology within engineering learning environments.

This upward trend continued, reaching its peak in 2023 with 18 publications, marking the highest level of research productivity within the four-year span. The data suggests that AR had, by this time, entered a more mature phase characterized by deeper implementation and evaluation efforts in educational contexts. Despite a slight decline in 2024, during which 15 publications were recorded, the number remained substantially high, underscoring the sustained relevance of AR as a topic of academic inquiry.

From a cumulative perspective, a total of 57 documents were published across the four-year period, with annual distribution percentages of 14,0 % (2021), 28,1 % (2022), 31,6 % (2023), and 26,3 % (2024). This consistency in publication output highlights that the application of AR in engineering education is not merely a passing trend but has evolved into a sustainable and strategic research domain. The findings serve as a significant indicator of the increasing acceptance and integration of immersive technologies within the broader discourse of technology-enhanced education and innovation.

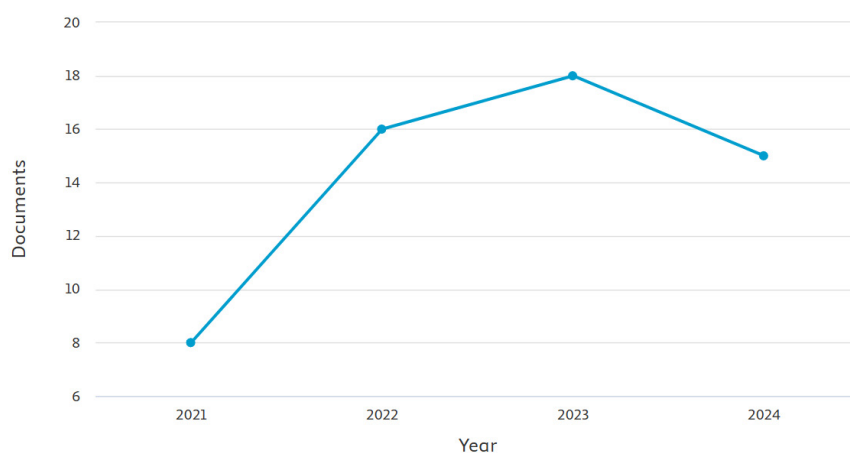


Figure 2. Analysis of Trends in Scientific Publications

Documents by Source: a 5-Year Overview

An analysis of publication trends over the past five years reveals the distribution of research output on the application of Augmented Reality (AR) in engineering education across various academic journals. The data illustrates that IEEE Access has consistently served as one of the primary sources of AR-related publications, contributing two articles in both 2021 and 2022. This number rose significantly to five articles in 2023, marking the journal's peak involvement, before declining to two articles in 2024. Similarly, the International Journal of Emerging Technologies in Learning demonstrated consistent engagement with the topic, increasing its contribution from one article in 2021 to two articles each in 2022 and 2023. In contrast, Electronics (Switzerland) recorded two articles in 2021, which declined to one in 2022, with no further publications on the topic in subsequent years.

The journal Computer Applications in Engineering Education began publishing on AR in engineering education in 2023 with one article, followed by an increase to two articles in 2024, indicating growing attention within the engineering education domain. Interestingly, Applied Mathematics and Nonlinear Sciences contributed a single article in 2024, signaling an emerging interest in the subject from the perspective of applied mathematics. These trends suggest a steady and expanding interest in the integration of AR into engineering education, with contributions spanning diverse academic disciplines and publication outlets. The data reflects not only the sustained relevance of the topic but also its interdisciplinary appeal, as it continues to attract scholarly attention across fields such as engineering, computer science, education, and applied mathematics.

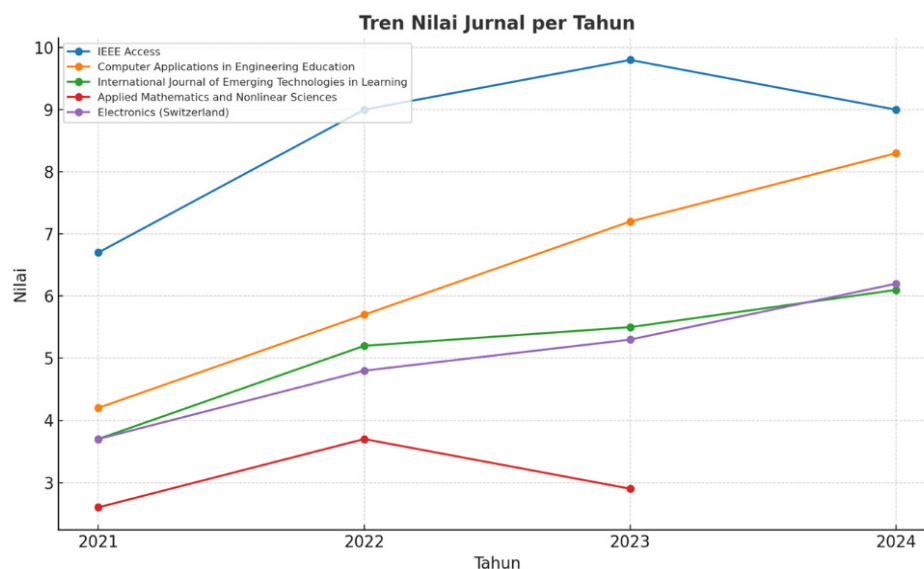


Figure 3. Documents by Source: A 5-Year Overview

The figure illustrates the development of CiteScore values from 2021 to 2024 for several journals focusing on technology and engineering education, particularly within the context of augmented reality. The *IEEE Access* journal demonstrates a significant upward trend, increasing from approximately 6.7 in 2021 to nearly 9.9 in 2023, followed by a slight decline to 9.0 in 2024. Similarly, *Computer Applications in Engineering Education* exhibits consistent growth, rising from 4.3 in 2021 to 8.3 in 2024. The *International Journal of Emerging Technologies in Learning* shows a gradual increase from 4.2 in 2021 to 6.1 in 2024. Conversely, *Applied Mathematics and Nonlinear Sciences* experienced an initial rise from 2.6 in 2021 to 3.7 in 2022, followed by a decline in 2023 and a subsequent recovery to 2.9 in 2024. *Electronics (Switzerland)* maintains a steady upward trajectory, increasing from 3.8 in 2021 to 6.1 in 2024. Overall, this trend analysis reflects an enhancement in the scientific influence and publication quality of these journals, indicating a growing academic interest in augmented reality applications within engineering education on a global scale.

Bibliographic Linkages between Countries

A total of 37 countries have contributed to research on the application of Augmented Reality (AR) in engineering education. Based on the data obtained, approximately 84 % of the total publications—comprising both single-country publications and multinational collaborations originate from 20 countries, indicating a concentration of scientific productivity within these regions. China emerges as the most prolific contributor, with a total of 10 publications, followed by Germany with 6 publications, and India, Spain, and the United States, each producing 4 publications. Other notable contributors include Colombia, Malaysia, and the United Kingdom, each with 3 publications. Countries such as Australia, Chile, Greece, Hong Kong, Italy, Mexico, Pakistan, Saudi Arabia, South

Korea, Turkey, and the United Arab Emirates each contributed 2 publications. Meanwhile, 19 other countries including Canada, France, Indonesia, and Portugal each contributed a single publication.

These findings reflect a growing global interest in the application of Augmented Reality in engineering education, with a dominance of developed countries possessing substantial capacities for educational technology research and development. Simultaneously, the emerging involvement of developing countries indicates a progressively balanced global participation in this interdisciplinary field. Countries with major research centers tend to be more active in advancing research and fostering collaborations, whereas other nations remain more focused on independent research development. Therefore, understanding these patterns of engagement is crucial for guiding research development strategies, both in strengthening international networks and supporting domestic collaborations, to enhance the impact of research in Augmented Reality within engineering education.

The 20 leading countries in productivity

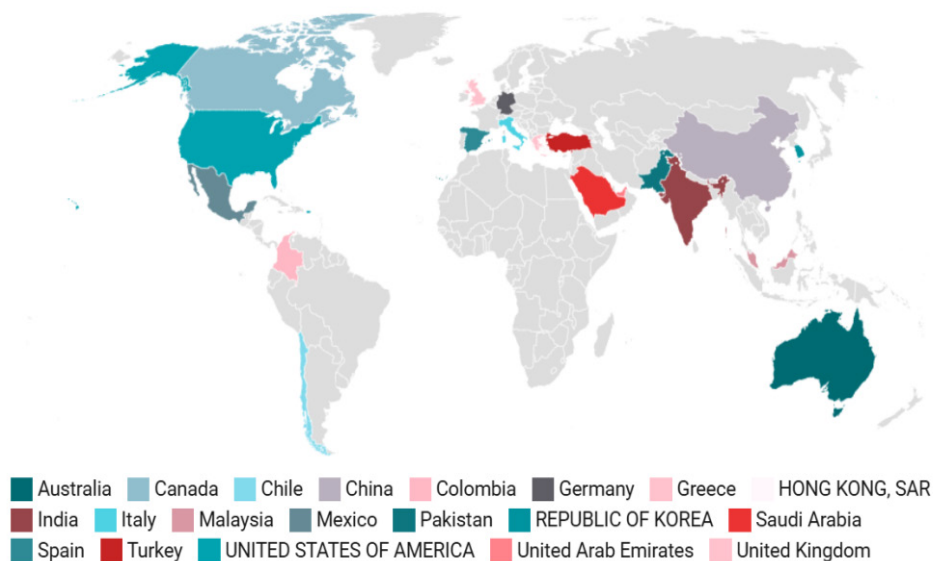


Figure 4. The 20 leading countries in productivity

This visualization depicts the bibliographic relationships among countries engaged in research on Augmented Reality (AR) technology in engineering education, highlighting the highly interconnected nature of the field through extensive international collaboration. China occupies the most central and dominant position, as evidenced by the large size of its node and numerous connecting lines, indicating its leading role both as a primary contributor of publications and as a global hub of collaboration. Additionally, countries such as the United States, India, and Spain hold significant central roles, demonstrating their status as key actors actively building scientific networks and supporting the advancement of AR research in engineering education on a global scale.

Beyond illustrating connectivity, the distinct colors of the nodes represent the formation of regional or thematic collaboration clusters. The red cluster, centered around China and several Asian countries, signifies a strong research group within this geographic area. The green cluster reflects major collaborative networks among European countries, including Spain and Germany. The blue cluster indicates close relationships between countries such as India, the United States, and the United Kingdom, which may share similar research foci or methodologies. Although countries with smaller nodes, such as Malaysia and the United Kingdom, contribute relatively fewer publications, they remain actively engaged, underscoring the importance of international collaboration networks as crucial mechanisms for enhancing the quality and impact of research. Overall, this visualization demonstrates the rapid development of AR research in engineering education, supported by a globally interconnected and mutually influential collaborative network.

Co-Occurrences of Author Keywords

A network visualization was employed to illustrate the co-occurrence relationships among author keywords. In this analysis, only keywords appearing at least five times were included, resulting in a total of 13 keywords meeting this criterion. Each keyword was analyzed based on its frequency of occurrence and the total strength of its association with other keywords in the network. The keyword “augmented reality” appeared most frequently, with 56 occurrences and the highest association strength of 199. Additionally, “engineering

education” stood out with 48 occurrences and an association strength of 185, followed by “virtual reality” (26 occurrences; 122) and “e-learning” (18 occurrences; 92). Other significant contributing keywords included “learning systems” (9 occurrences; 43), “education computing” (8; 40), and “artificial intelligence” (7; 38). Keywords such as “computer aided instruction” and “internet of things” appeared six times each, both with an association strength of 30. Meanwhile, keywords with lower but still relevant frequencies included “digital technologies” (5; 27), “emerging technologies” (5; 26), and “usability engineering” (5; 18). This data provides an overview of the dominant concepts and the patterns of interconnection among topics within the analyzed literature, with “augmented reality” and “engineering education” emerging as central foci in the discourse on educational technology and innovative learning.

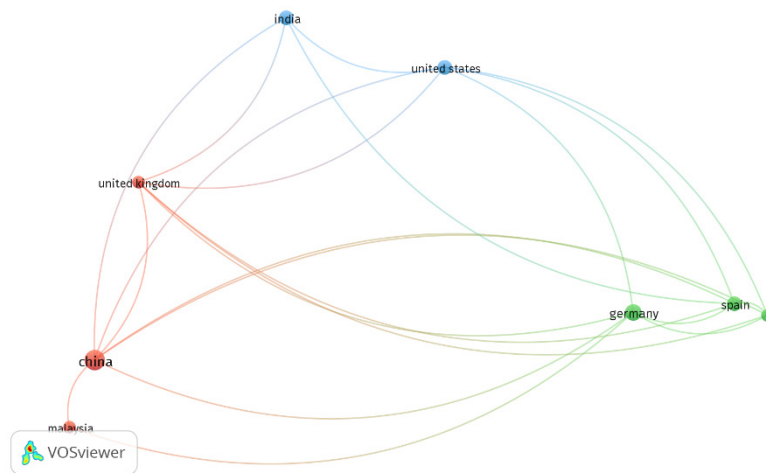


Figure 5. Bibliographic Coupling of the Journals

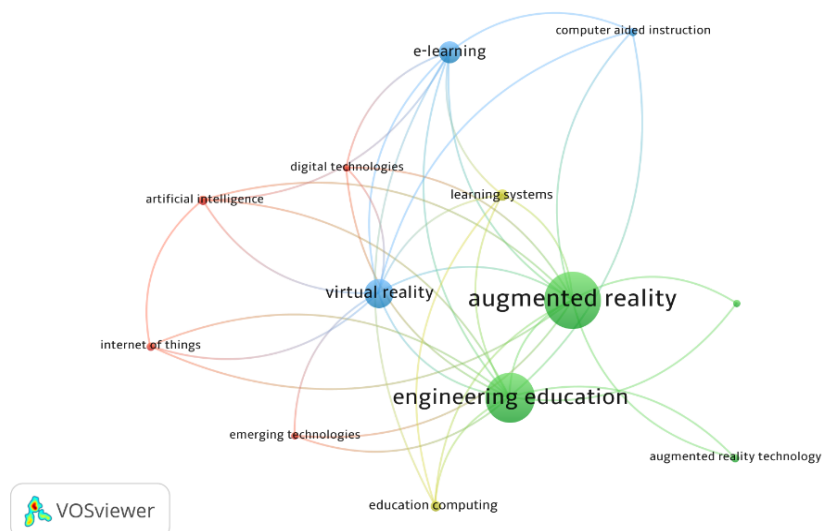


Figure 6. Interconnection of Augmented Reality and engineering education

Top 10 Articles Citations

As part of the bibliometric analysis in this study, table 1 presents the top ten most cited articles related to the use of augmented reality (AR) technology in engineering education. The article with the highest citation count is titled “*Augmented Reality and Virtual Reality for Learning: An Examination Using an Extended Technology Acceptance Model*,” published in 2021, with a total of 206 citations and an average of 41,2 citations per year. This highlights the significant academic attention towards studies on the acceptance of AR/VR technologies in engineering learning. The second most cited article, “*A Modern Approach towards an Industry 4.0 Model: From Driving Technologies to Management*,” published in 2022, recorded 103 citations with an average of 25,75 citations per year, indicating the strong relevance of Industry 4.0 technologies to engineering education.

Other articles in the list explore diverse topics including AR-based mathematics function learning, spatial

ability training, development of mobile applications for engineering education, and the integration of artificial intelligence in non-technical education. The majority of these articles were published within the past three years (2021-2023) and exhibit relatively high citation averages per year, reflecting the rapid growth of research interest in AR applications within engineering education. These findings underscore that AR technology is not only advancing theoretically but also making tangible contributions to fostering technological innovation in engineering pedagogy.

Table 1. Top 10 articles with the highest citations

No	Title	Year	Average Citations per Year	Total Citations
1	Augmented Reality and Virtual Reality for Learning: An Examination Using an Extended Technology Acceptance Model ⁽²²⁾	2021	41,2	206
2	A Modern Approach towards an Industry 4.0 Model: From Driving Technologies to Management ⁽²³⁾	2022	25,75	103
3	Ultracompact multifunctional metalens visor for augmented reality displays ⁽²⁴⁾	2022	20	80
4	Application in augmented reality for learning mathematical functions: A study for the development of spatial intelligence in secondary education students ⁽²⁵⁾	2021	12	60
5	Towards a new learning experience through a mobile application with augmented reality in engineering education ⁽²⁶⁾	2021	11,2	56
6	Taxonomy of Virtual and Augmented Reality Applications in Education ⁽²⁷⁾	2021	10	50
7	Personalization of the Learning Path within an Augmented Reality Spatial Ability Training Application Based on Fuzzy Weights ⁽²⁸⁾	2022	11,5	46
8	Development of an AR-Based AI Education App for Non-Majors ⁽²⁹⁾	2022	11	44
9	Technological Spotlights of Digital Transformation in Tertiary Education ⁽³⁰⁾	2023	12,67	38
10	Industrial Internet of Things and Emerging Digital Technologies-Modeling Professionals' Learning Behavior ⁽³¹⁾	2021	7,4	37

DISCUSSION

Annual Publication Trends (2021-2025)

A bibliometric analysis of Scopus data reveals that publications concerning the application of Augmented Reality (AR) in engineering education have experienced a non-linear yet strategically progressive growth during the period from 2021 to 2025. In 2021, the volume of publications was relatively low, indicating limited adoption of AR within engineering education at that time. This limited uptake can be attributed to various challenges, including constraints in digital infrastructure, an underdeveloped AR research ecosystem,⁽³²⁾ and engineering curricula that had not sufficiently incorporated immersive technologies.⁽³³⁾ Consequently, AR was still regarded as an emerging technology predominantly investigated by early adopters rather than representing a widespread trend.

The notable surge observed in 2022, culminating in a peak in 2023, was not incidental but the outcome of the convergence of three principal catalysts. First, advancements in AR hardware and software technologies rendered the tools more affordable, portable, and compatible with existing digital learning systems. Second, the global experience of post-COVID-19 online education accelerated the adoption of interactive technologies as solutions to the fatigue associated with conventional e-learning models.⁽³⁴⁾ Third, educational and research policies in influential countries explicitly prioritized the integration of immersive technologies within STEM education, thereby stimulating a wave of international publications.

Interestingly, a decline in publication numbers was observed in 2024. Rather than indicating waning interest, this phenomenon is better interpreted as a shift in research focus. Following an intensive exploratory phase, AR research began transitioning toward multidimensional integration, particularly with Artificial Intelligence (AI) and Virtual Reality (VR), aiming to develop adaptive, contextualized learning ecosystems capable of simulating the complexities of industrial environments in real-time.⁽³⁵⁾ This reorientation necessitates more complex methodologies,⁽¹⁶⁾ closer interdisciplinary collaboration, and extended research durations prior to publication.

Preliminary data for 2025 remain insufficiently representative to draw definitive conclusions; however, initial indications suggest the continuation of this integrative trend. Thus, it can be concluded that AR in

engineering education has progressed from a proof-of-concept phase toward a consolidation phase, wherein research emphasis has shifted from merely technical validation to pedagogical optimization, long-term impact assessment,⁽³⁶⁾ and the creation of added value through integration with next-generation educational technology.⁽³⁷⁾ These developments bear significant implications for global research strategies, intensifying competition and underscoring that successful publication outcomes will increasingly depend on the ability to synthesize technological innovation with robust pedagogical frameworks and industry relevance.

Journals with the Highest Number of Publications

The distribution of publications reveals the presence of key journal clusters that serve as the primary hubs for disseminating knowledge related to Augmented Reality (AR) in engineering education. Notably, *Education and Information Technologies*, *IEEE Access*, and *Computer Applications in Engineering Education* occupy dominant positions. These journals are ranked within the Q1-Q2 quartiles according to CiteScore metrics, reflecting their high standards in manuscript selection processes, broad international reach, and substantial citation impact.

This dominance underscores two critical points. First, AR research in engineering education has established a strong interdisciplinary identity bridging educational technology, engineering sciences, and computer science, consistent with findings by Huang *et al.*⁽³⁸⁾ Second, the preferred publication venues for researchers are high-impact journals with expectations of substantial theoretical and practical contributions. To gain acceptance in these journals, studies must not only present technical innovations but also clearly articulate their relevance to global challenges in engineering education, such as readiness for Industry 4.0, the development of 21st-century competencies, and the implementation of sustainable engineering education principles.

Strategically, this pattern indicates that the AR publication ecosystem within engineering education is well-established at the international level. Researchers from developing countries face a dual challenge: competing on the basis of rigorous methodological quality and innovation while simultaneously cultivating global collaborative networks to enhance the relevance and competitiveness of their work. Therefore, understanding this publication landscape is crucial not only for effective research planning but also for maximizing academic visibility and impact.

International distribution and collaboration

Most Productive Countries

An analysis of publication distribution indicates that China, Germany, and the United States occupy dominant positions in research on Augmented Reality (AR) in engineering education. This leadership is attributable to well-structured research ecosystems, substantial investments in technological innovation, and close ties to manufacturing and high-tech industries that provide real-world testbeds for AR development. Academically, these countries function as knowledge hubs that not only produce high-quality research but also serve as methodological and disciplinary standards within the field.

Developing countries such as Colombia, Malaysia, and Indonesia have begun to show increased productivity, albeit still trailing in absolute publication numbers. This growth suggests a shifting trend of AR adoption toward regions previously underrepresented in the international literature. In countries with limited physical laboratory facilities, AR offers an efficient solution for engineering education, which traditionally requires expensive equipment, specialized spaces, and carries significant safety risks. Consequently, the rising publication output from developing countries not only reflects academic advancement but also represents a potential strategy to mitigate educational infrastructure disparities.

Collaboration Patterns

The international collaboration map (figure 5) reveals a polarized network configuration. The largest nodes, representing countries such as China, Germany, and the United States, exhibit high and diverse collaboration intensity, including intercontinental partnerships. The thick connection pathways between the United States, Germany, Spain, and China reflect high-frequency collaboration clusters characterized by intensive exchange of knowledge, technology, and research resources. This pattern reinforces their positions as innovation hubs and accelerates the diffusion of AR technology within engineering education.

Conversely, developing countries such as Malaysia and India appear as peripheral nodes with limited connections, often maintained through one or two dominant partners. Furthermore, low intensity of international collaboration may impede the adoption of AR technology in engineering education, as its development frequently depends on robust research and development networks.^(39,40) These characteristics indicate structural barriers including limited access to international funding, challenges in building extensive research networks, and restrictions related to publication in globally recognized languages and journals. The relatively weak international collaboration in these groups potentially hinders technology transfer and slows the adoption process of AR in engineering education.

Alternatively, some scholars argue that developing countries may leverage their unique cultural and social

contexts to independently foster innovation, potentially leading to alternative pathways for technology adoption and research collaboration. This perspective suggests that localized strategies can mitigate some of the challenges posed by global structural barriers.⁽⁴⁰⁾

Implications for Research and Practice

The findings carry strategic implications for both research and policy in engineering education. For developed countries, expanding collaborations with developing nations presents opportunities to conduct context-specific research that enriches the global understanding of AR implementation. Conversely, for developing countries, active engagement in international research networks is critical to enhancing the quality and visibility of their scholarly output. Joint funding programs, research mobility schemes, and open-access repositories can serve as effective policy instruments to bridge these gaps. In the long term, equitable collaboration will determine whether AR evolves into an inclusive educational technology or merely reinforces the dominance of established research hubs. Therefore, a well-planned global collaboration strategy emerges as a key determinant for the sustainability of AR innovation within the field of engineering education.

Main theme, keywords, highest citation

Keyword Analysis

The co-occurrence mapping of keywords reveals that research on Augmented Reality (AR) in engineering education is evolving along three interdependent axes. The first axis, the *AR & VR Technology Cluster*, characterizes the early phase of development focused on the technical infrastructure—such as hardware, software, and mobile learning platforms. This cluster lays the technological foundation that is essential for the effective integration of AR into engineering curricula.

The second axis, the *AI Integration & Adaptive Learning Cluster*, reflects a shift in orientation from merely delivering content to leveraging intelligent analytics for personalized learning. In this context, the effectiveness of AR is assessed not only by its visual sophistication but also by its ability to adapt instructional content to learners' cognitive profiles. The third axis, the *Simulation and Technical Training Cluster*, highlights AR's function as a medium for practical skill transfer, enabling the replication of real-world work environments with minimal risk and controlled costs. The central position of the keyword "augmented reality" within the network indicates its cross-cutting nature—not as a standalone technology, but as a strategic platform that integrates both pedagogical and technological approaches. This interconnected pattern signifies a paradigmatic shift in AR's role, from a supplementary innovation to a strategic component within the engineering education ecosystem. As such, AR is now recognized as fundamental in shaping the competitiveness of engineering graduates.

Most-Cited Articles

The articles with the highest citation counts consistently address three core themes: technology acceptance through the Technology Acceptance Model (TAM), the development of spatial skills, and project-based learning. The emphasis on TAM underscores that user acceptance—by both instructors and students—is as critical a determinant of success as the technical design of the technology itself. Studies have shown that perceived usefulness and ease of use significantly influence user acceptance.^(41,42) Research on spatial skills highlights the advantage of augmented reality (AR) in facilitating three-dimensional visualization, a crucial competency in engineering disciplines.⁽⁴²⁾ Meanwhile, project-based learning approaches demonstrate the effectiveness of AR in integrating theory with practice while promoting active learner engagement in contextual problem-solving. Further findings suggest that AR can significantly enhance spatial skills, which are essential for technical problem-solving.⁽⁴³⁾ The high citation rates of these articles indicate their normative value, as they provide key references that shape the direction and standards of AR development in engineering education.

Research Development Trajectories

A synthesis of keyword analyses and influential articles suggests that future research in AR for engineering education is converging along three strategic trajectories. First, the integration of AR with artificial intelligence (AI) aims to create adaptive learning systems that can accommodate differences in learners' readiness levels, learning styles, and cognitive needs. Second, the development of AR for remote training in high-risk simulated environments—such as industrial equipment operations or safety procedures—enables the application of the "safe failure" principle. Third, the innovation of low-cost AR solutions accessible to institutions with limited resources is crucial to promoting the global democratization of educational technology in engineering.

The application of Augmented Reality (AR) in high-risk simulations—such as industrial equipment operation and safety procedures—enables the implementation of the "safe failure" concept, wherein learners can engage in practice and make mistakes without real-world consequences. Additionally, the development of AR offers a low-cost solution for institutions with limited resources, broadening access to advanced educational technologies and supporting the global democratization of engineering education.⁽⁴⁴⁾

The strategic implications of these findings underscore the need for a research agenda that simultaneously integrates technical and pedagogical dimensions in order to create a sustainable learning ecosystem. From a policy perspective, this highlights the urgency of long-term investment in AR as an integral component of digital transformation in engineering education. From a practical standpoint, instructors and curriculum developers must position AR as a permanent pedagogical infrastructure to enhance students' technical competencies, critical thinking skills, and industry readiness.

Synthesis of Findings, Gaps, and Recommendations

Findings from the keyword analysis, influential articles, and current research trends indicate that AR research in engineering education revolves around three core pillars: strengthening technological infrastructure, integrating artificial intelligence for adaptive learning, and utilizing simulation as a medium for practical skills transfer. While significant contributions have emerged from developed countries with robust research infrastructures, research gaps persist. These include a lack of studies from developing countries, limited innovation in low-cost AR solutions, and a scarcity of longitudinal studies that comprehensively link technical and pedagogical aspects.

Furthermore, issues related to the sustainability of technology adoption, economic impact, and the alignment of graduate skills with industry demands remain underexplored. Therefore, future research should strategically emphasize the development of integrative models that combine technical innovation with pedagogical strategies, promote adaptive AR solutions tailored to infrastructural limitations, and expand cross-disciplinary and cross-national collaborations to establish inclusive and sustainable global standards.

Limitations

This study has several limitations that should be acknowledged. First, the keyword analysis and literature review primarily relied on databases and publications accessible within certain academic and regional constraints, potentially overlooking relevant research published in less widely indexed journals or languages other than English. Second, the focus on engineering education might limit the generalizability of the findings to other educational fields where AR applications may differ significantly. Third, the analysis emphasized recent trends and influential articles, which may have introduced bias toward more prominent research, possibly underrepresenting emerging or niche studies. Finally, this study did not include primary empirical data, which limits the ability to validate theoretical insights with practical implementation outcomes. Addressing these limitations in future research will strengthen the robustness and applicability of AR integration strategies in engineering education.

The synthesis of the findings provides a comprehensive overview indicating that research on Augmented Reality (AR) in engineering education has evolved rapidly from the early stages of adoption to becoming a strategic component of learning infrastructure. The exponential growth of publications, together with the strengthening of international collaboration networks, reflects a dynamic and expanding global research landscape. This development is led by several prominent research hubs, yet it still presents opportunities for broader participation from regions with limited resources.

Thematic and article analyses reveal three primary research focuses: AR & VR technologies, AI integration and adaptive learning, and technical simulation and training. These findings highlight that successful implementation of AR requires a synergy between technical sophistication and pedagogical relevance. High citation rates in studies addressing technology acceptance, spatial skills, and project-based learning further emphasize that AR is not merely a visual aid but a strategic platform for producing graduates capable of meeting the demands of Industry 4.0. Future research should therefore prioritize the integration of technology and pedagogy, improving accessibility, and validating applications in real-world industrial contexts.

CONCLUSION

Based on the results of the bibliometric review, the application of Augmented Reality (AR) technology in engineering education has demonstrated significant growth and is increasingly being integrated into teaching and learning processes. AR offers interactive and immersive learning experiences that facilitate a more accessible and practical understanding of complex engineering concepts. Numerous studies highlight that AR can enhance learning motivation, student engagement, and teaching effectiveness, particularly in simulations and visualizations that are challenging to achieve through conventional methods.

Nevertheless, several challenges must be addressed to optimize the use of AR in engineering education, including hardware limitations, the scarcity of curriculum-aligned educational content, and the need for adequate teacher training. With continuous improvements and innovations, AR holds substantial potential to become a primary instructional tool in engineering education, supporting the development of student competencies through more practical, realistic, and engaging approaches in the future.

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CONFLICT OF INTEREST

None.

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