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

p-ISSN:XXXXX; e-ISSN: XXXXX
SiBET, Vol. 1, No. 3, August 2026
Page 1-16
©2026 SiBET

Shaping the Future of Physics Education through Intelligent Virtual Environments: A Global Bibliometric Analysis of Research Trends and Emerging Learning Technologies

***Hanan Zaki Alhusni[1], Binar Kurnia Prahani[1], Budi Jatmiko[1], Titin Sunarti[1], Noval Maleakhi Hulu[2]**
[1]Department of Physics, Faculty of Mathematics and Natural Science, Universitas Negeri Surabaya, Indonesia
[2]Department of Mechanical Engineering, Monash University, Malaysia

Article Info

Article history:

Received: 25 June 2026
Revised: 14 July 2026
Accepted: 27 July 2026
Available Online: 31 July 2026

Keywords:

Bibliometric Analysis
Inquiry-Based Learning
Physics Education
Reflective Practice
Science Education

ABSTRACT

This study maps global research trends, intellectual structures, and emerging technologies in physics education through intelligent virtual environments, including virtual reality, artificial intelligence, and immersive simulations. A descriptive quantitative approach using bibliometric analysis was employed. Data were collected from the Scopus database (2015–2024) with a final dataset of 3,318 documents. We used VOSviewer and Biblioshiny to examine publication trends, citation patterns, collaboration networks, and keyword co-occurrence. The findings reveal a significant annual growth rate of 13.49% in publications, indicating increasing global interest in intelligent virtual environments. Research is dominated by keywords such as virtual reality, machine learning, and artificial intelligence. Three major research clusters were identified: virtual learning environments, artificial intelligence in education, and simulation-based physics learning. The United States and China are the leading contributors, while international collaboration remains relatively moderate at 19.11%. These trends show the growing integration of immersive and AI-based technologies to enhance physics learning. This study provides a comprehensive bibliometric mapping of intelligent virtual environments in physics education, integrating technological trends with a sustainability perspective. It offers strategic insights into future research directions and supports the development of innovative, technology-based physics education aligned with Sustainable Development Goal 4.

Check for updates OPEN ACCESS CC BY NC ND

INTRODUCTION

The rapid development of digital technology over the past decade has brought great hope for the transformation of physics education toward more interactive, adaptive, and experience-based learning (Dhanaraj et al., 2025; Hare & Tang, 2022; KAHE, 2025; Nordin et al., 2026; Şengül & Karabacak, 2026). The integration of intelligent virtual environments such as virtual reality (VR), augmented reality (AR), artificial intelligence (AI), and immersive simulation is believed to overcome the limitations of conventional physics learning, which has been dominated by theoretical and abstract approaches (Cossich et al., 2023; Hosny et al., 2026; Mallek et al., 2024; Wang et al., 2026). In the context of physics learning, this technology is expected to visualize phenomena that cannot be directly observed, such as particle interactions, electromagnetic fields, and the dynamics of complex systems, allowing students to build deeper conceptual understanding through contextual and meaningful learning experiences (Acevedo et al., 2024; Georgiou et al., 2021; Lindgren et al., 2016; Tarng & Pei, 2023; Vidak et al., 2026; Villada Castillo et al., 2025). This hope is further strengthened by the growing need for learning innovations that can address the challenges of 21st-century education.

Ideally, the use of intelligent virtual environments in physics education is expected to encourage the development of critical thinking, complex problem-solving, digital literacy, and computational thinking, which are core competencies in modern STEM education (Mafarja et al., 2025; Setyawarno et al., 2026; Taloba et al., 2023; Yusvana & Papadakis, 2026). Furthermore, the integration of digital technology in education aligns with the global Sustainable Development Goals (SDGs) agenda, particularly SDG 4, which emphasizes the importance of providing inclusive, high-quality education that leverages technological innovation (Abuhassna et al., 2025; Kangwa et al., 2026; Kaur & Kaur, 2024; Makinde et al., 2024; Tripon,

2025). Smart digital learning environments are expected to expand access to learning, improve the quality of learning experiences, and support a sustainable education ecosystem through the effective and efficient use of technology (Bautista & López-Costa, 2025; Mhlongo et al., 2023; Selden et al., 2013; Zeeshan et al., 2022). Therefore, the existence of smart virtual technology is seen not only as a pedagogical innovation but also as part of a sustainable educational transformation (Cebrián et al., 2020; Cheung et al., 2021; Kinshuk et al., 2016; Zhu et al., 2016).

However, implementing smart virtual technology in physics learning still presents significant challenges. Many educational institutions still face limitations in technological infrastructure, human resource readiness, and educators' digital competency, which hinder the effective integration of technology into learning (Le et al., 2025; Okoye et al., 2023; Purwadi et al., 2024; Singun, 2025; Siregar & Siregar, 2024). Furthermore, most physics learning practices still focus on lectures and routine problem-solving, which offer students few opportunities for exploration (Dai et al., 2019; Good et al., 2019; Musengimana et al., 2025; Weaver et al., 2018). Research shows that while VR and AI technologies have significant potential to enhance learning engagement, their implementation remains uneven and often experimental on a small scale (Bekteshi, 2025; Chimbo et al., 2026; Koukaras et al., 2025; Niyazova et al., 2026). This situation indicates that digital transformation in physics education is still in a transitional stage and has not been fully integrated systematically.

The gap between the high hopes for intelligent virtual environments and the reality of their implementation indicates a research gap that warrants further study. Although the number of studies on virtual technologies in education continues to increase, most research still focuses on testing the effectiveness of specific technologies without providing a comprehensive overview of global research developments. Furthermore, few studies systematically map the knowledge structure, research collaboration trends, and development directions of physics learning technologies based on intelligent virtual environments. Such mapping is crucial for understanding the direction of the research field and identifying future research opportunities.

Several previous studies have shown positive results related to the use of virtual technologies in physics learning. Studies show that the use of virtual laboratories and immersive simulations can increase motivation to learn, aid the visualization of abstract concepts, and provide safe, flexible experimental experiences for students (Aruanno et al., 2025; Hu-Au, 2024; Kolil & Achuthan, 2024; Lu et al., 2024; Pang et al., 2024). Furthermore, immersive VR technology has been shown to increase learning engagement and concept retention through exploration-based learning experiences. These findings strengthen the argument that intelligent virtual technology has significant potential to improve the quality of physics learning if implemented appropriately.

On the other hand, several studies also revealed limitations of previous studies that could provide opportunities for further research development. Many studies still use a traditional systematic review approach without utilizing a bibliometric approach that can provide a macro analysis of developments in the research field. Furthermore, previous studies have been limited in their ability to identify global collaboration maps, citation structures, and the evolution of emerging research themes in the field of intelligent virtual environments in physics education. These limitations highlight the need for a bibliometric analysis approach that provides a comprehensive overview of the research landscape, both quantitatively and visually.

Based on these conditions, this study aims to address this research gap by mapping global research trends on intelligent virtual environments in physics education using a bibliometric approach. This study not only analyzes publication trends but also identifies the most influential authors, research collaboration networks, developments in research themes, and emerging learning technologies. With this approach, the research is expected to make a strategic contribution to understanding the global direction of development in virtual technology-based physics education research and provide a basis for decision-making for researchers and education practitioners.

The novelty of this research lies in its comprehensive approach to mapping the intellectual structure of intelligent virtual environments research, specifically in the context of physics education, where such mapping remains relatively limited compared to STEM fields in general. Furthermore, this study integrates analysis of future learning technology trends with a sustainability education perspective, a topic that has not been widely explored in previous research. Thus, this research not only contributes to scientific mapping but also provides strategic direction for the development of innovations in digital technology-based physics learning.

Furthermore, this research is also relevant to the global development agenda, particularly in supporting the achievement of Sustainable Development Goal 4 on quality education. By mapping the evolution of digital learning technology, this research is expected to contribute to a more innovative, adaptive, and sustainable physics learning ecosystem. Therefore, the results of this study are expected to serve as an important reference for the development of digital education policies and future innovations in smart-technology-based physics learning.

RESEARCH METHOD

General Description of Research Methodology

This study uses a descriptive quantitative approach and bibliometric methods to map the development of global research on intelligent virtual environments in physics education. This approach was chosen because it provides a comprehensive overview of knowledge structures, research trends, scientific collaboration networks, and the development of research themes systematically based on scientific publication data. Methodologically, bibliometric analysis allows the identification of publication patterns, citations, author collaborations, and relationships between keywords to objectively understand research evolution and the direction of scientific field development. Furthermore, this method offers advantages in transparency and replicability because of standardized data collection and analysis procedures. This research followed stages of database identification, search strategy development, data selection, bibliometric analysis, and visualization and interpretation of research results, in accordance with modern bibliometric research guidelines that emphasize dataset validity and the reliability of analysis procedures.

Participants and Data Source

In this bibliometric study, participants were not individuals but rather scientific documents relevant to the research topic. Therefore, the research sample consisted of scientific articles indexed in the Scopus database. Scopus was chosen for its extensive international publication coverage, high indexing quality, and comprehensive metadata, such as citation data, author affiliations, keywords, and references, which strongly support bibliometric analysis. Data collection used advanced search techniques, combining keywords related to intelligent virtual environments and physics education and applying Boolean operators (AND, OR) to obtain a comprehensive literature base. The publication year range was limited to 2015–2024 to ensure relevance to the latest developments in digital learning technology. Inclusion criteria included English-language articles and conference papers on virtual technology, immersive learning, or AI in physics education, with complete metadata. Exclusion criteria included irrelevant documents, missing abstracts, and duplicate documents. After screening, the final dataset met the eligibility criteria for further analysis, supporting the validity and scientific quality of the research results. Based on a predetermined query in the Scopus database, 3,318 documents were retrieved: 1,698 articles and 1,620 conference papers. Next, a filtering process was conducted based on subject areas relevant to the research: Computer Science, Physics and Astronomy, Social Sciences, and Engineering, to ensure the dataset's relevance to the field of virtual technology-based physics education. This process improved the dataset's quality so bibliometric analysis could provide a more accurate picture of research developments in this field.

Research Instruments and Procedures

The main instruments in this research were the Scopus database as a data source and bibliometric analysis software, namely VOSviewer and Biblioshiny (Bibliometrix R-package). VOSviewer was used to visualize bibliometric networks, including co-authorship, co-citation, and keyword co-occurrence, while Biblioshiny was used for descriptive statistical analysis, thematic mapping, and tracking the evolution of research themes. The research procedure was carried out in several stages, including keyword identification and search query development; publication metadata extraction (author, year, journal, citations, keywords, and affiliation); data cleaning; bibliometric analysis using predetermined software; and interpretation of the visualization results to identify research trends and directions for development. To ensure research reliability, all procedures followed standardized bibliometric methodology guidelines, providing a strong scientific foundation and facilitating replication by other researchers.

Data Analysis Techniques

This study used several key bibliometric techniques common in knowledge mapping, including publication trend analysis to identify publication growth over time, citation analysis to identify the most influential articles, authors, and journals, and co-authorship analysis to examine collaboration patterns

between researchers and countries. In this study, keyword co-occurrence analysis was used to identify key themes and relationships among research topics, and thematic mapping analysis was used to examine theme development, emerging themes, and future research opportunities. To strengthen the interpretation of the results, this study also used network visualization to comprehensively depict the relationship structure among bibliometric elements. The entire analysis process followed standard procedures for modern bibliometric research to ensure the reliability and validity of the results.

Research Validity and Reliability

To ensure research quality, data validity was maintained by using the Scopus database, which has high curation standards for scientific publications. Furthermore, analysis reliability was maintained through the use of bibliometric analysis software validated in numerous international studies. Transparency of research procedures was also crucial to maintaining the study's credibility and enabling future replication by other researchers.



Figure 1. PRISMA Flowchart of the Process of Identifying, Screening, Eligibility, and Selection of Research Documents

RESULTS AND DISCUSSION

Result

Descriptive analysis using Biblioshiny shows that the research dataset spans 1982–2026 and includes 3,318 documents from 1,687 publication sources. This research involved 10,919 authors, with only 253 documents written by a single author, and an average collaboration of 4.46 authors per document. The international collaboration rate was 19.11%, indicating global cooperation in this research field.



Figure 2. General Bibliometric Characteristics of the Research Dataset

Furthermore, annual publication growth reached 13.49%, indicating a significant increase in research related to intelligent virtual environments. The number of author keywords recorded was 7,747, and a total of 256,754 references were used across all documents. The average document age was 5.21 years, with 12.43 citations per document, indicating that this research field is relatively new and actively developing.

Figure 3 shows the average annual citations of publications related to intelligent virtual environments in physics education. In general, the citation trend fluctuated upward from 1982 to 2026, with a significant increase beginning after 2000. The highest citation peak occurred in 2016, with an average of approximately 8.5 citations per document, indicating the high scientific impact of publications during that period.

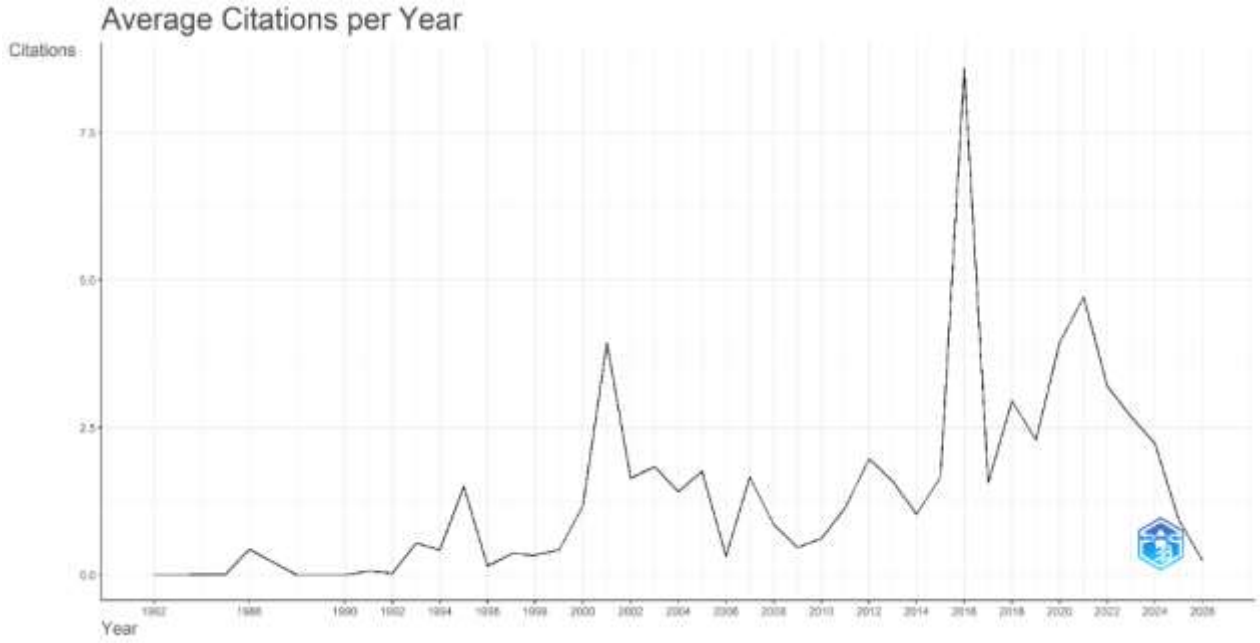


Figure 3. Average Citations Per Year of Publications Related to Intelligent Virtual Environments in Physics Education

Furthermore, an increase was again observed during the 2019–2021 period, with an average citation rate ranging from 3 to 4.7, indicating growing academic attention to virtual and immersive learning technologies. However, the decline in citations in more recent years, such as 2024–2026, is a common phenomenon in bibliometric analysis, as recent publications have not had sufficient time to accumulate citations. Overall, this trend indicates that research in intelligent virtual environments has grown in scientific impact and become increasingly relevant in recent years.

Figure 4 shows the most relevant publication sources based on the number of documents on research on intelligent virtual environments in physics education. The analysis shows that Lecture Notes in Computer Science is the most dominant publication source, with 71 documents, followed by Proceedings of SPIE – The International Society for Optical Engineering, with 64 documents, and Journal of Physics: Conference Series, with 51 documents. These findings indicate that the majority of publications originate from conference proceedings and publication series in the fields of technology and physics.

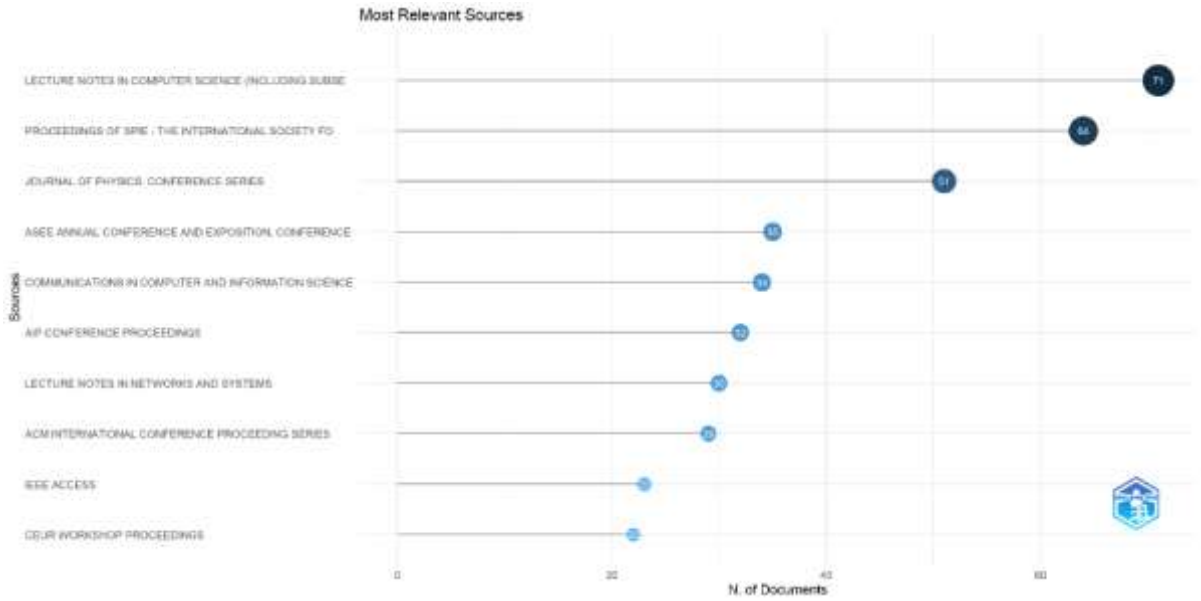


Figure 4. Most Relevant Publication Sources Based on the Number of Documents

Other significant sources include the ASEE Annual Conference and Exposition (35 documents), Communications in Computer and Information Science (34 documents), and AIP Conference Proceedings (32 documents). This indicates that research in this field is widely published at international conferences focused on educational technology and applied science. Overall, the distribution of these publication sources indicates that research on intelligent virtual environments is developing across computer science, engineering, and physics education.

Figure 5 shows the most productive authors in research on intelligent virtual environments in physics education, ranked by publication count. The analysis shows that Li Y is the most productive author, with 47 documents, followed by Wang Y (38) and Zhang Y (36). Furthermore, several other authors, such as Wang Z (31 documents), Liu Y (30 documents), and Zhang X (30 documents), also made significant contributions to this research field.

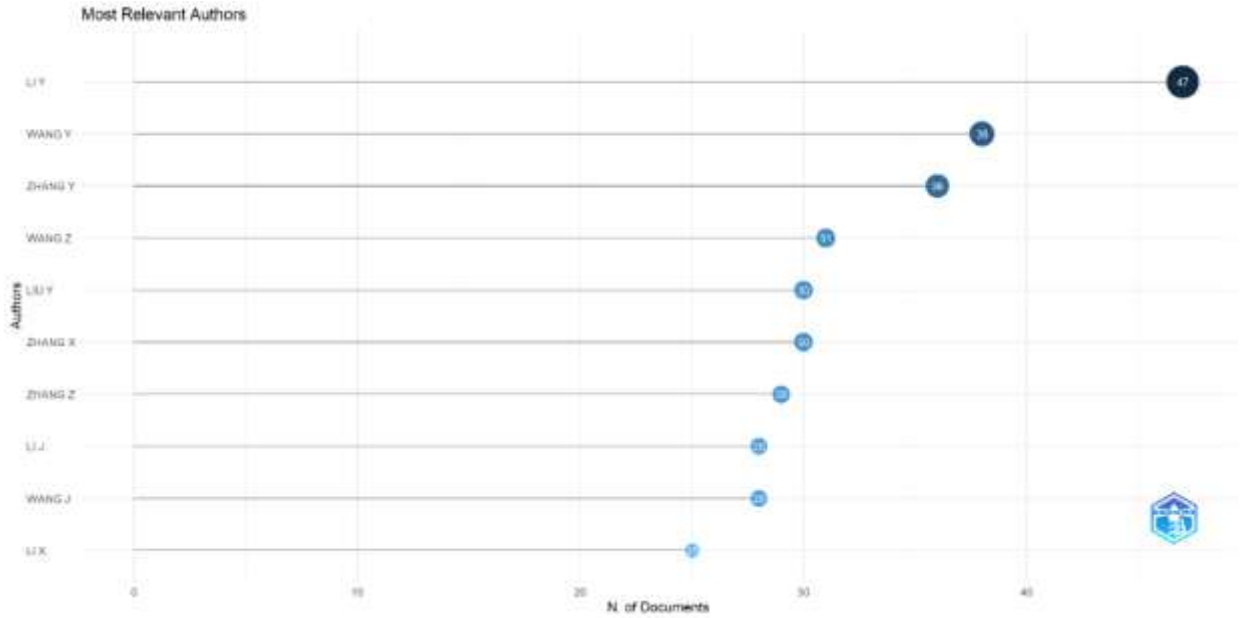


Figure 5. Most Relevant Authors Based on the Number of Publications

Furthermore, authors such as Zhang Z (29 papers), Li J (28 papers), Wang J (28 papers), and Li X (25 papers) are also among the most active researchers. This finding indicates that research development in this field is dominated by highly productive researchers who consistently contribute to the development of virtual environment-based learning technologies.

Figure 6 shows the institutions that contribute the most to research on intelligent virtual environments in physics education, based on publication counts. The analysis shows that the University of California is the most productive institution, with 87 publications, followed by the Massachusetts Institute of Technology (MIT) with 75 and Zhejiang University with 72. Furthermore, Tsinghua University (69 publications) and Peking University (66 publications) are also among the institutions with significant contributions.

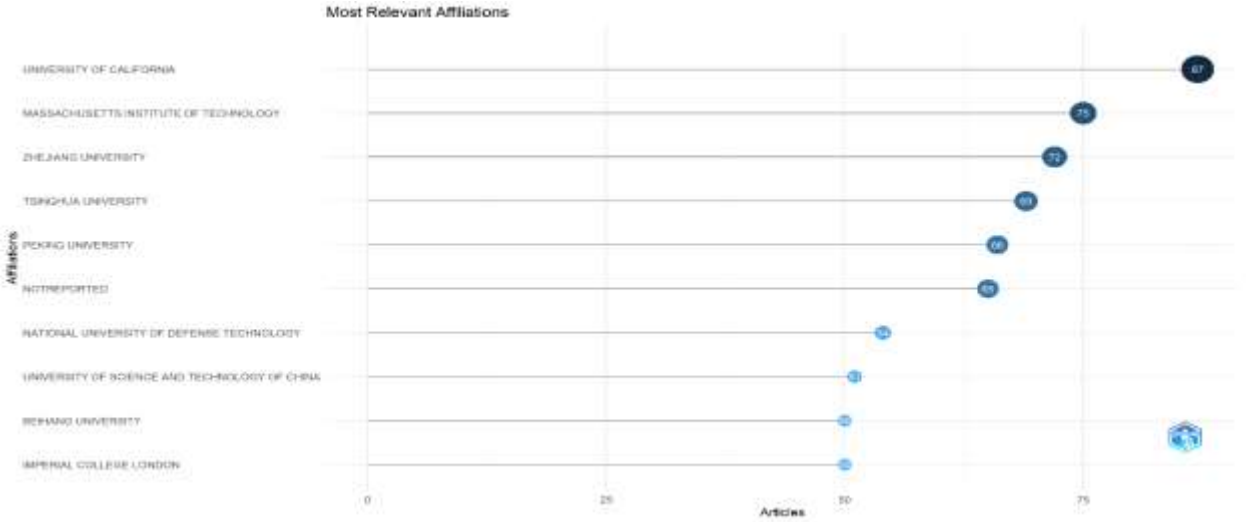


Figure 6. Most Relevant Affiliations Based on the Number of Publications

Several other institutions, such as the National University of Defense Technology (54 publications), the University of Science and Technology of China (51 publications), Beihang University (50 publications), and Imperial College London (50 publications), also contributed significantly. These findings indicate that research in this field is dominated by large research universities in the United States, China, and the United Kingdom, which have strong strengths in technology and STEM education.

Figure 7 shows the distribution of countries by corresponding author in research on intelligent virtual environments in physics education. The analysis reveals that the United States has the highest contribution, with approximately 470 papers, followed by China with approximately 460 and India with approximately 110. Furthermore, other countries, such as Germany (approximately 95 papers) and the United Kingdom (approximately 75 papers), also make significant contributions.

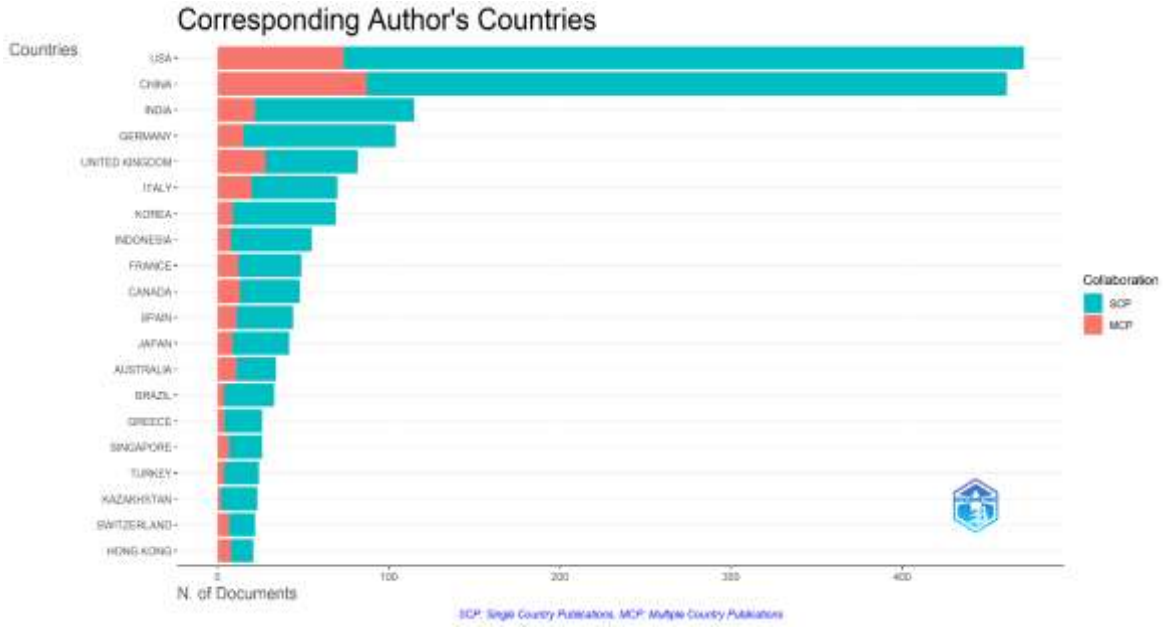


Figure 7. Corresponding Author's Countries Based on Publication Distribution and Collaboration Type (SCP and MCP)

Furthermore, countries such as Italy (±65 documents), South Korea (±60 documents), and Indonesia (±55 documents) are also among the top ten countries by publication contributions. This graph also shows that most publications are single-country publications (SCP) rather than multiple-country publications (MCP), indicating that international collaboration still has potential for improvement in this research field.

Figure 8 shows the most cited documents globally in the field of intelligent virtual environments and related learning technologies. The analysis shows that Castelvecchi (2016) in Nature is the most-cited document, with 1,499 citations, followed by Dunjko (2018) in Reports on Progress in Physics, with 833 citations, and Hamilton (2021) in the Journal of Computer Education, with 810 citations. Furthermore, Potkonjak (2016) in Computers & Education also shows significant influence, with 785 citations.

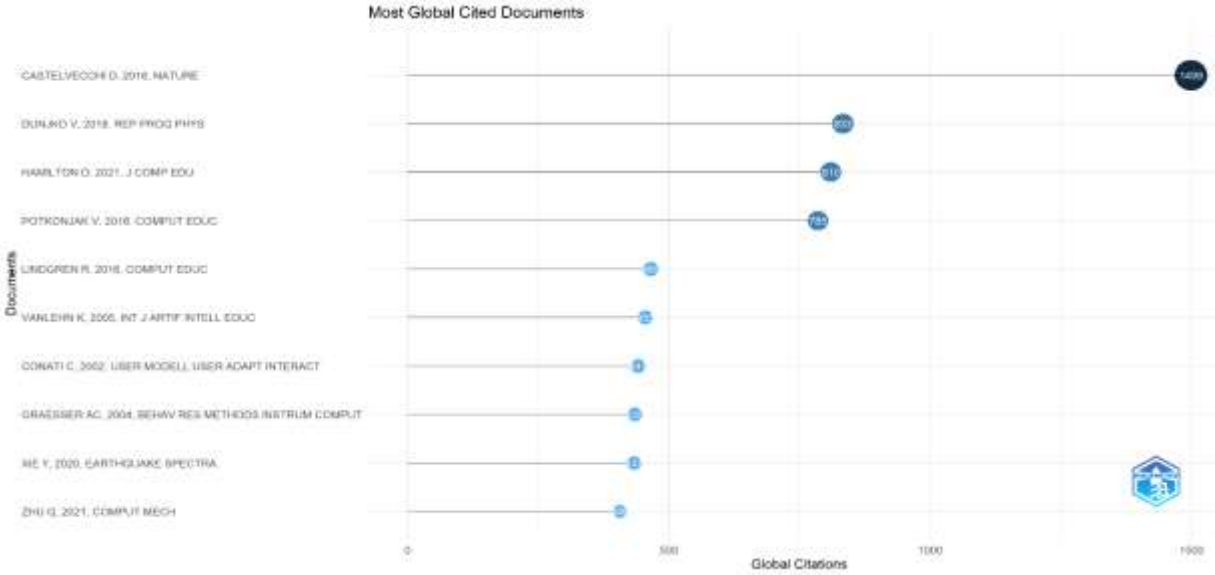


Figure 8. Most Globally Cited Documents Based on Total Global Citations

Other publications, such as Lindgren (2016) (466 citations), VanLehn (2005) (455 citations), and Conati (2002) (441 citations), are also among publications with high scientific impact. These findings indicate that research on digital learning technology, artificial intelligence, and immersive learning significantly influences the development of research in technology-based education.

Figure 9 shows the most frequently cited references in the research dataset (local citations). The analysis shows that publications by Ba J. (2014) are the most influential with 59 local citations, followed by Klimov O. (2017) with 46 citations, and Hinton G. (2015) with approximately 39 citations. Furthermore, references by Courville A. (2016) (35 citations) and Yang L. (2021) (33 citations) also demonstrate important contributions to building the theoretical foundation for research in this field.

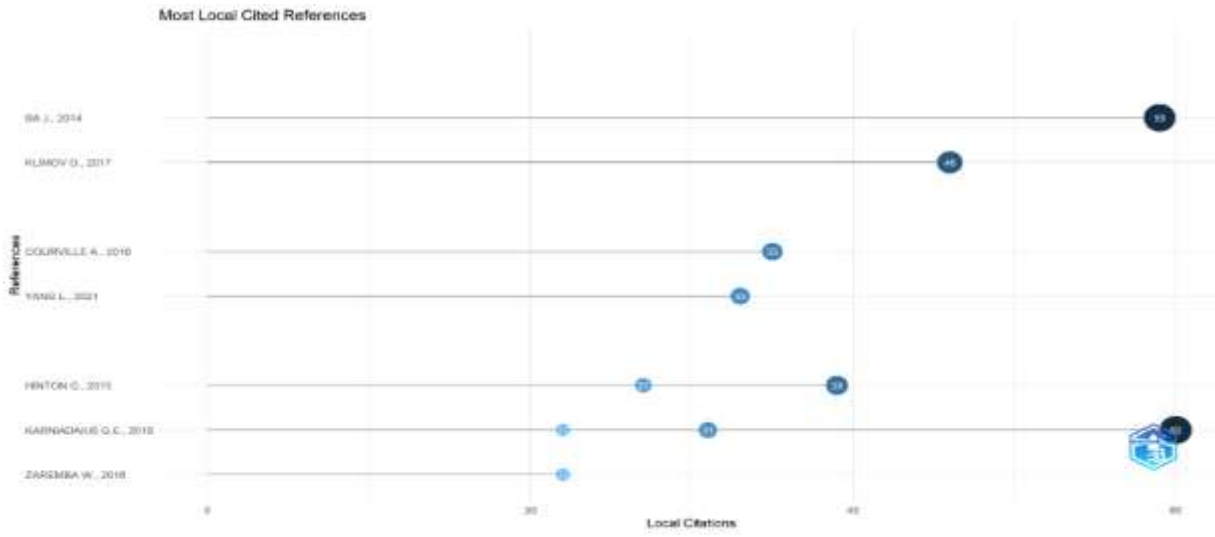


Figure 9. Most Locally Cited References Based on Local Citation Frequency

Other references, such as Karniadakis G.E. (2019) (31 citations) and Zaremba W. (2016) (22 citations), are also frequently cited in the research dataset. These findings indicate that research in intelligent virtual environments is heavily supported by literature on artificial intelligence, deep learning, and intelligent computing technologies, which are the main foundations for the development of digital learning technologies.

Figure 10 shows the most frequently occurring keywords in publications on intelligent virtual environments in physics education. The analysis results indicate that virtual reality is the most dominant term with 772 occurrences, followed by learning systems (717 occurrences) and machine learning (640 occurrences). Furthermore, other keywords, such as deep learning (525 occurrences) and artificial intelligence (497 occurrences), also demonstrate the important role of AI technology in the development of virtual learning.

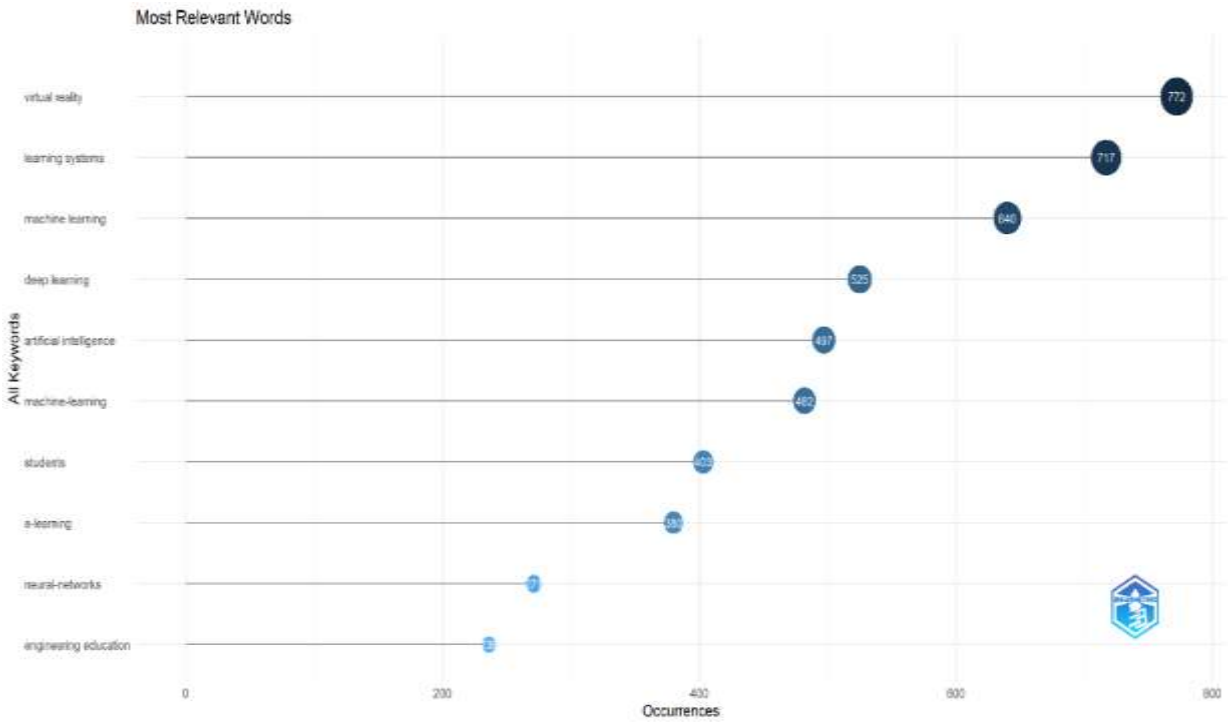


Figure 10. Most Relevant Keywords Based on Occurrence Frequency in the Research Dataset

Furthermore, keywords such as "students" (403 occurrences), "e-learning" (380 occurrences), "neural networks" (271 occurrences), and "engineering education" (236 occurrences) indicate that research in this field focuses on integrating artificial intelligence into digital learning systems. This finding indicates that research trends are dominated by integrating virtual reality, artificial intelligence, and machine learning in the development of modern learning systems.

Figure 11 shows a keyword co-occurrence network map depicting conceptual relationships between research topics in the field of intelligent virtual environments in physics education. The visualization indicates three main clusters. The first cluster (blue) is dominated by keywords such as "virtual reality," "students," "teaching," and "e-learning," indicating a research focus on the use of virtual technology in the learning process. The second cluster (red) focuses on artificial intelligence, with dominant keywords such as "machine learning," "learning systems," "deep learning," "artificial intelligence," and "neural networks," indicating the integration of AI into the development of intelligent learning systems. Meanwhile, the third cluster (green) relates to aspects of simulation and science learning, such as physics, computer simulation, and learning, and shows the use of virtual environments for experiments and the visualization of physics concepts.

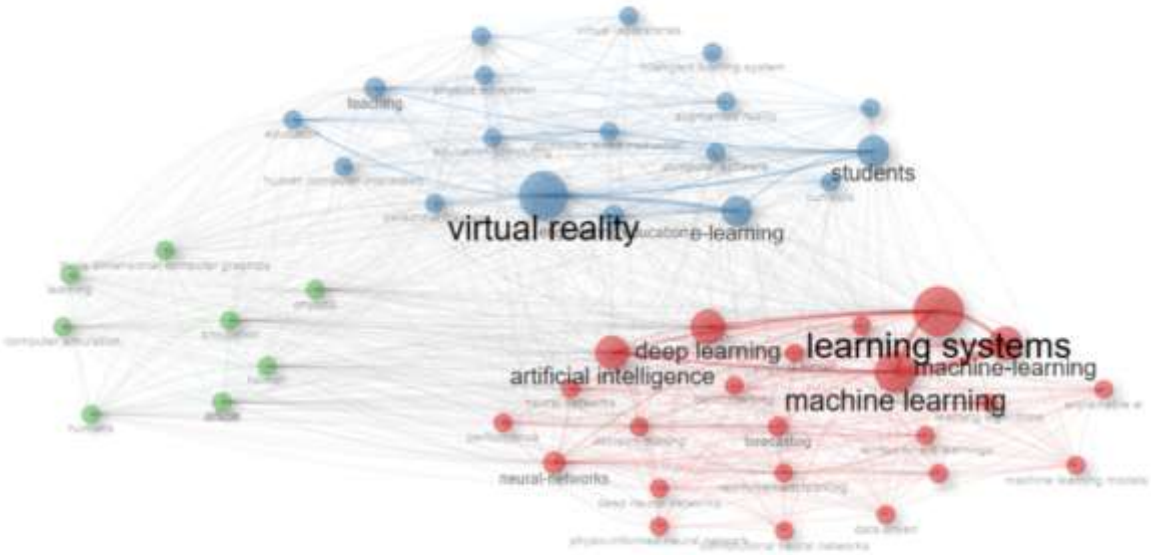


Figure 11. Keyword Co-Occurrence Network Showing Thematic Relationships in Intelligent Virtual Environments Research

Overall, this network demonstrates that virtual reality and machine learning are central nodes connecting various research themes, indicating that the integration of immersive technology and artificial intelligence is a major trend in the development of digital-based physics education.

Figure 12 shows the results of a factorial analysis that depicts the conceptual structure of the research based on keyword groupings using hierarchical clustering. The analysis results indicate three main groups of research themes. The first cluster relates to physics learning and simulation topics such as physics, computer simulation, and learning, indicating a focus on using virtual technologies to support understanding of scientific concepts. The second cluster is dominated by themes such as machine learning, deep learning, neural networks, and data mining, indicating research developments toward AI-based intelligent learning systems. Meanwhile, the third cluster focuses on digital learning technologies such as virtual reality, virtual laboratories, educational computing, and human-computer interaction, emphasizing the development of interactive digital learning environments.

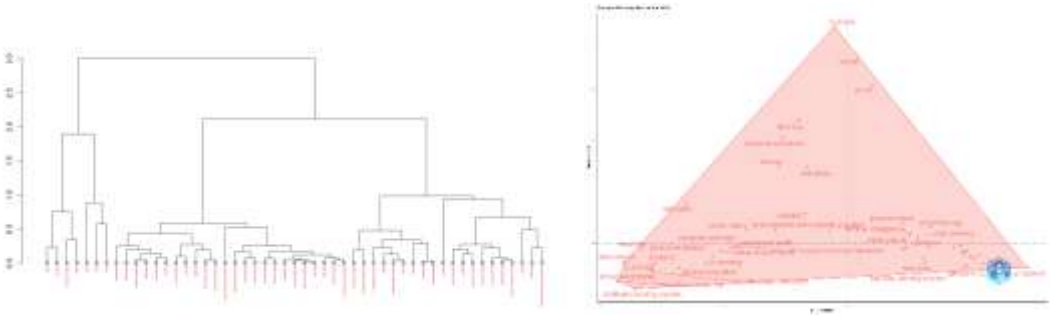


Figure 12. Factorial Analysis of the Conceptual Structure Showing Keyword Clustering Based on Thematic Similarity

Overall, these results indicate that the research structure in this field is developing around three main pillars: virtual learning environments, artificial intelligence in education, and simulation-based physics learning, reflecting the direction of future developments in digital educational technology.

Figure 13 shows a co-citation network depicting intellectual relationships between authors based on the frequency of co-citations in the research dataset. The visualization reveals several main clusters representing groups of authors with interrelated theoretical contributions. The largest cluster is dominated

by authors such as Perdikaris P. and Kingma D.P., demonstrating the strong influence of machine learning and physics-informed neural network-based research on the development of this field. Another cluster includes authors such as Graesser A.C., Koedinger K.R., and Zacharia Z.C., who focus on educational technology, intelligent tutoring systems, and science education. This network structure shows that research on intelligent virtual environments develops through the integration of artificial intelligence, educational technology, and physics education research.

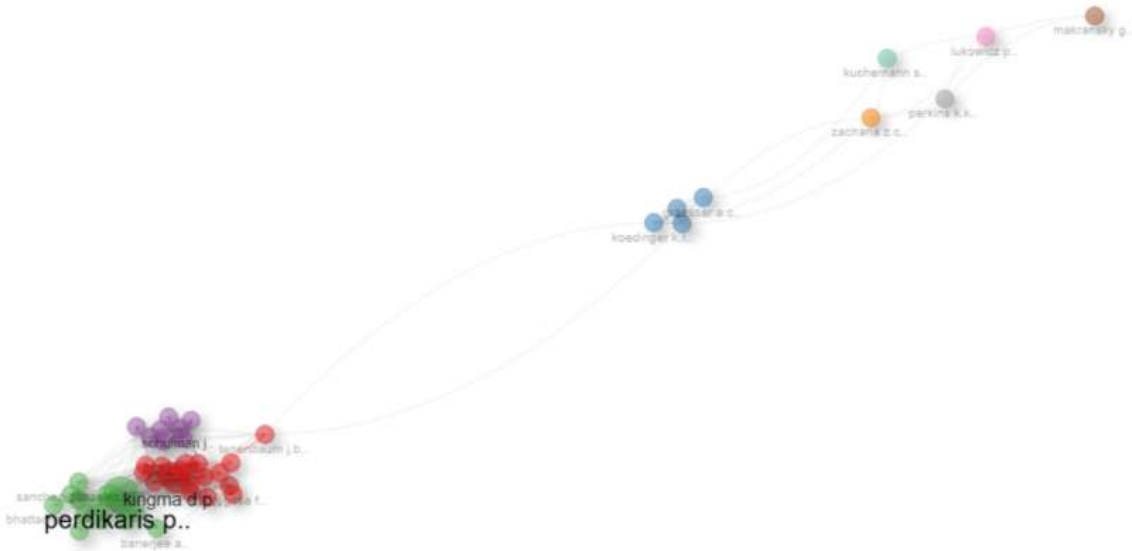


Figure 13. Co-citation Network Showing the Intellectual Structure of the Research Field Based on Author Co-Citation Relationships

Overall, this co-citation network demonstrates a strong connection between artificial intelligence literature and science education research, serving as the primary conceptual foundation for this research.

Figure 14 shows the author collaboration network in research on intelligent virtual environments in physics education. The visualization reveals several collaborative clusters formed based on co-publishing relationships between researchers. The largest cluster is dominated by authors such as Li Y, Wang Y, and Zhang Y, indicating a high level of collaboration in research development in this field. Furthermore, several other collaborative clusters, such as those of Wang J, Liu J, and Zhu Y, demonstrate a fairly strong research network, particularly from the same institution or country. Conversely, several authors, such as Noguez J and Ren L, are in smaller clusters, indicating more limited collaboration.

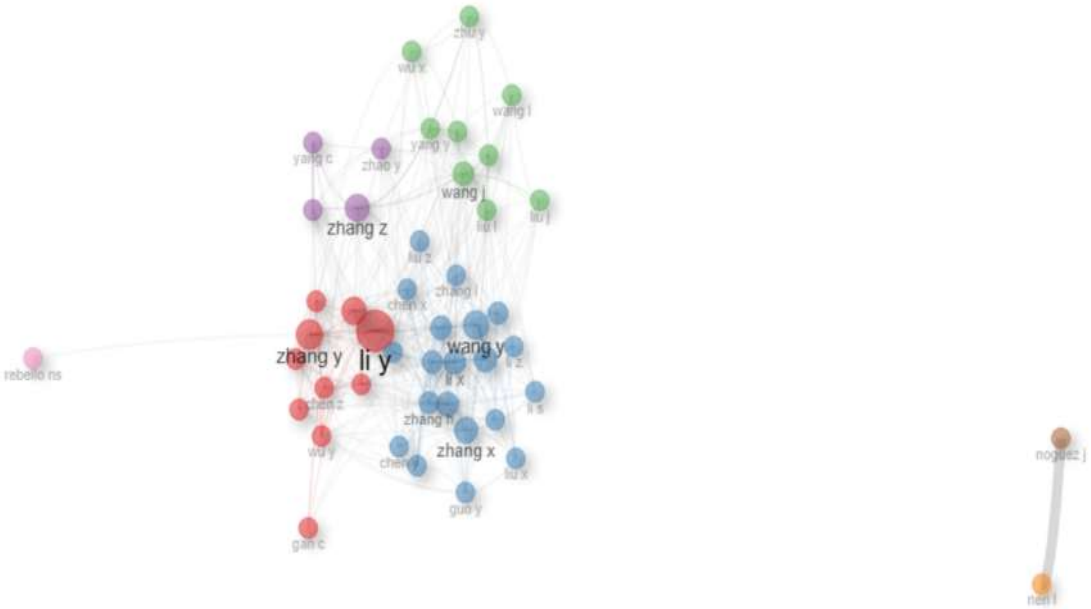


Figure 14. Author Collaboration Network Showing Co-Authorship Relationships Among Researchers

Overall, this network shows that the pattern of research collaboration in this field is still centered on certain groups of researchers, but has the potential to develop through increased international and interdisciplinary collaboration in the future.

Discussion

Bibliometric analysis results indicate that research on intelligent virtual environments in physics education has grown significantly, with an annual publication growth rate of 13.49%. This finding indicates that integrating technologies such as virtual reality, artificial intelligence, and immersive simulation is increasingly a primary focus in developing modern physics education. This increase aligns with previous research that suggests immersive technology can enhance learning engagement and understanding of abstract concepts in science and physics learning. Furthermore, the increasing number of publications also reflects the global need for digital technology-based learning innovations to address the challenges of 21st-century education.

The dominance of keywords such as virtual reality, machine learning, and artificial intelligence indicates that current research is moving toward integrating artificial intelligence technology into physics learning. This aligns with research by Zawacki-Richter et al., (2019), which found that the use of artificial intelligence in education has increased significantly over the past decade, with a focus on adaptive learning systems, intelligent tutoring systems, and data-driven learning analytics. This technological integration makes physics learning more personalized, adaptive, and experience-based, thereby deepening students' conceptual understanding.

Furthermore, keyword co-occurrence results indicate three main clusters: virtual learning environments, artificial intelligence, and simulation-based learning. This thematic structure shows that digital technology-based physics education research is developing in a multidisciplinary manner, combining education, computing, and physics. This finding is consistent with research by Fitriah & Zawanis, (2024), which states that virtual laboratories and interactive simulations can improve problem-solving skills and conceptual understanding in physics learning. Thus, intelligent virtual environments function not only as visualization aids but also as learning media that enable safe, flexible, and accessible digital experiments.

Other findings indicate that developed countries such as the United States, China, and the United Kingdom dominate publication contributions in this field. This dominance suggests that the development of digital learning technology is still shaped by technological infrastructure capacity and strong research support. However, the growing contributions of developing countries, including Indonesia, show an opportunity to expand digital technology-based physics education research globally. Furthermore, the international collaboration rate of 19.11% indicates that global collaboration still needs improvement. Previous research has shown that international collaboration can significantly improve publication quality and the citation impact of research. Therefore, increasing cross-national and cross-disciplinary collaboration is a crucial strategy for accelerating innovation in physics learning based on intelligent virtual technology.

Moreover, co-citation analysis indicates that research on intelligent virtual environments is supported by the literature on machine learning, deep learning, and educational technology. This suggests that the future of physics education will increasingly integrate artificial intelligence and data-driven learning. Research by Strielkowski et al., (2025) also shows that AI in education can improve learning efficiency, provide automated feedback, and support adaptive learning based on student needs.

Overall, these research findings demonstrate that intelligent virtual environments play a strategic role in transforming physics education toward more innovative, interactive, and sustainable learning. Integrating technologies such as VR, AI, and digital simulations not only improves learning quality but also supports the development of 21st-century skills, including critical thinking, creativity, and digital literacy. These findings also reinforce the role of educational technology in advancing Sustainable Development Goal 4 on quality education through the inclusive and sustainable use of digital technology.

CONCLUSION

This study shows that intelligent virtual environments in physics education are developing rapidly, with research trends increasingly dominated by technologies such as virtual reality, artificial intelligence, and digital simulation. The bibliometric analysis reveals that research is developing along three main pillars: virtual learning environments, artificial intelligence in education, and simulation-based physics learning, indicating a shift in physics education toward more interactive, adaptive, and technology-based

learning. Furthermore, the increasing global contribution and opportunities for international collaboration indicate that this field has great potential for continued growth. Overall, this study provides a strategic basis for developing sustainable physics learning innovations and supports the achievement of SDG 4 and The Impact Rankings indicators by improving the quality of technology-based education.

REFERENCES

Abuhassna, H., Qi, P., & Ting, L. (2025). Understanding the technological innovations in higher education: inclusivity, equity, and quality toward sustainable development goals. Open Education Studies, 7(1), 20250114. https://doi.org/10.1515/edu-2025-0114

Acevedo, P., Magana, A. J., Walsh, Y., Will, H., Benes, B., & Mousas, C. (2024). Embodied immersive virtual reality to enhance the conceptual understanding of charged particles: A qualitative study. Computers & Education: X Reality, 5, 100075. https://doi.org/10.1016/j.cexr.2024.100075

Aruanno, B., Tamburrino, F., Neri, P., & Barone, S. (2025). Virtual reality laboratory for engineering and material science immersive learning. Computer Applications in Engineering Education, 33(3), e70041. https://doi.org/10.1002/cae.70041

Bautista, G., & López-Costa, M. (2025). Smart learning spaces considering the integration of the pedagogical, environmental and digital dimensions: A systematic review. Learning Environments Research, 28(3), 455-472. https://doi.org/10.1007/s10984-025-09551-2

Bekteshi, L. (2025). Education in the era of AI and immersive technologies: A systematic review. Journal of Research in Engineering and Computer Sciences, 3(1), 1-14. https://doi.org/10.63002/jrecs.31.779

Cebrián, G., Palau, R., & Mogas, J. (2020). The smart classroom as a means to the development of ESD methodologies. Sustainability, 12(7), 3010. https://doi.org/10.3390/su12073010

Cheung, S. K. S., Kwok, L. F., Phusavat, K., & Yang, H. H. (2021). Shaping the future learning environments with smart elements: challenges and opportunities. International Journal of Educational Technology in Higher Education, 18(1), 16. https://doi.org/10.1186/s41239-021-00254-1

Chimbo, B., Maguraushe, K., & Mutunhu Ndlovu, B. (2026). Immersive equity: virtual reality and agentic artificial intelligence as catalysts for equity in education. Frontiers in Education, 11, 1761456. https://doi.org/10.3389/feduc.2026.1761456

Cossich, V. R. A., Carlgren, D., Holash, R. J., & Katz, L. (2023). Technological breakthroughs in sport: Current practice and future potential of artificial intelligence, virtual reality, augmented reality, and modern data visualization in performance analysis. Applied Sciences, 13(23), 12965. https://doi.org/10.3390/app132312965

Dai, R., Fritchman, J. C., Liu, Q., Xiao, Y., Yu, H., & Bao, L. (2019). Assessment of student understanding on light interference. Physical Review Physics Education Research, 15(2), 20134. https://doi.org/10.1103/PhysRevPhysEducRes.15.020134

Dhanaraj, R. K., Krishnasamy, B., Rajendran, U., Sellappan, S., & Jaikumar, R. (2025). Generative AI for personalized learning: foundations, trends, and future challenges. CRC Press. https://doi.org/10.1201/9781003537359

Fitriah, I., & Zawanis, S. F. (2024). The effectiveness of virtual laboratory media in physics education: A meta-analysis on students' conceptual understanding and higher-order thinking skills. ISEJ: Indonesian Science Education Journal, 5(2), 65-74. https://doi.org/10.62159/isej.v5i2.1761

Georgiou, Y., Tsivitanidou, O., & Ioannou, A. (2021). Learning experience design with immersive virtual reality in physics education. Educational Technology Research and Development, 69(6), 3051-3080. https://doi.org/10.1007/s11423-021-10055-y

Good, M., Maries, A., & Singh, C. (2019). Impact of traditional or evidence-based active-engagement instruction on introductory female and male students' attitudes and approaches to physics problem solving. Physical Review Physics Education Research, 15(2), 20129. https://doi.org/10.1103/PhysRevPhysEducRes.15.020129

Hare, R., & Tang, Y. (2022). Player modeling and adaptation methods within adaptive serious games. IEEE Transactions on Computational Social Systems, 10(4), 1939-1950. https://doi.org/10.1109/TCSS.2022.3203926

Hosny, F., Mantha, B. R. K., Abu Dabous, S., Al-Khateeb, G., Omar, M., Arab, M. G., Zeiada, W., Merabtene, T., & Hamad, K. (2026). Advancing civil engineering education: a systematic review of

opportunities, trends, challenges, and future research directions in immersive digital technologies. Journal of Computers in Education, 1-61. https://doi.org/10.1007/s40692-026-00403-3

Hu-Au, E. (2024). Learning abstract chemistry concepts with virtual reality: An experimental study using a VR chemistry lab and molecule simulation. Electronics, 13(16), 3197. https://doi.org/10.3390/electronics13163197

Kahe, C. (2025). Education at Crossroads: A Paradigm Shift and Emerging Methodologies in Teaching-Learning. Emerging Methodologies In Teaching And Learning: A Contemporary Overview, 37-45.

Kangwa, D., Msafiri, M. M., Charles, K., & Antony, F. (2026). Advancing Sustainable Development Goal 4 through systemic digital transformation in African higher education. Sustainable Development. https://doi.org/10.1002/sd.71178

Kaur, N., & Kaur, J. (2024). Innovating Education Through Technology: A Pathway to Achieving the Sustainable Development Goals in the Context of National Education Policy 2020. Synergy: International Journal of Multidisciplinary Studies, 1(3), 28-33.

Kinshuk, Chen, N.-S., Cheng, I.-L., & Chew, S. W. (2016). Evolution is not enough: Revolutionizing current learning environments to smart learning environments. International Journal of Artificial Intelligence in Education, 26(2), 561-581. https://doi.org/10.1007/s40593-016-0108-x

Kolil, V. K., & Achuthan, K. (2024). Virtual labs in chemistry education: A novel approach for increasing student's laboratory educational consciousness and skills. Education and Information Technologies, 29(18), 25307-25331. https://doi.org/10.1007/s10639-024-12858-x

Koukaras, C., Koukaras, P., Ioannidis, D., & Stavrinides, S. G. (2025). AI-driven telecommunications for smart classrooms: Transforming education through personalized learning and secure networks. Telecom, 6(2), 21. https://doi.org/10.3390/telecom6020021

Le, H. Van, Huynh, D. T., & Nguyen, T. T. (2025). Technology integration in English language teaching: assessing the digital readiness of Vietnamese high school teachers. The International Journal of Information and Learning Technology, 42(5), 449-465. https://doi.org/10.1108/IJILT-03-2025-0085

Lindgren, R., Tscholl, M., Wang, S., & Johnson, E. (2016). Enhancing learning and engagement through embodied interaction within a mixed reality simulation. Computers & Education, 95, 174-187. https://doi.org/10.1016/j.compedu.2016.01.001

Lu, Y., Xu, W., Leng, J., Liu, X., Xu, H., Ding, H., Zhou, J., & Cui, L. (2024). Review and research prospects on additive manufacturing technology for agricultural manufacturing. Agriculture, 14(8), 1207. https://doi.org/10.3390/agriculture14081207

Mafarja, N., Zulnaidi, H., & Mohamad, M. M. (2025). Developing critical thinking skills through AI-enhanced science education for sustainability. In Rethinking the pedagogy of sustainable development in the AI era (pp. 173-196). IGI Global Scientific Publishing. https://doi.org/10.4018/979-8-3693-9062-7.ch009

Makinde, S. O., Ajani, Y. A., & Abdulrahman, M. R. (2024). Smart learning as transformative impact of technology: A paradigm for accomplishing sustainable development goals (SDGs) in education. Indonesian Journal of Educational Research and Technology, 4(3), 213-224.

Mallek, F., Mazhar, T., Shah, S. F. A., Ghadi, Y. Y., & Hamam, H. (2024). A review on cultivating effective learning: synthesizing educational theories and virtual reality for enhanced educational experiences. PeerJ Computer Science, 10, e2000. https://doi.org/10.7717/peerj-cs.2000

Mhlongo, S., Mbatha, K., Ramatsetse, B., & Dlamini, R. (2023). Challenges, opportunities, and prospects of adopting and using smart digital technologies in learning environments: An iterative review. Heliyon, 9(6). https://doi.org/10.1016/j.heliyon.2023.e16348

Musengimana, T., Yadav, L. L., Uwamahoro, J., & Nizeyimana, G. (2025). Instructional strategies for enhancing students' problem-solving skills in physics: a systematic review. Discover Education, 4(1), 380. https://doi.org/10.1007/s44217-025-00733-x

Niyazova, G. Z., Duisekeyeva, B. M., Berdi, D. K., Usembayeva, I. B., & Mindetbayeva, A. A. (2026). The effects of gamified AI-supported digital learning environments on personalized learning and student engagement in school education: a systematic review and meta-analysis. Frontiers in Education, 11, 1754080. https://doi.org/10.3389/feduc.2026.1754080

Nordin, N. A., Abd Halim, N. D., & Dahri, N. A. (2026). An empirically validated pedagogical framework to reduce cognitive load in online learning environments. Iran Journal of Computer Science, 9(1), 24. https://doi.org/10.1007/s42044-025-00382-1

Okoye, K., Hussein, H., Arrona-Palacios, A., Quintero, H. N., Ortega, L. O. P., Sanchez, A. L., Ortiz, E. A., Escamilla, J., & Hosseini, S. (2023). Impact of digital technologies upon teaching and learning in

higher education in Latin America: an outlook on the reach, barriers, and bottlenecks. Education and Information Technologies, 28(2), 2291-2360. https://doi.org/10.1007/s10639-022-11214-1

Pang, S., Lv, G., Zhang, Y., & Yang, Y. (2024). Enhancing students' science learning using virtual simulation technologies: a systematic review. Asia Pacific Journal of Education, 1-21. https://doi.org/10.1080/02188791.2024.2441676

Purwadi, R. E., Chadijah, S., & Suhana, A. (2024). Analysis of teacher competence in using digital learning media. Jurnal Ilmiah Edukatif, 10(2), 237-247. https://doi.org/10.37567/jie.v10i2.3315

Selden, R., Widdowson, P., & Brooker, P. (2013). A reader's guide to contemporary literary theory. Routledge. https://doi.org/10.4324/9781315835358

Şengül, Ö., & Karabacak, N. N. (2026). Sustainable Inquiry-Based Learning Through Adaptive Management: A Phenomenological Study of Physics Teachers in Türkiye. Sustainability, 18(3), 1481. https://doi.org/10.3390/su18031481

Setyawarno, D., Borhan, M. T., Maryati, M., & Rahayu, D. P. (2026). Virtual laboratories with interactive simulations and computational thinking to enhance higher-order thinking skills. Revista de Investigación En Educación, 24(2), 219-250. https://doi.org/10.35869/reined.v24i2.6938

Singun, A. J. (2025). Unveiling the barriers to digital transformation in higher education institutions: a systematic literature review. Discover Education, 4(1), 37. https://doi.org/10.1007/s44217-025-00430-9

Siregar, L. A., & Siregar, S. (2024). Assessing teacher competency and preparedness for integrating digital media in 21st-century education: An exploratory review. Al-Ishlah: Jurnal Pendidikan, 16(4), 5794-5804. https://doi.org/10.35445/alishlah.v16i4.5619

Strielkowski, W., Grebennikova, V., Lisovskiy, A., Rakhimova, G., & Vasileva, T. (2025). AI-driven adaptive learning for sustainable educational transformation. Sustainable Development, 33(2), 1921-1947. https://doi.org/10.1002/sd.3221

Taloba, A. I., Elhadad, A., Rayan, A., Abd El-Aziz, R. M., Salem, M., Alzahrani, A. A., Alharithi, F. S., & Park, C. (2023). A blockchain-based hybrid platform for multimedia data processing in IoT-Healthcare. Alexandria Engineering Journal, 65, 263-274. https://doi.org/10.1016/j.aej.2022.09.031

Tarng, W., & Pei, M.-C. (2023). Application of virtual reality in learning quantum mechanics. Applied Sciences, 13(19), 10618. https://doi.org/10.3390/app131910618

Tripon, C. (2025). Towards quality education for all: integrating EdTech, mentorship, and community in support of SDG 4. Education Sciences, 15(9), 1184. https://doi.org/10.3390/educsci15091184

Vidak, A., Movre Šapić, I., Gomzi, V., & Mešić, V. (2026). Immersive virtual reality in learning physics: a systematic review of opportunities and challenges. European Journal of Physics, 47(3), 33001. https://doi.org/10.1088/1361-6404/ae72d3

Villada Castillo, J. F., Bohorquez Santiago, L., & Martínez García, S. (2025). Optimization of physics learning through immersive virtual reality: A study on the efficacy of serious games. Applied Sciences, 15(6), 3405. https://doi.org/10.3390/app1506340

Wang, L., Xu, W., Liu, Y., Wang, M., Wang, B., Yang, X., Xu, L., Tan, Z., Fan, R., & Wang, Z. (2026). Artificial intelligence for virtual reality: a review. Science China Information Sciences, 69(1), 111101. https://doi.org/10.1007/s11432-024-4541-9

Weaver, J. P., Chastain, R. J., DeCaro, D. A., & DeCaro, M. S. (2018). Reverse the routine: Problem solving before instruction improves conceptual knowledge in undergraduate physics. Contemporary Educational Psychology, 52, 36-47. https://doi.org/10.1016/j.cedpsych.2017.12.003

Yusvana, R., & Papadakis, S. (2026). Computational Thinking, Basic Coding Skills, and STEM Education in the Era of Artificial Intelligence. International Journal of Educational Reform, 10567879261434028. https://doi.org/10.1177/10567879261434027

Zawacki-Richter, O., Marín, V. I., Bond, M., & Gouverneur, F. (2019). Systematic review of research on artificial intelligence applications in higher education-where are the educators? International Journal of Educational Technology in Higher Education, 16(1), 39. https://doi.org/10.1186/s41239-019-0171-0

Zeeshan, K., Hämäläinen, T., & Neittaanmäki, P. (2022). Internet of Things for sustainable smart education: An overview. Sustainability, 14(7), 4293. https://doi.org/10.3390/su14074293

Zhu, Z., Sun, Y., & Riezebos, P. (2016). Introducing the smart education framework: Core elements for successful learning in a digital world. International Journal of Smart Technology and Learning, 1(1), 53-66. https://doi.org/10.1504/IJSMARTTL.2016.078159

Author (s):

*Hanan Zaki Alhusni (Corresponding Author)
Department of Physics, Faculty of Mathematics and Natural Science,
Universitas Negeri Surabaya,
Ketintang Street, Surabaya 60231, Indonesia
Email: hanan.20068@mhs.unesa.ac.id

Binar Kurnia Prahani
Department of Physics, Faculty of Mathematics and Natural Science,
Universitas Negeri Surabaya,
Ketintang Street, Surabaya 60231, Indonesia
Email: binarprahani@unesa.ac.id\

Budi Jatmiko
Department of Physics, Faculty of Mathematics and Natural Science,
Universitas Negeri Surabaya,
Ketintang Street, Surabaya 60231, Indonesia
Email: budijatmiko@unesa.ac.id

Titin Sunarti
Department of Physics, Faculty of Mathematics and Natural Science,
Universitas Negeri Surabaya,
Ketintang Street, Surabaya 60231, Indonesia
Email: titinsunarti@unesa.ac.id

Noval Maleakhi Hulu
Department of Mechanical Engineering,
Monash University Malaysia,
Jalan Lagoon Selatan, Bandar Sunway, 47500 Subang Jaya, Selangor, Malaysia
Email: novalmaleakhi2@gmail.com