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Trends, Themes, and Conceptual Networks of Immersive Technologies in Quantum Science Education: A Bibliometric Analysis

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ABSTRACT

This study presents a bibliometric analysis of research on immersive technologies in quantum-related education, based on 32 Scopus-indexed publications published between 2017 and 2025. The dataset was obtained through a structured search and screened using predefined inclusion and exclusion criteria, focusing on empirical studies implementing immersive technologies (e.g., virtual reality, augmented reality, and extended reality) in quantum-related learning contexts. The analysis was conducted using Bibliometrix and Biblioshiny, applying techniques such as publication trend analysis, country productivity mapping, keyword co-occurrence, and thematic analysis. The results show a steady increase in the number of scientific publications, with the United States, Indonesia, and China emerging as major contributors. Keyword co-occurrence analysis and thematic mapping identified virtual reality and augmented reality as dominant themes, reflecting their central role in supporting visualization and learning processes. Trend analysis also indicates increasing attention to virtual laboratories and modern physics contexts. However, given the relatively small size of the dataset, these findings should be interpreted with caution and viewed as early indications of a developing research domain, rather than as definitive trends. Overall, this study highlights the growing importance of immersive technologies in addressing representation challenges in quantum science education and identifies opportunities for deeper conceptual integration, methodological diversification, and interdisciplinary collaboration in future research.

Keyword: Augmented reality, bibliometric analysis, immersive technologies, quantum education, virtual reality

INTRODUCTION

Quantum science is often characterized as one of the most abstract domains in science education, and this level of abstraction has been linked to documented learning difficulties among students (Chhabra & Das, 2017, 2023). Its basic concepts operate on scales and in ways that are fundamentally detached from everyday sensory experience (Lehka et al., 2022; Zaman

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Ahmed et al., 2021). Concepts such as superposition, quantum entanglement, and wave-particle duality are inherently non-intuitive, making them difficult for students to grasp (Yan et al., 2026). Consequently, quantum science learning requires strong visual and interactive support, including multiple representations, dynamic simulations, and innovative learning approaches capable of translating complex quantum behavior into forms that are pedagogically meaningful and interpretable by learners (Abualrob & Awad, 2024; Coban et al., 2025). Furthermore, understanding quantum mechanics often relies on prior knowledge of classical physics concepts such as energy, momentum, and force. However, many students still struggle to grasp these fundamental concepts, which ultimately further limits their ability to visualize and understand quantum phenomena (Chhabra & Das, 2018). Traditional learning approaches, which are often based on historical or narrative perspectives, also tend to be unable to accommodate in-depth discussions of core quantum concepts such as superposition and entanglement, thus limiting the achievement of meaningful conceptual understanding (Lovisetti & Giliberti, 2025). Taken together, these challenges demonstrate that the abstract nature of quantum science is not only conceptual but also has measurable implications for student learning. This further underscore the need for instructional designs that bridge the gap between theoretical models and students' conceptual understanding.

These challenges can be further understood through established learning theories. Previous studies have shown that the abstract and non-intuitive nature of quantum concepts imposes a high intrinsic cognitive load on learners, as they require the simultaneous processing of complex mathematical and conceptual representations (Ekin et al., 2025). These limitations in working memory make it difficult for learners to integrate new knowledge effectively (Kiliç, 2010), while the steep learning curve in quantum science further contributes to cognitive overload that can hinder meaningful understanding (Hernandez et al., 2026). These challenges are further exacerbated by the need for conceptual shifts in quantum learning. Learners often rely on classical, deterministic intuitions, which conflict with the probabilistic and counterintuitive nature of quantum mechanics, creating significant barriers to understanding concepts like superposition and entanglement (Bouchée et al., 2022; Halim et al., 2025). This mismatch leads to persistent misconceptions, as students struggle to transition from classical to quantum thinking. Furthermore, the abstract nature of quantum mechanics makes it difficult for students to connect the mathematical formalism to physical phenomena, further hindering the development of scientifically accurate mental models (Kim et al., 2025). Spatial cognition also plays a crucial role in quantum learning, as students are required to mentally represent and manipulate abstract, dynamic, and three-dimensional phenomena. Studies have shown that strong spatial reasoning skills are closely linked to improved understanding of complex scientific concepts, including quantum mechanics, and can be enhanced through spatially rich learning environments, such as immersive technology (Nwobodo et al., 2025; Plummer et al., 2022). Overall, these theoretical perspectives suggest that difficulties in quantum learning arise from a combination of high cognitive load demands, the need for conceptual restructuring, and the need for advanced spatial reasoning skills. Therefore, this further emphasizes the importance of learning approaches that integrate visualization, interaction, and experiential learning.

In response to these challenges, immersive technologies such as augmented reality, virtual reality, and mixed reality have emerged as promising tools for enhancing quantum science education. These technologies provide interactive, three-dimensional visualizations that allow learners to explore submicroscopic structures, dynamic quantum phenomena, and complex spatial relationships in ways that are difficult to achieve through traditional representations (Cai et al., 2021; Weymuth & Reiher, 2021; Xiao et al., 2023). By allowing learners to manipulate models, observe simulated quantum behavior, and experience abstract concepts through embodied interactions, immersive environments have the potential to strengthen conceptual understanding in physics, chemistry, engineering, and other related fields. Mufit et al (2024) and Abdelhamid et al., 2024) show that immersive technology can increase student engagement, support the development of spatial reasoning, and make previously inaccessible quantum processes more understandable, thus positioning this technology as an increasingly valuable component in contemporary science learning.

Previous studies have demonstrated various ways in which immersive technology can be used to support the visualization of phenomena at the quantum level. For example, several studies have utilized virtual reality to visualize atomic structure, electron orbitals, and molecular dynamics (Seritan et al., 2021; Suno & Ohno, 2023; Syamiluddin et al., 2025), this allows learners to interact with three-dimensional models that more clearly represent submicroscopic behavior. Other studies have utilized augmented reality to represent concepts such as atomic orbitals, wave-particle behavior, and the spatial configuration of electrons (D'Souza et al., 2025; Migdał et al., 2022; Zable et al., 2020), projecting these abstract ideas into the learner's physical environment for more intuitive exploration. Empirical evidence suggests that immersive technology can significantly enhance learning outcomes. A study conducted by (Nwobodo et al., 2025) implemented an augmented reality-based Mach–Zehnder interferometer, which resulted in a 45.45% increase in students' conceptual understanding. The results of the virtual reality experiment also showed that students in the experimental group significantly outperformed those who participated in traditional learning based on ANCOVA analysis. This finding was further strengthened by higher levels of learning motivation and lower cognitive load in students, indicating that the immersive environment is able to support both cognitive processes and learning engagement (Tarng & Pei, 2023). These findings suggest that immersive technologies contribute not only to improved visualization, but also to measurable improvements in learning effectiveness in quantum education.

The integration of immersive technologies in quantum science education also aligns with broader global trends in educational technology, which emphasize interactive learning environments and experiential approaches to support conceptual understanding (Song et al., 2024; Yadav, 2025). This shift reflects an increasing pedagogical focus on simulation-based learning, scientific visualization, and multimodal representations that enable learners to construct meaning through active exploration. Immersive technologies also provide a medium for directly interacting with abstract quantum phenomena, previously accessible only through mathematical formalisms or symbolic models, thus expanding opportunities for inquiry-based learning, hands-on experience, and rich visualization (Coban et al., 2025; Phelps et al., 2025; Sinensis et al., 2025). Unlike many other scientific domains, quantum phenomena occur at atomic and subatomic scales, which are inherently not directly observable and are governed by probabilistic and non-intuitive principles (Jankiewicz et al., 2022). Therefore, simulation is not just a complementary tool, but a fundamental need in representing these concepts. Previous research has also shown that simulations play a central role in quantum science education by enabling the visualization of microscopic processes and supporting the development of learners' mental models, particularly through platforms such as PhET Interactive Simulations and the QuVis Quantum Mechanics Visualization Project (Kohnle et al., 2015). Furthermore, more sophisticated simulation approaches have been used to support advanced learning and research contexts, allowing users to interact with quantum systems through representations such as state vectors and density matrices (Krötz et al., 2025). Thus, these technologies are not only relevant but increasingly essential in mediating the unobservable, probabilistic, and abstract nature of quantum phenomena, thus facilitating deeper conceptual understanding in quantum science education.

Despite the increasing integration of immersive technologies in science education, the body of knowledge in this field remains fragmented and unevenly developed. Previous systematic reviews have examined immersive technologies in the general science domain, highlighting global trends, implementation challenges, and technological developments (Kurniawan et al., 2026). However, these studies generally focused on broad disciplinary contexts such as physics, chemistry, and biology, without specifically addressing domain-specific conceptual complexities. More recent reviews have begun to explore immersive technologies in more specific contexts, such as quantum education, identifying the emerging use of extended reality (XR) to visualize abstract and non-intuitive phenomena (Song et al., 2024). However, these studies remain limited in scope and do not provide a comprehensive map of the conceptual structure, thematic evolution, or research networks within the field. Furthermore, systematic investigations in applied physics domains, such as medical physics and radiation physics, have shown that immersive technologies significantly improve student learning outcomes, engagement, and performance, with most studies reporting positive educational impacts (Tene et al., 2024). However, this body of research is generally characterized by small-scale implementations, fragmented methodologies, and a lack of standardized frameworks or integrative analyses. As a result, the existing literature is scattered across multiple domains, including physics education, medical training, and educational technology, creating a multidisciplinary but poorly connected knowledge base. Consequently, understanding how this research field has evolved over time, how knowledge structures are formed, what themes dominate scientific discourse, and how conceptual connections exist across domains remains limited. To address this gap, a comprehensive bibliometric analysis is needed to map global trends, thematic developments, and conceptual relationships in the use of immersive technologies for quantum science education.

Based on these considerations, this study conducts a bibliometric analysis to map the global research landscape on immersive technologies in quantum science education. The goal is to provide a comprehensive overview of how this multidisciplinary field is developing, what intellectual structures are emerging, and what thematic directions characterize recent scholarship. By analyzing publication trends, influential contributions, author and institutional networks, and conceptual patterns derived from keyword analysis, this study seeks to provide an integrated understanding of the field's evolution and its thematic composition (Mukherjee et al., 2022; Phoong et al., 2022). To guide this investigation, the following research questions were formulated: (1) RQ1: How has global research on immersive technologies in quantum science education evolved during the period 2017-2025?; (2) RQ2: What dominant research themes and conceptual structures characterize studies employing immersive technologies in quantum science education?

METHOD

Scope and Retrieval Strategy

This study focuses on mapping the research landscape related to the use of immersive technologies in quantum science education. Its scope includes educational applications of augmented reality, virtual reality, mixed reality, and extended reality across various quantum-related domains, including physics, chemistry, engineering, and other disciplines that address concepts at the submicroscopic or quantum level. Scopus was chosen as the primary data source due to its extensive coverage of reputable journals and peer-reviewed conference proceedings, as well as the availability of rich bibliographic metadata suitable for bibliometric analysis (Pranckutė, 2021). The final retrieval string used was: TITLE-ABS-KEY (("quantum" OR "quantum physics" OR "modern physics" OR "atomic model" OR "Bohr model" OR "photoelectric effect" OR "wave-particle duality") AND ("augmented reality" OR "mixed reality" OR "Virtual reality" OR "Extended Reality") AND (education OR learning OR teaching OR instruction)). The search was limited to documents published between 2017 and 2025, as research on augmented reality and virtual reality in education has increased significantly since 2017, particularly focusing on its impact on learning outcomes, motivation, and learner experience (Abazi-Bexheti et al., 2022). This period reflects the early emergence and rapid development of immersive technologies in educational contexts, marked by increasing accessibility and adoption of virtual reality and augmented reality devices. Only peer-reviewed articles and conference papers were included, while document types such as reviews, book chapters, editorials, and notes were excluded.

Data Collection and Cleaning

The initial dataset was screened using the inclusion and exclusion criteria established in this study. Only documents developing or implementing immersive media such as augmented reality, virtual reality, mixed reality, or extended reality for quantum-related learning were retained. Studies that did not use immersive technologies or focused on non-quantum topics were excluded. Review articles, book chapters, and other non-empirical document types were also eliminated at this stage. Given the specificity of the topic of combining immersive technologies with quantum science education, the resulting dataset is relatively limited, reflecting the burgeoning nature of this research field, not overly restrictive search parameters. However, the relatively small size of the dataset is also a limitation, as it may limit the generalizability of bibliometric patterns and reduce the density of network-based analyses. Therefore, the study findings should be interpreted with caution and viewed as indicative of early trends, rather than as established structures.

To ensure data validity, all documents obtained through the search process underwent a multi-step screening process that included reviewing titles, abstracts, and full texts, ensuring that only studies that explicitly met the inclusion criteria were retained. This selection process followed the PRISMA 2020 framework (Page et al., 2021), which includes identification, screening, eligibility assessment, and final inclusion, as illustrated in Figure 1.

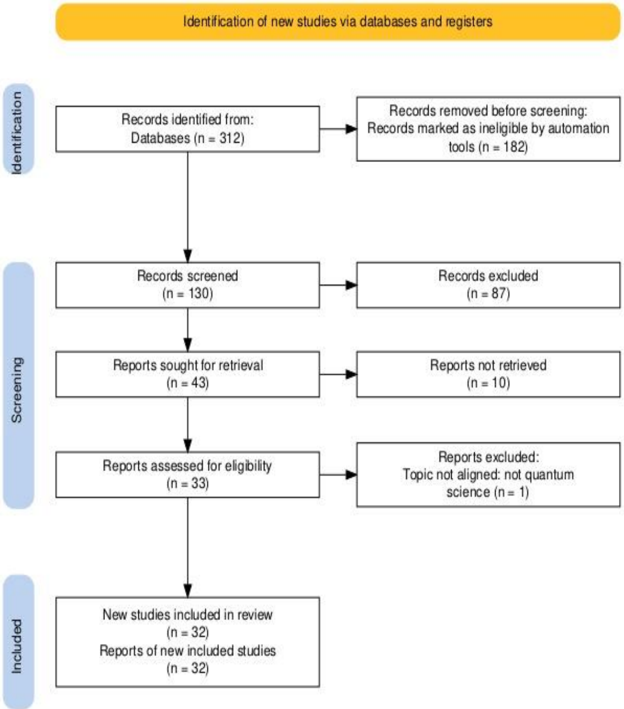

Figure 1. The Process of Article Selection

Data Analyis

The final dataset was analyzed using the Bibliometrix package in R and its graphical interface, Biblioshiny. Biblioshiny is an interactive, web-based interface built on top of the Bibliometrix package, allowing researchers to perform bibliometric analysis within R without the need for direct programming (Aria & Cuccurullo, 2017). Performance analysis was used to examine publication trends, authorship patterns, institutional and country contributions, and citation impact. These indicators provide a quantitative overview of the evolution of research on immersive technologies in quantum science education. Furthermore, keyword co-occurrence analysis was used to identify dominant research themes and visualize conceptual linkages through network maps. Thematic mapping and thematic evolution analyses were also conducted to trace the development of key topics over time and illustrate shifts in research clusters across time periods.

RESULTS AND DISCUSSION

Results

The key information displayed in Figure 2, extracted from the dataset, provides an initial overview of the structural characteristics of research on immersive technologies in quantum science education. The presence of only one single-author article reinforces the notion that the development of immersive technologies tends to involve interdisciplinary teamwork integrating expertise from science education, physics, computer science, and learning technology. The authorship pattern suggests a collaborative research culture, as evidenced by the 106 authors contributing to the dataset, with an average of 3.55 authors per document. Furthermore, the international collaboration rate of 12.12% indicates that while global collaboration does exist, it remains relatively limited, opening up opportunities for strengthening international partnerships in the future.

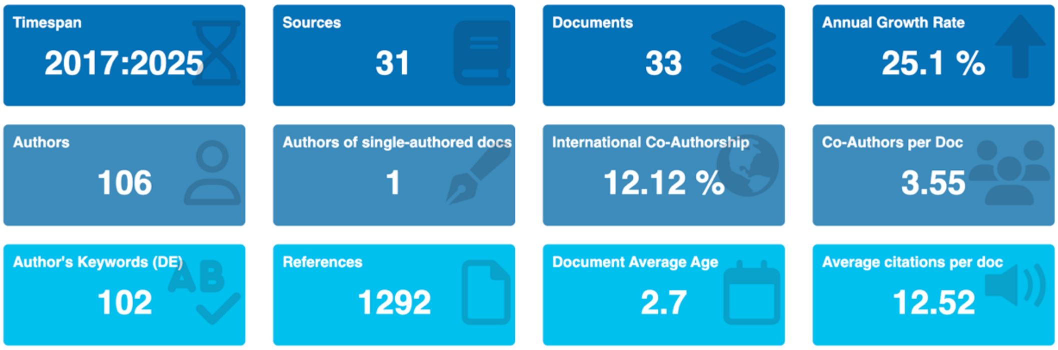

Figure 2. Main Information

This dataset includes 102 author keywords, demonstrating conceptual diversity and the presence of various thematic directions in this field. Overall, the documents reference 1,292 sources, indicating that research in this domain is based on a broad literature, reflecting its multidisciplinary nature. The average document age of 2.7 years indicates that most publications are relatively recent, further confirming that the application of immersive technologies in quantum learning is a burgeoning research field. The average citation rate of 12.52 citations per document indicates a relatively strong level of academic attention, especially considering the relative youth of this field.

Publication Growth and Global Contributions

The analysis for RQ1 examines research productivity and global contributions through five key indicators. Annual publication trends are used to illustrate the growth of scientific output over time, while country distribution highlights the global landscape of contributing regions. Institutional analysis identifies universities and research centers that are key drivers in the field, and author mapping reveals the most active researchers shaping the field's development. Complementing these patterns, identifying the most cited documents provides insight into the studies that have the strongest academic influence in research on immersive technologies for quantum-related learning.

Yearly Trend of Publication Number

Figure 3 shows that initial activity in this field was very limited, with only one publication per year between 2017 and 2019. A significant increase began in 2020, when the number of publications rose to four, followed by a sharp spike in 2021 with seven papers, indicating growing academic interest and wider adoption of AR/VR/XR technologies in science education research. Despite a temporary decline in 2022, the field regained momentum in the following years, reaching another significant peak in 2024 with eight publications. Overall, this pattern reflects a rapidly growing research field that is gaining increasing attention, particularly after 2020, in line with global advances in the development of immersive technologies and the increasing integration of digital tools in educational contexts.

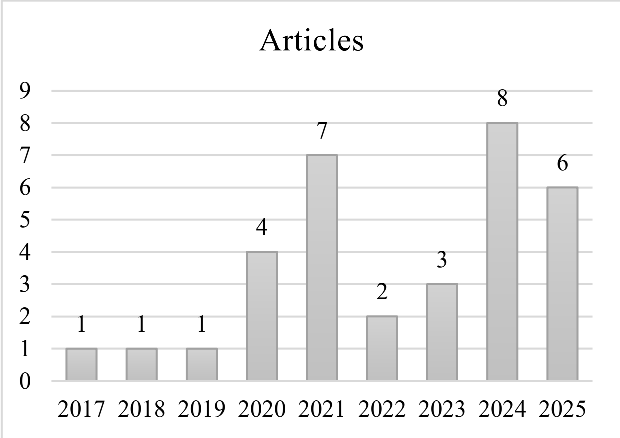

Figure 3. Annual Production

Top Authors

Figure 4 shows that all of the most active authors have contributed two publications each. This consistent pattern indicates that the field is not centered on a small group of highly productive authors, but rather reflects a broad and collaborative research community. The presence of multiple authors with comparable levels of contribution also suggests that research on immersive technologies in quantum-related contexts is developing simultaneously across multiple geographic regions and disciplines, with contributions coming from education researchers, physicists, chemists, engineers, and computer scientists.

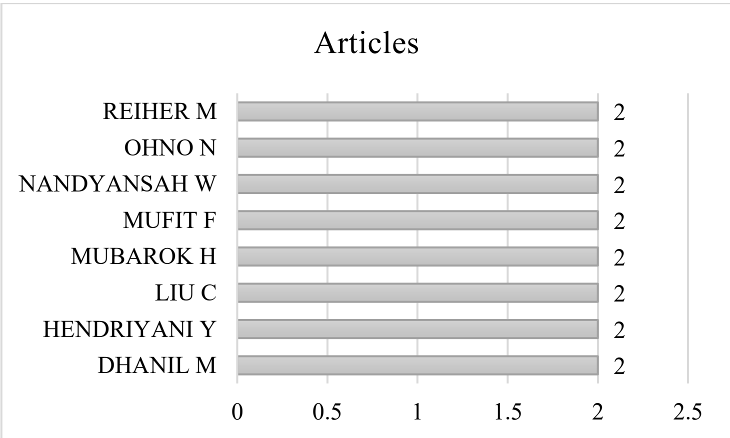

Figure 4. Most productive authors

Most Productive Affiliations

Figure 5 shows that the most productive affiliates are Ludwig-Maximilians-Universität München (LMU), Stanford University, and Padang State University, each of which contributed six publications to the dataset. Several other institutions, including the Laboratory of Physical Chemistry, Nurul Huda University, and the University of Bristol, each contributed four publications. Additional contributions also came from Beijing Normal University, Ohio University, and the Hong Kong University of Science and Technology, each of which produced three publications. Overall, this distribution suggests that immersive technology research in quantum science is not concentrated in one particular region or academic tradition, but rather is characterized by broad and growing involvement from institutions with diverse disciplinary strengths.

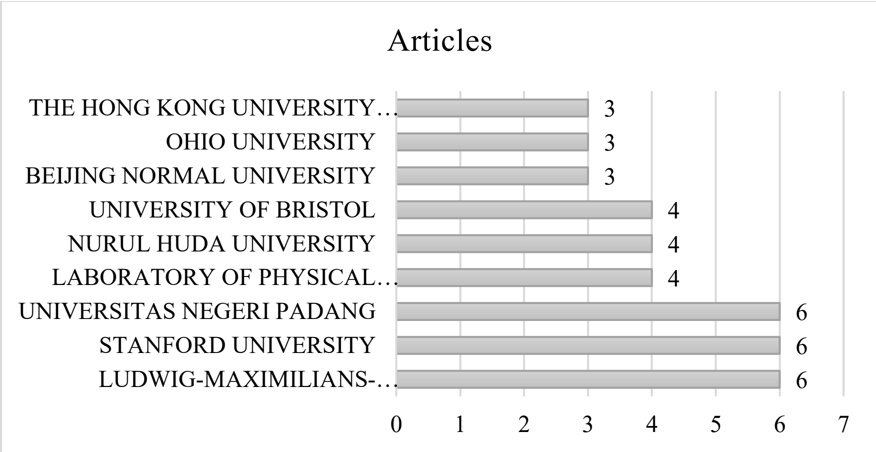

Figure 5. Top Affiliations

Top Country Production

The country-level analysis in Figure 6 shows that research on immersive technologies in quantum science education has a wide geographic distribution, with contributions from various regions. The reported frequencies and percentages are based on country occurrences derived from author affiliations, so a single publication may have contributions from more than one country. Therefore, the total number of occurrences exceeds the number of documents analyzed (N = 32). The United States emerged as the most dominant contributor with 28 occurrences (27%), reflecting the country's strength in both immersive technology development and science education research. Indonesia followed with 24 occurrences (23%), indicating a rapid growth in interest in the application of AR/VR/XR technologies for quantum-related learning in the Southeast Asian region. China contributed 12 occurrences (12%), in line with its broader expansion in educational innovation and digital learning technologies. Additional contributions also came from countries with strong research traditions. The United Kingdom (10%), Japan (7%), and Germany (6%) each made significant contributions, demonstrating the active involvement of institutions with strengths in science and engineering. Meanwhile, Australia, Poland, and Switzerland each contributed four occurrences (4%), and Mexico three occurrences (3%), further underscoring the global spread of interest in immersive learning in quantum science education. This broad geographic distribution thus demonstrates that immersive technology is increasingly recognized as a valuable tool in addressing the representational challenges inherent in quantum science learning.

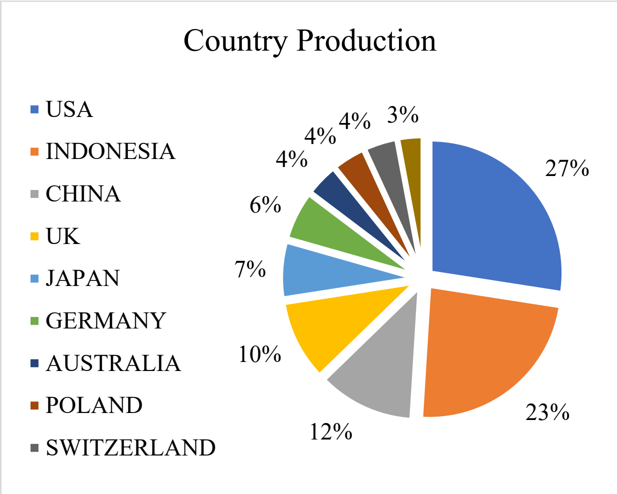

Figure 6. Country Production Over Time

Top Cited Paper

The most influential publication in this dataset is the study by Cai et al. (2021), which has received 152 citations with a TC/year of 30.40, thus placing it as a central reference in the field. This high citation performance reflects the broad impact of augmented reality-based interventions on self-efficacy and learning conceptions in physics education. The second most cited article, Amabilino et al. (2019), with 73 citations, demonstrates the significance of virtual reality in promoting interactive quantum chemistry learning through neural network-based simulations. Studies such as Migdał et al. (2022) and Seritan et al. (2021) also show considerable influence, each receiving 29 citations, underscoring the growing importance of interactive virtual reality environments for visualizing quantum mechanics and molecular dynamics. Furthermore, Suprapto et al. (2020) stands out with 29 citations, highlighting the use of augmented reality in supporting conceptual mastery. Other studies, including Zable et al. (2020) and Tarng and Pei (2023) also contributed through an immersive virtual reality approach to learning quantum computing and quantum mechanics. A list of the most highly cited articles is presented in Table 1.

Overall, these documents demonstrate that highly cited studies come from a wide range of disciplinary backgrounds, further underscoring the interdisciplinary nature of immersive technology research. Citation patterns also indicate that the field is driven by a combination of early pioneering work and rapidly expanding recent contributions, reflecting a dynamic and evolving research landscape.

Table 1. Top 10 the Most Cited Paper

Authors	Title	Journal	Total Citation	TC Per Year	Norma-lized TC
Cai et al. (2021)	Effects of learning physics using Augmented Reality on students' self-efficacy and conceptions of learning	British Journal of Educational Technology	152	30.40	5.27

Amabilino et al. (2019)	Training Neural Nets to Learn Reactive Potential Energy Surfaces Using Interactive Quantum Chemistry in Virtual Reality	The Journal of Physical Chemistry	73	10.43	1.00
Migdał et al. (2022)	Visualizing quantum mechanics in an interactive simulation – Virtual Lab by Quantum Flytrap	Optical Engineering	29	7.25	1.81
Seritan et al. (2021)	InteraChem: Virtual Reality Visualizer for Reactive Interactive Molecular Dynamics	Journal of Chemical Education	29	5.80	1.00
Suprapto et al. (2020)	An evaluation of the "PicsAR" research project: An augmented reality in physics learning	International Journal of Emerging Technologies in Learning	29	4.83	1.97
Zable et al. (2020)	Investigating Immersive Virtual Reality as an Educational Tool for Quantum Computing	Proceedings of the ACM Symposium on Virtual Reality Software and Technology	23	3.83	1.56
Mufit et al. (2024)	Design immersive virtual reality (IVR) with cognitive conflict to support practical learning of quantum physics	Journal of Turkish Science Education	13	6.50	4.95
Weymuth and Reiher (2021)	Immersive interactive quantum mechanics for teaching and learning chemistry	Chimia	13	2.60	0.45
Tarng and Pei (2023)	Application of Virtual Reality in Learning Quantum Mechanics	Applied Sciences	11	3.67	2.54
Park et al. (2024)	Quantum Reinforcement Learning for Spatio-Temporal Prioritization in Metaverse	IEEE Access	8	4.00	3.05

Dominant Themes and Conceptual Structures

The analysis for RQ2 explores the thematic and conceptual structure underlying research on immersive technologies in quantum education. Keyword co-occurrence mapping was used to identify key conceptual clusters and relationships between frequently occurring terms, while a three-field plot illustrates the interrelationships between authors, sources, and keywords that shape the intellectual structure of the field. The thematic map provides insight into the maturity and centrality of key research themes, while thematic evolution analysis explores how these themes change from one publication period to another. Keyword trend analysis highlights emerging and declining areas of focus. All components of this analysis were then integrated through a thematic synthesis that illustrates the dominant directions, conceptual linkages, and evolving research priorities in the literature.

Keyword Co-Occurrence Structure

Figure 7 shows that the prominent blue cluster centers on “virtual reality” and is strongly associated with terms such as e-learning, learning systems, visualization, quantum entanglement, and quantum computing, indicating VR’s central role in building simulation-based learning environments for advanced quantum topics. The red cluster centered on “students” is closely connected to teaching, curriculum, quantum optics, and quantum electronics, reflecting a pedagogical approach focused on learning outcomes and instructional design. The relatively dense purple cluster groups chemistry-based keywords such as “atoms,” “atomic waves,” “hydrogen atoms,” and “education tool,” highlighting the application of immersive media for atomic and molecular visualization. Meanwhile, the green cluster centered on “augmented reality” relates to 3D modeling, atomic modeling, abstract thinking, and high-school students, indicating that AR is frequently used for representational tasks and interventions in the classroom.

Based on this network structure, the word frequency distribution in Figure 8 further emphasizes the centrality of immersive technologies in the research corpus. The most frequently occurring terms, such as “virtual reality,” “augmented reality,” and “students,” reflect the dominant clusters identified in the co-occurrence map and emphasize their fundamental role in shaping research related to immersive approaches in quantum education. Furthermore, the frequent occurrence of pedagogical terms such as “teaching,” “e-learning,” and “learning systems,” along with domain-specific terms such as “atoms,” “quantum chemistry,” and “atomic orbital,” demonstrates that the literature consistently integrates aspects of learning with disciplinary visualization needs. This lexical dominance provides an initial glimpse into the field’s conceptual footprint, complementing the structural patterns identified in the co-occurrence network and helping to identify established and emerging themes.

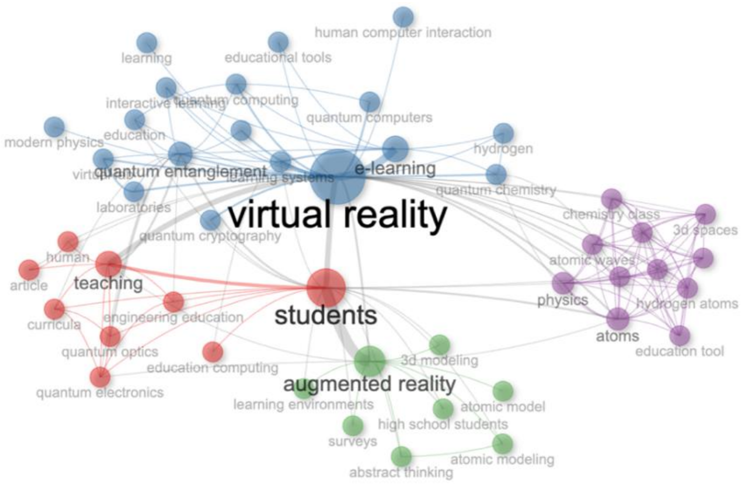

Figure 7. Keyword Network Visualization

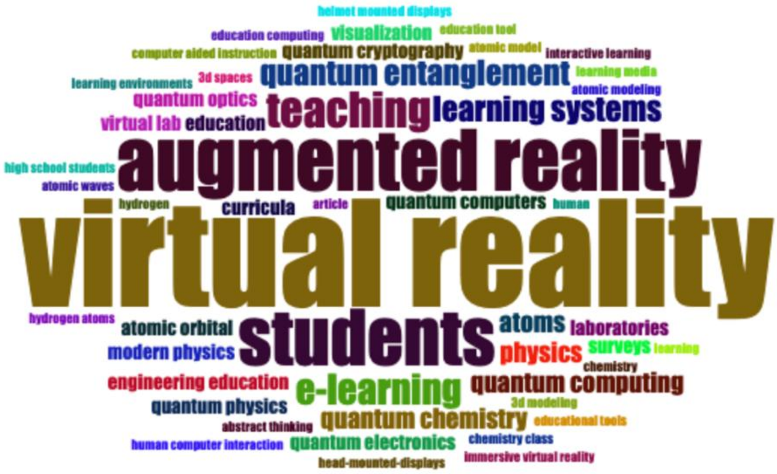

Figure 8. Word-Frequency Distribution

Thematic Development, Map and Evolution

Figure 9 shows that Indonesia, China, Japan, and the United States emerge as the most active contributing countries, supplying the largest number of authors located at the center of the diagram. These authors act as intermediary nodes connecting national research output with thematic priorities in the field. Their work is closely related to keywords such as virtual reality, augmented reality, students, physics, atoms, and e-learning, demonstrating a blend of pedagogical, disciplinary, and technological aspects.

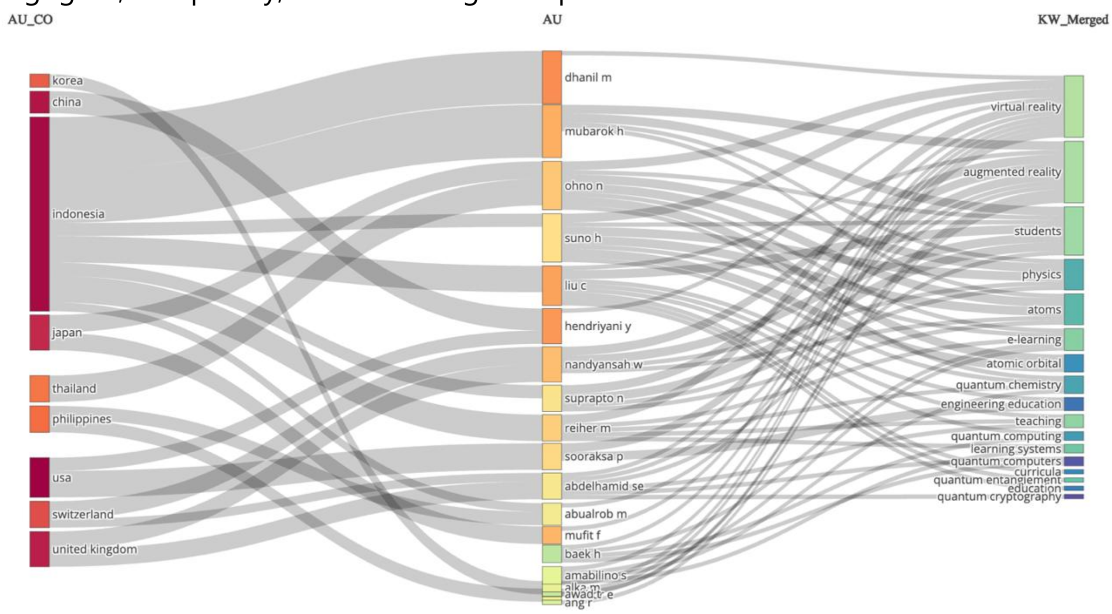

Figure 9. Thematic Development Using Sankey Diagram

The three-area visualization also reveals that countries tend to converge on similar thematic priorities. Several countries, particularly Indonesia, China, Japan, and the United States, show strong and overlapping associations with key keywords such as virtual reality, augmented reality, students, physics, and atoms. This pattern suggests a shared international focus on leveraging immersive technologies to support conceptual understanding of quantum-related topics. The association of many countries with similar core concepts indicates that the challenges and learning objectives of teaching abstract science content are globally recognized, fostering parallel research efforts across regions. This visualization provides important insights for researchers and policymakers by highlighting the specific educational priorities emphasized across countries.

The thematic map in Figure 10 shows four distinct thematic zones that characterize the conceptual structure of immersive technology research in quantum science education. The upper right quadrant (motor themes) contains clusters with high centrality and density such as virtual reality, augmented reality, students, atoms, and atomic orbitals, indicating that immersive visualization of atomic and subatomic structures is the most influential and well-developed line of research. The upper left quadrant (niche themes) displays more specific but relatively isolated topics, such as abstract thinking, atomic models, and atomic modeling, indicating focused studies that are not yet strongly connected to the broader research network. Themes in the lower right quadrant (basic themes), such as quantum chemistry and hydrogen, represent fundamental topics that support the field but are still less developed internally. Meanwhile, the lower left quadrant (emerging or declining themes) includes less integrated concepts such as human–computer interaction, which may indicate research directions that are still in their infancy or are experiencing a decline in attention. Thus, this map shows that immersive technologies have become an established key driver in research, while more disciplinary-specific quantum topics remain peripheral or in a developmental stage in terms of thematic maturity.

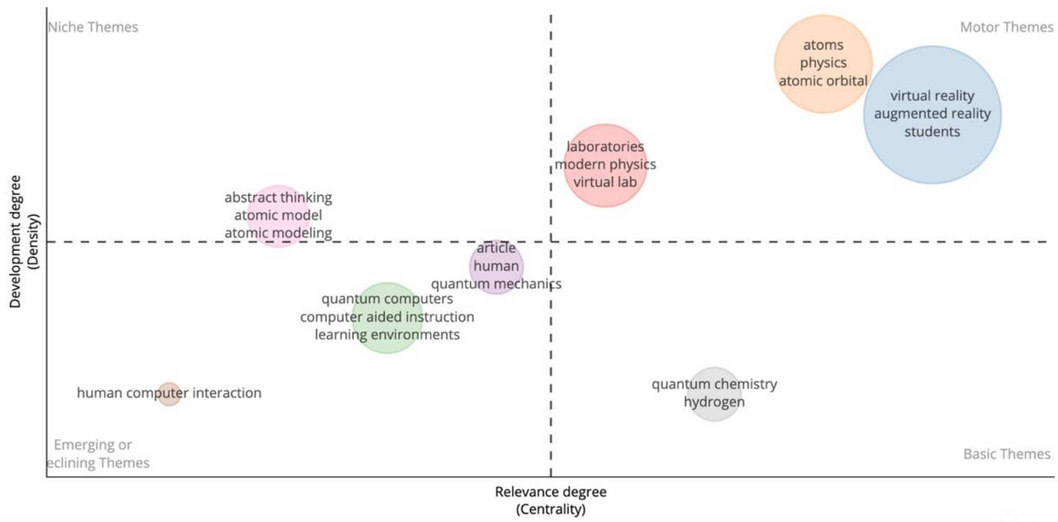

Figure 10. Thematic Map

Figures 7 and 10 show that both the co-occurrence network and thematic map place virtual reality, augmented reality, and students at the conceptual core of the field. In Figure 7, these terms emerge as the largest and most interconnected nodes, with broad associations with e-learning, teaching, and various quantum-related topics. This strong centrality is reaffirmed in Figure 10, where all three are located in the motor themes quadrant, representing mature, influential, and high-impact themes. Similarly, the dense cluster centered on atoms, physics, and atomic orbitals in the co-occurrence network correlates with well-developed but more specific themes in the thematic map. Meanwhile, less connected topics such as quantum chemistry, hydrogen, and human–computer interaction appear peripheral in both visualizations, indicating that these areas are still in their infancy or not yet fully mature in the literature. Overall, both visualizations display a consistent pattern: immersive technologies dominate the conceptual research landscape, while more specific quantum subdomains continue to develop at the periphery of the field.

Figure 11 presents the temporal distribution of key keywords, illustrating how specific concepts experienced increases or decreases throughout the study period. Virtual reality showed the strongest and most sustained growth, particularly after 2022, indicating the increasingly dominant role of this technology in immersive approaches to quantum learning. Augmented reality maintained a relatively stable presence but peaked earlier, reflecting its role in basic representational tasks before virtual reality became more central. Terms such as e-learning and teaching showed moderate but consistent usage, indicating stable pedagogical relevance. Meanwhile, quantum entanglement emerged later and developed gradually, signaling a shift towards more complex quantum topics. On the other hand, the term "students" remained a consistent anchor throughout, confirming the learner-centered orientation of learning in this field. Overall, these patterns should be understood as exploratory indications of emerging trends, given the relatively limited number of publications analyzed.

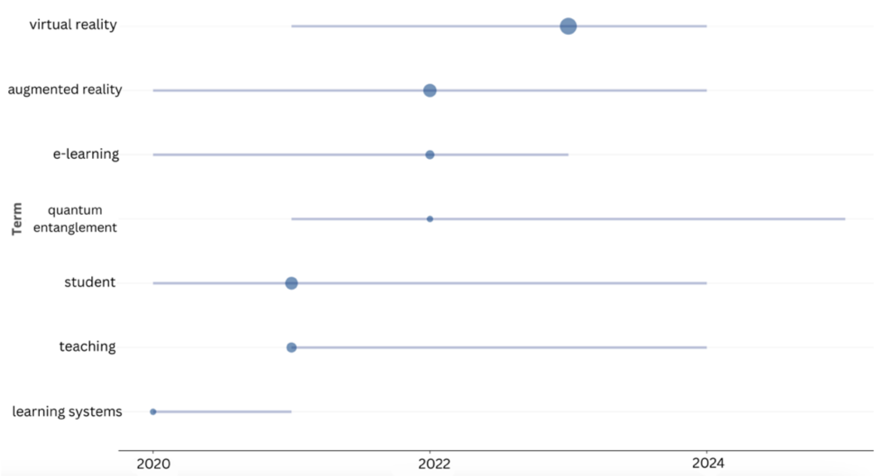

Figure 11. Term Evolution

Discussion

The findings from this bibliometric review provide an integrated picture of how immersive technologies have been adopted and conceptualized in quantum education over the past decade. However, it is important to note that this analysis is based on a relatively small dataset (N = 32), reflecting the burgeoning nature of this research field and limiting the generalizability of the findings. Therefore, the insights generated are best understood as indicative of trends that can guide future research directions and ensure that the field continues to evolve in line with changing educational and technological demands (Ball, 2020; Vaishya et al., 2025). Results from the first research question (RQ1) indicate a clear upward trend in the number of publications, particularly after 2020, reflecting a broader expansion of the use of immersive learning technologies across STEM domains. The United States, Indonesia, and China emerged as key contributors, demonstrating strong research capacity and increasing institutional investment in immersive learning innovations. Authorship patterns and affiliations suggest a dispersed yet collaborative research landscape, with diverse teams across institutions contributing to the field's development. Highly cited articles mostly focus on the design, implementation, and evaluation of VR or AR-based learning modules (Amabilino et al., 2019; Cai et al., 2021; Migdał et al., 2022), which confirms that pedagogical effectiveness and visualization challenges remain the main motivations in the adoption of immersive technologies.

The second research question (RQ2) complements these descriptive patterns by revealing the conceptual architecture of the field. Keyword co-occurrence analysis highlights virtual reality, augmented reality, students, atoms, and e-learning as dominant nodes, indicating a dual emphasis: on the technological layer of immersive systems and on the representational challenges of quantum and atomic-scale phenomena. Thematic mapping places VR and AR in the motor themes quadrant, indicating their central role and high level of maturity as key research anchors (Hariyanto et al., 2024; Kaya et al., 2023). Meanwhile, niche themes (e.g., atomic modeling and abstract thinking) reflect more specific applications, while emerging themes (e.g., quantum chemistry and hydrogen) indicate expanding disciplinary integration beyond physics. However, given the relatively limited dataset, these thematic patterns should be understood as exploratory indications, rather than as fully established statistical trends. Overall, this pattern is consistent with previous research emphasizing that immersive technologies, particularly VR and AR, are increasingly being used to support conceptual visualization and experiential learning in advanced science education (Crogman et al., 2025; Patel et al., 2025; Ugli et al., 2025).

Overall, these findings suggest a shift in the use of immersive technologies from basic visualization tools to more structured and interactive learning applications in the abstract quantum domain. This interpretation can be conceptually linked to broader educational technology frameworks, such as experiential learning, embodied cognition, and multi-representational scaffolding (Mayer & Schwemmle, 2023; Walkington et al., 2024; Zhou et al., 2021). However, it should be noted that these studies did not systematically analyze the extent to which these theoretical frameworks were explicitly integrated into the reviewed research designs. The field also continues to exhibit gaps across disciplines. Studies in chemistry, engineering, and computational quantum science remain relatively limited and selective (Amabilino et al., 2019; Seritan et al., 2021; Zable et al., 2020), while some advanced quantum concepts, such as superposition, tunneling, and measurement, remain underexplored in the context of immersive technologies. Furthermore, because this study lacks a systematic methodological analysis, conclusions regarding research design trends (e.g., the preference for perceptual or short-term measures) should be interpreted with caution. Furthermore, while immersive technologies have significant potential for enhancing visualization and learning engagement, there are also pedagogical challenges to consider. These include the risk of cognitive overload in complex three-dimensional environments, the potential for visual distraction or novelty effects, and the potential oversimplification of quantum concepts through semi-classical representations.

While providing insights, several methodological limitations should be acknowledged. This study used bibliometric tools such as Bibliometrix and Biblioshiny, which rely heavily on metadata, including keywords, author affiliations, and citation information, the consistency of which can vary across publications. Furthermore, co-occurrence analysis reflects patterns of association between terms but does not always capture the conceptual depth of the topics studied. Similarly, the thematic mapping in this study is descriptive and exploratory, rather than explanatory or causal. Therefore, while this approach is effective for mapping research trends and structural relationships in the literature, it is not designed to directly evaluate pedagogical effectiveness or learning outcomes.

These patterns highlight several important implications. First, future research should direct the development of immersive technologies toward a deeper conceptual understanding of quantum, rather than simply representational tasks, by leveraging the advantages of spatial interactions and embodied-based simulations (Chehimi & Saad, 2023; Damaševičius, 2025). Second, interdisciplinary collaborations between physicists, chemists, computer scientists, and learning scientists have the potential to accelerate the development of content-rich XR environments with a strong theoretical foundation (Song et al., 2024; Trigos & Tamayo, 2023). Third, future research is recommended to adopt more diverse and rigorous methodological approaches, including controlled experiments, design-based research, and cognitive diagnostic assessments, to strengthen the evidence base regarding the effectiveness of immersive learning (Cai et al., 2021; Mufit et al., 2024). Finally, the field would benefit greatly from the development of a scalable framework for integrating immersive technologies into the formal curriculum, while addressing issues of accessibility, teacher readiness, and sustainability of classroom use.

CONCLUSION

This bibliometric analysis shows that research on immersive technologies in quantum education is experiencing steady growth, with virtual reality and augmented reality emerging as key tools for visualizing abstract quantum concepts and supporting learning. The identified thematic patterns indicate a possible shift from early exploratory applications to more structured, content-oriented uses, although this trend should be interpreted with caution given the limitations of the datasets used. These developments suggest that immersive technologies are increasingly positioned as integral parts of quantum learning environments, rather than simply novelty tools. However, because this analysis is based on a relatively small sample size, the generalizability of the findings is limited, and therefore, the results are best viewed as indicative of a developing field rather than as definitive conclusions. Furthermore, research remains unevenly distributed across quantum subtopics, with some advanced concepts receiving limited attention in the literature.

While indicating a positive growth trend, these findings should be interpreted with caution due to the relatively limited dataset and the exclusion of non-empirical document types, such as review articles and book chapters, which could potentially provide important theoretical syntheses. Consequently, this analysis primarily reflects empirical research patterns and may not fully capture broader conceptual developments in the field. Rather than drawing definitive conclusions about research design practices, this study serves to identify future research directions. Future research is recommended to adopt more rigorous and diverse methodological approaches, including controlled experimental designs, longitudinal studies, and cognitive diagnostic assessments, to strengthen the evidence base regarding the effectiveness of immersive learning in quantum science. Future research should also prioritize deeper conceptual integration and expanded interdisciplinary collaborations between science educators, physicists, and technology developers.

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