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Metaverse in Science Education: Immersive and Interactive Learning for Future

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ABSTRACT

Objective: *This study aimed to analyze the trends, collaborations, and contributions in Metaverse-related research within the context of science education from 2021 to 2024. The research identifies the growth dynamics, key countries, institutions, and thematic keywords in Metaverse research, emphasizing its educational applications.* ***Method:*** *A bibliometric analysis was conducted on 64 articles from 51 sources, spanning 2021-2024 with PRISMA. The data were collected using citation metrics, keyword analysis, author collaboration, and geographical distribution of publications. VOSviewer were employed to visualize the relationships between key themes and institutions.* ***Results:*** *The study revealed a significant increase in research output, particularly from 2021 to 2023, with a growth rate of 100%. China and the United States emerged as the leading contributors, with distinct research patterns: China focused on national studies, while the USA engaged in more international collaborations. Keywords such as Augmented Reality, Machine Learning, and Science Education were central to the discourse, highlighting the growing intersection of technology and education. Leading institutions included the University of Zilina and Jakarta State University.* ***Novelty:*** *This research provides a detailed bibliometric overview of the metaverse in science education, highlighting the gap in bibliometric studies focused specifically on science education within the metaverse. It offers insights into emerging trends, key collaborations, and potential areas for further exploration.*

INTRODUCTION

The Metaverse refers to a conceptual virtual space where individuals can interact with digital environments and other users within a shared online universe (Allam et al., 2022). It is essentially an immersive, three-dimensional virtual reality platform that replicates real-world experiences using advanced technologies such as augmented reality (Gattullo et al., 2022), virtual reality (Kuleto et al., 2024), and blockchain (Rafique & Qadir, 2024). In the metaverse, users can design and personalize their avatars (Ahn et al., 2024), navigate virtual landscapes (Mourtzis et al., 2022), participate in social interactions (Oh et al., 2023), compete in games and challenges (Jungherr & Schlarb, 2022), and carry out business transactions (Koohang et al., 2023). The term "Metaverse" was first coined in Neal Stephenson's 1992 science fiction novel Snow Crash, which portrayed a virtual realm bearing the same name (Garon, 2022). The idea has become more and more well-liked over time, especially in the fields of social networking and online gaming. However recently, the metaverse has also shown promise as a platform for innovation and change in a variety of industries, including as banking, healthcare, retail, and education (Monaco & Sacchi, 2023).

Some of the drawbacks of contemporary online settings, namely their lack of social presence, immersion, and interaction, may be addressed via the metaverse. The Metaverse creates new chances for cooperation, communication, and creativity by allowing people to engage in real time with digital items in a shared virtual environment. (Mourtzis et al., 2022). Consequently, it has garnered significant interest from academics, practitioners, and policymakers who are eager to explore the potential and implications of this emerging technology (Dwivedi et al., 2022). As such, it is essential to conduct rigorous and systematic analyses to better understand the past and future trends of the metaverse. Among the sectors most profoundly impacted by the metaverse is education (Kaddoura & Al Husseiny, 2023; Pregowska et al., 2024). This technology enhances learning experiences by making them more immersive, interactive, and collaborative through the integration of augmented reality (AR), virtual reality (VR), and artificial intelligence (AI).

The metaverse in the context of science offers transformative potential for education and research, creating immersive virtual environments where students and researchers can explore scientific concepts interactively and collaboratively. By leveraging technologies such as VR and AR, the metaverse enables the simulation of complex experiments, multidimensional data visualization, and the exploration of environments inaccessible in the real world, such as outer space or microscopic realms (Korkut & Surer, 2023). Additionally, the metaverse can facilitate global collaboration among scientists, allowing real-time exchange of ideas and resources without geographical constraints. Integrating the metaverse into science education can also enhance student engagement through experiential learning, making abstract concepts more tangible and engaging (Singh et al., 2024; Wang et al., 2024). Thus, the metaverse not only expands the traditional boundaries of science education and research but also opens new avenues for innovation and discovery (Dwivedi et al., 2022; Samala et al., 2024). To identify these opportunities and trends, bibliometric analysis can serve as an effective tool (Amiruddin et al., 2025; Prahani, Rizki, et al., 2024). This analysis allows researchers to map research developments, identify emerging topics, and understand collaborative networks among researchers in a specific field.

Several previous studies have applied bibliometric analysis to the topic of the metaverse. For instance Akhil et al. (2024), examined metaverse trends in education from 1995 to 2023 using the WoS database. Verma et al. (2024), analyzed metaverse trends in education from 2010 to 2022, also utilizing the WoS database. Meanwhile, George-Reyes et al. (2023), explored the opportunities of the metaverse in relation to complex thinking, whereas Wider et al. (2024), reviewed comprehensive metrics on the metaverse research landscape. Although various bibliometric analyses on the metaverse have been conducted, no comprehensive study has thoroughly examined trends, thematic mapping (three-filed plot), and the relationship between the metaverse and science education, along with its learning processes. Moreover, existing research predominantly focuses on the technological aspects or applications of the metaverse in other fields, such as entertainment and business, leaving a significant knowledge gap regarding its potential and implications in the context of science education

The bibliometric approach offers a unique contribution to identifying research trends in a particular field (Amiruddin et al., 2024; Suliyanah et al., 2024). Through knowledge network analysis, which includes co-authorship and citation analysis, bibliometrics may

identify connections between authors, scientific publications, and organizations that propel research forward. This method assists in locating important impacts and cooperation trends that conventional qualitative evaluations could overlook. Additionally, bibliometric analysis provides a more accurate knowledge of the evolution of research on the metaverse in scientific education by identifying new trends and changing keywords over time. The following research questions (RQs) are addressed in this study:

RQs1: What is the main information about metaverse?
RQs2: What are the top countries and collaboration, affiliations, authors, and sources?
RQs3: What are the keyword trends and network visualization?
RQs4: What is the three field flot?
RQs5: What is the review of top-cited articles of metaverse?

RESEARCH METHOD

This study employed a bibliometric approach to analyze and describe research trends in the field of the metaverse within science education. Research trends represented the collective interest of scholars in specific topics and served as indicators of the alignment between contemporary scientific discoveries and societal demands (Aria et al., 2020; Prahani et al., 2023). Bibliometric analysis facilitated the mapping of relationships and intellectual developments within the ever-evolving landscape of scientific knowledge (Amiruddin et al., 2024; Prahani et al., 2024), aiding researchers in identifying potential future research directions. Conducting a bibliometric analysis required access to bibliographic databases that provided key information on scientific publications, including titles, authors, abstracts, keywords, and references. Scopus was a preferred database as it included a wide range of scientific journals, conferences, and books at both global and regional levels. One of Scopus' key strengths was its rigorous selection and indexing process, which ensured the reliability and quality of the data it provided (Halevi et al., 2017; Pranckutė, 2021). Moreover, Scopus supported various formats and platforms, making it easier to conduct comprehensive data analysis.

Data Collection and Processing

To comprehensively explore the intersection between the metaverse and science in the context of education and learning, a bibliometric analysis was conducted in February 1st 2025 using the Scopus database. This database was chosen in accordance with Amiruddin et al. (2025) suggestion that Scopus is among the best databases out there. Scopus is well known for covering a wide range of scholarly literature in many different fields. This search's temporal scope, which runs from 2021 to 2024, aims to find noteworthy contributions and new developments in the metaverse sector. Table 1 displays the precise syntax and filtering criteria used in this study.

Table 1. An overview characteristics databases

Category	Specific standard requirements
Research Database	Scopus
Query Keywords	(TITLE-ABS-KEY ("metaverse" OR "metaverses") AND TITLE-ABS-KEY ("science") AND TITLE-ABS-KEY ("education" OR "learning") AND TITLE-ABS-KEY

Category	Specific standard requirements
	("virtual reality" OR "mixed reality" OR "augmented reality" OR "extended reality"))
Searching Periode	2021 – 2024
Documents type	Articles
Language	English
Pubstage	Final
Data Format	CSV, Ris, and BibTex

Finding and filtering publications according to the given time period (2021–2024) was the first step in the selection process, which restricted the results to English-language articles with "final article" status. This action was made because articles, which usually contain original research findings that can be examined and contrasted using bibliometric techniques and indicators, are thought to be the most prevalent and representative type of scientific publication. Because English is the most commonly used worldwide language in academia, the selection procedure also gave special attention to publications written in that language. A number of articles were then vetted to make sure they were pertinent to the research topic and to eliminate duplicates. 64 articles were ultimately chosen and added to this bibliometric analysis. Figure 1 depicts the complete selection procedure in accordance with PRISMA criteria (Page et al., 2021).

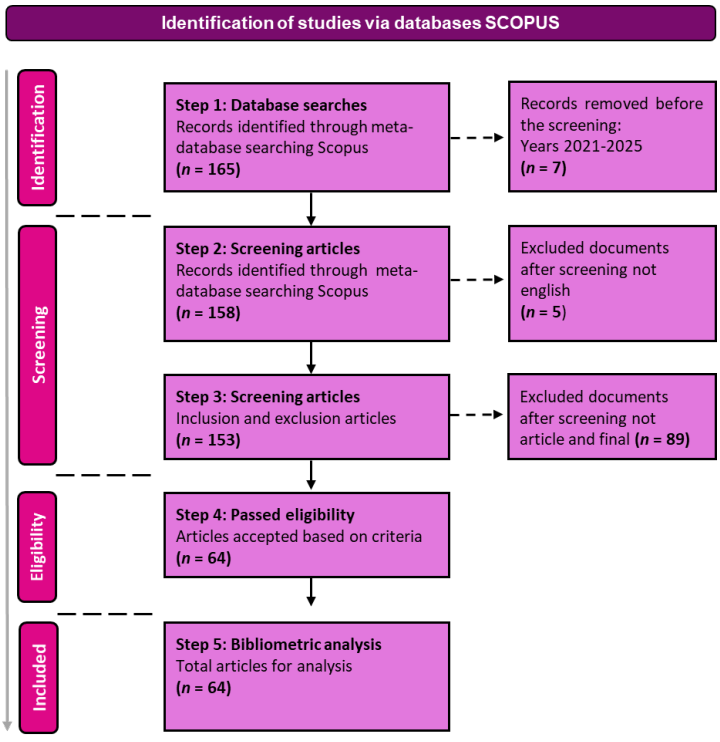

Figure 1. The process of article selection

Data Analysis and Visualization

Science mapping is a spatial visual representation of the linkages and trends across different scientific subjects, materials, or authors within a research topic. With the help of this approach, researchers may comprehend the connections between diverse subjects and ideas as well as the ways in which different writers and journals have advanced the

area. Thus, scientific mapping provides a more thorough view of the composition and development of research by assisting in the identification of patterns and dynamics that propel knowledge creation in a certain field (Cheng & So, 2017). The Scopus database is available in CSV and RIS formats for use by programs like Biblioshiny and VOSviewer. Additionally, the mapping results from the database retrieved from Scopus are shown using the R package, which includes Biblioshiny, Excel, and VOSviewer (Aria & Cuccurullo, 2017; Prahani et al., 2023; Van Eck & Waltman, 2017; Van Eck & Waltman, 2010).

RESULTS AND DISCUSSION

Results

The Main Information About Metaverse

The analyzed data comprises 64 documents from 51 sources, spanning the period 2021–2024, demonstrating an annual growth rate of 100% and an average document age of 1.98 years, indicating rapid development and a focus on recent research. The average citation rate of 24.42 per document highlights significant scholarly impact, while 3,140 references and 382 Keywords Plus reflect a broad thematic scope. Author collaboration is substantial, with an average of 3.58 authors per document and 28.12% international co-authorships, underscoring strong cross-country partnerships. Among 219 authors, 16 authored single-authored documents, while Author's Keywords total 278. Overall, the data portrays a dynamic, collaborative, and influential research field. Details of the main information are presented in Table 2.

Table 2. Main information of metaverse

Description	Results
Main Information About Data	
Timespan	2021:2024
Sources (Journals, Books, etc)	51
Documents	64
Annual Growth Rate %	100
Document Average Age	1.98
Average citations per doc	24.42
References	3140
Document Contents	
Keywords Plus (ID)	382
Author's Keywords (DE)	278
Authors	
Authors	219
Authors of single-authored docs	16
Authors Collaboration	
Single-authored docs	16
Co-Authors per Doc	3.58
International co-authorships %	28.12
Document Types	
article	64

Distribution of Annual Documents

Figure 2 depicts the "Documents by Year" graph in the field of metaverse in science education, which shows a significant increase in the number of articles published from 2021 to 2023. In 2021, there were only 2 articles, but this number increased dramatically to 11 articles in 2022, and peaked in 2023 with 35 articles. This increase shows an exponential growth in the production of research or publications in the analyzed field. This could be due to a variety of factors, such as increased research interest, availability of resources, or more intensive collaboration among researchers.

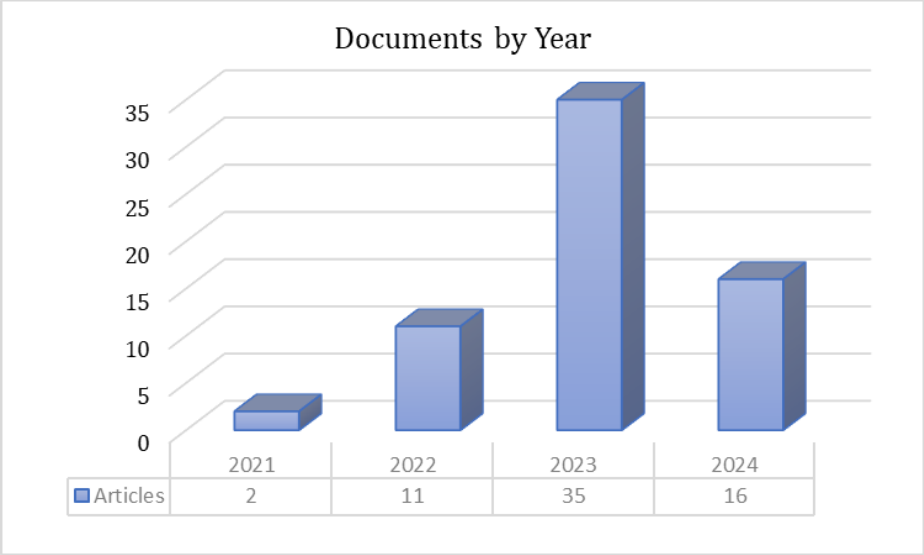

Figure 2. Annual publications

However, in 2024, there was a decrease in the number of articles to 16, although this is still higher than in 2021 and 2022. This decline may indicate challenges or changes in research dynamics, such as reduced funding, shifts in research focus, or other external factors. Overall, this data illustrates a very positive trend in the first three years, with the potential to continue growing if the challenges faced in 2024 can be overcome.

Most Relevant Countries and Collaborations

Table 3 depicts the publication data related to the metaverse, indicating that China and the United States have the most publications, each contributing 9 articles (14.1%) of the total publications. However, these two countries have notable differences in research patterns. China predominantly focuses on national research; 8 out of 9 articles are classified as Single Country Publications (SCP), suggesting that metaverse research in China is primarily conducted independently with limited international collaboration. In contrast, the United States is more active in global cooperation, with 3 out of 9 articles being Multiple Country Publications (MCP), reflecting a broader engagement in cross-country research initiatives. This divergence highlights distinct approaches to metaverse research, with China emphasizing self-reliance and the United States leveraging international collaboration to advance its research efforts.

Table 3. Top productive country colloboration

Country	Articles	Articles %	SCP	MCP
China	9	14.1	8	1
Usa	9	14.1	6	3
United Kingdom	6	9.4	5	1
Romania	4	6.3	0	4
Malaysia	3	4.7	1	2
Australia	2	3.1	1	1
Indonesia	2	3.1	2	0
Korea	2	3.1	1	1
Mexico	2	3.1	2	0
Spain	2	3.1	2	0

SCP: Single country publication, MCP: Multple country publications

Additionally, the United Kingdom, Romania, and Malaysia have made significant contributions to metaverse publications. The United Kingdom contributed 6 articles (9.4%), with the majority of its publications being nationally focused. Romania exhibits a unique pattern, with all 4 of its articles (100%) classified as Multiple Country Publications (MCP), indicating that research in this country is entirely dependent on international collaboration. Malaysia, with 3 articles (4.7%), demonstrates a balance between national and international research, comprising 1 Single Country Publication (SCP) and 2 MCPs. Meanwhile, other countries such as Australia, Indonesia, South Korea, Mexico, and Spain each contributed 2 articles (3.1%), but with varying collaboration patterns. Indonesia, Mexico, and Spain remain limited to national research (SCP = 2, MCP = 0), while South Korea and Australia show involvement in international cooperation, with 1 MCP each. More detail is presented in Figure 3.

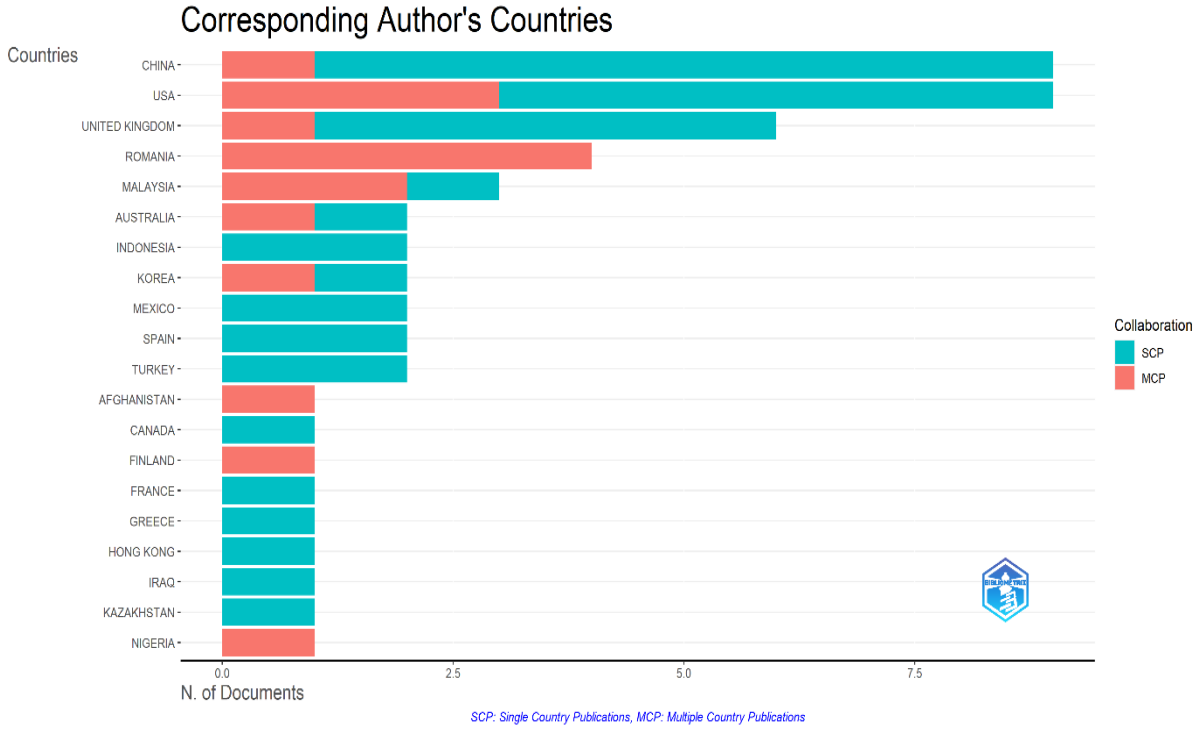

Figure 3. Corresponding author's country

Most Relevant Affiliations

Figure 4 highlights the most relevant affiliations in metaverse-related publications based on the number of articles published. The University of Zilina emerges as the leading institution, contributing (9 articles), followed by Jakarta State University (7 articles). Universitat Politècnica de València (6 articles) and Spiru Haret University have contributed (5 articles), respectively, while several other institutions, such as Hanyang University, Hub de l'Energie, INTI International University, Tulane University School of Medicine, Universiti Teknologi MARA (UiTM) Sungai Buloh, and Duke University, have each contributed 4 articles. This data illustrates that research contributions related to the metaverse are distributed across various institutions from different countries. From the observed patterns, the University of Zilina and Jakarta State University stand out as primary research hubs, indicating a strong research focus at these institutions in exploring the metaverse. The involvement of universities from diverse countries also suggests that research on the metaverse is gaining global attention. The diversity of affiliations demonstrates that metaverse studies are not confined to institutions in developed countries but also include those from broader regions, such as Asia and Europe.

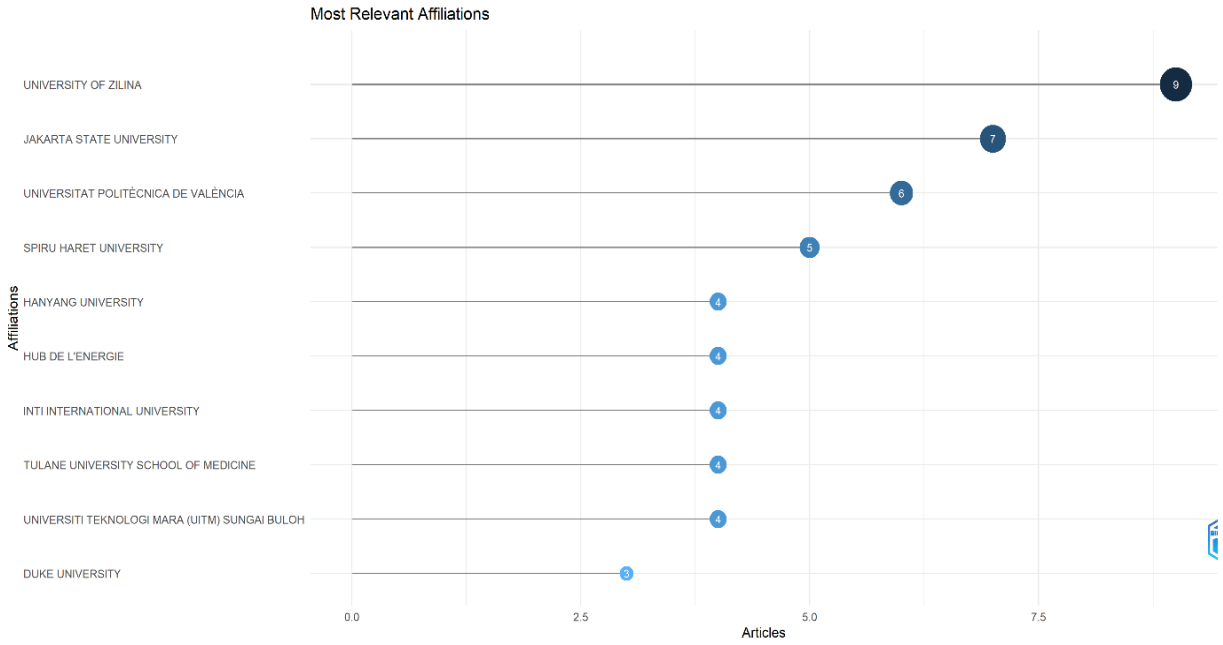

Figure 4. Most relevan affiliations

Most Relevant Authors

Figure 5 depicts the most relevant authors in metaverse-related publications based on the number of documents published. There are seven authors who have each published two documents: Muhammet Damar, Carlos Enrique George-Reyes, Jakub Horak, Edgar Omar López-Caudana, Elvira Nica, Milos Poliak, and Katarina Zvarikova. Meanwhile, three other authors—Luciano A. Abriata, Erif Ahdianto, and Yusuf Ayodeji Ajani—have each contributed only one document. This distribution indicates that there is no dominance by a single individual; rather, a group of authors has made relatively balanced contributions to metaverse-related research. Further analysis reveals that research on the metaverse is dispersed among various authors, with no single figure significantly

dominating publications in this field. This suggests that metaverse studies are still evolving, and no research group has yet established global dominance in this area.

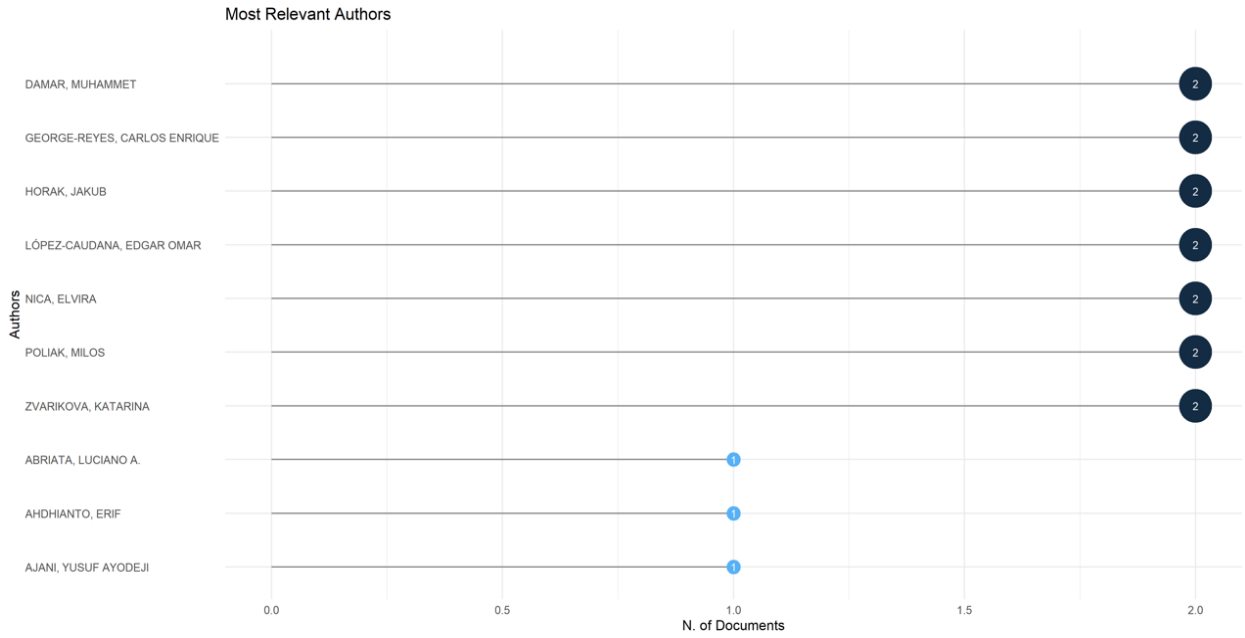

Figure 5. Most Relevant Authors

Most Relevant Sources

Table 4 provides insights into the distribution of research articles across various publishers and journals, highlighting their impact through H-Index values. The Auricle Global Society of Education and Research is the most active publisher, contributing 13 articles across four journals, including *Review of Contemporary Philosophy* (H-Index: 15) and *Linguistic and Philosophical Investigations* (H-Index: 17). Despite its high influence, *ACM Computing Surveys* (H-Index: 213) has only one article, while other high-impact journals, such as *Applied Sciences (Switzerland)* (H-Index: 130) and *Artificial Intelligence Review* (H-Index: 115), also feature a single publication each. *IEEE Transactions on Learning Technologies* (H-Index: 62) from the Institute of Electrical and Electronics Engineers Inc. (IEEE) contains three articles, indicating a strong focus on technology-enhanced learning. Similarly, *Frontiers in Education* (H-Index: 40) by Frontiers Media SA has two articles, showing a significant presence in educational research. Additionally, emerging journals such as the *Journal of Metaverse* (H-Index: 10) by the Izmir Academy Association reflect growing interest in new research areas.

Table 4. Most relevant source journal

Publisher	Sources (H-Index)	Articles
"Auricle Global Society of Education and Research"	Review of Contemporary Philosophy (H-Index: 15)	7
"Auricle Global Society of Education and Research"	Linguistic and Philosophical Investigations (H-Index: 17)	4
"Institute of Electrical and Electronics Engineers Inc."	IEEE Transactions on Learning Technologies (H-Index: 62)	3
"Frontiers Media SA"	Frontiers in Education (H-Index: 40)	2

Publisher	Sources (H-Index)	Articles
"Izmir Academy Association"	Journal of Metaverse (H-Index: 10)	2
"Association for Computing Machinery (ACM)"	Acm Computing Surveys (H-Index: 213)	1
"Auricle Global Society of Education and Research"	Analysis and Metaphysics (H-Index: 17)	1
"Multidisciplinary Digital Publishing Institute (MDPI)"	Applied Sciences (Switzerland) (H-Index: 130)	1
"Springer Netherlands"	Artificial Intelligence Review (H-Index:115)	1
"Australasian Society for Computers in Learning in Tertiary Education"	Australasian Journal of Educational Technology (H-Index: 68)	1

The Keyword Trends and Network Visualization

Figure 6 presents a network visualization from VOSviewer, illustrating the relationships between keywords in metaverse-related research and highlighting strong connections with various concepts such as Augmented Reality, Artificial Intelligence, Machine Learning, Bibliometric Analysis, and Science Education. The keyword "metaverse" serves as the central node in the network map, with strong ties to multiple themes, as indicated by interconnected lines. Keywords like "bibliometric analysis" and "science education" show significant relationships with metaverse studies, suggesting that research in this domain not only focuses on technological aspects but also explores its applications in education, particularly in the context of science learning. However, bibliometric studies directly related to science education are not yet evident, indicating a gap in research specifically addressing science education through bibliometric analysis.

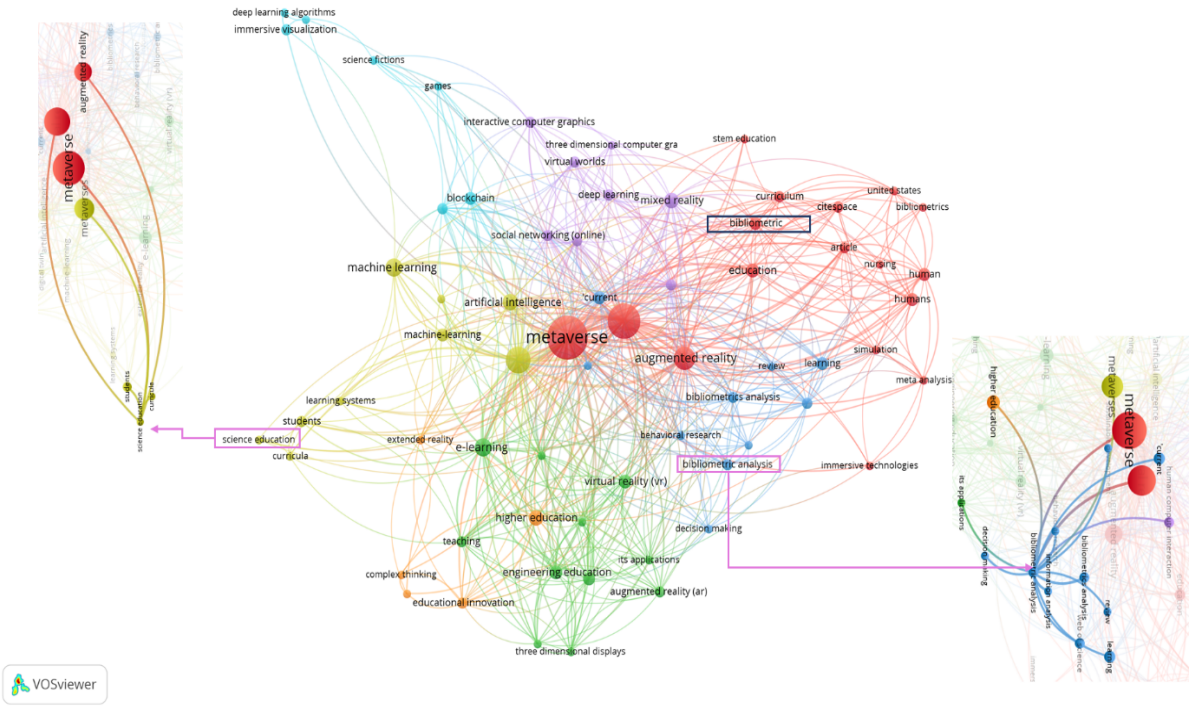

Figure 6. Network visualization of metaverse

From the analysis of keyword relationships, it is evident that metaverse research spans various academic disciplines, extending beyond technological aspects to include pedagogical approaches and higher education. Keywords such as "e-learning," "virtual reality," "higher education," and "learning systems" underscore the metaverse's potential to create more immersive and interactive learning environments. Additionally, connections with "complex thinking" and "decision making" suggest that metaverse research also addresses the development of students' cognitive skills. Thus, the research trend is moving toward exploring how the metaverse can enhance technology-based learning while supporting innovation in educational methodologies. This highlights the growing importance of the metaverse in shaping future educational practices and its potential to transform learning experiences.

The Three-Field Plot

Figure 7 presents a Three-Field Plot that illustrates the interconnections among three primary elements in the research: keywords plus on the left, publication sources in the center, and the authors' countries of origin on the right. From this visualization, it is evident that several prominent keywords, such as "metaverses," "e-learning," "augmented reality," and "machine learning," exhibit strong associations with various journals and conferences, including *IEEE Transactions on Learning Technologies* and *Contemporary Educational Technology*. This indicates that innovative technologies in education are a widely studied and published topic across diverse academic sources. Furthermore, keywords related to emerging trends in educational technology, such as "blockchain" and "mixed reality," are also linked to multiple journals, reflecting the growing interest in leveraging new technologies to enhance learning.

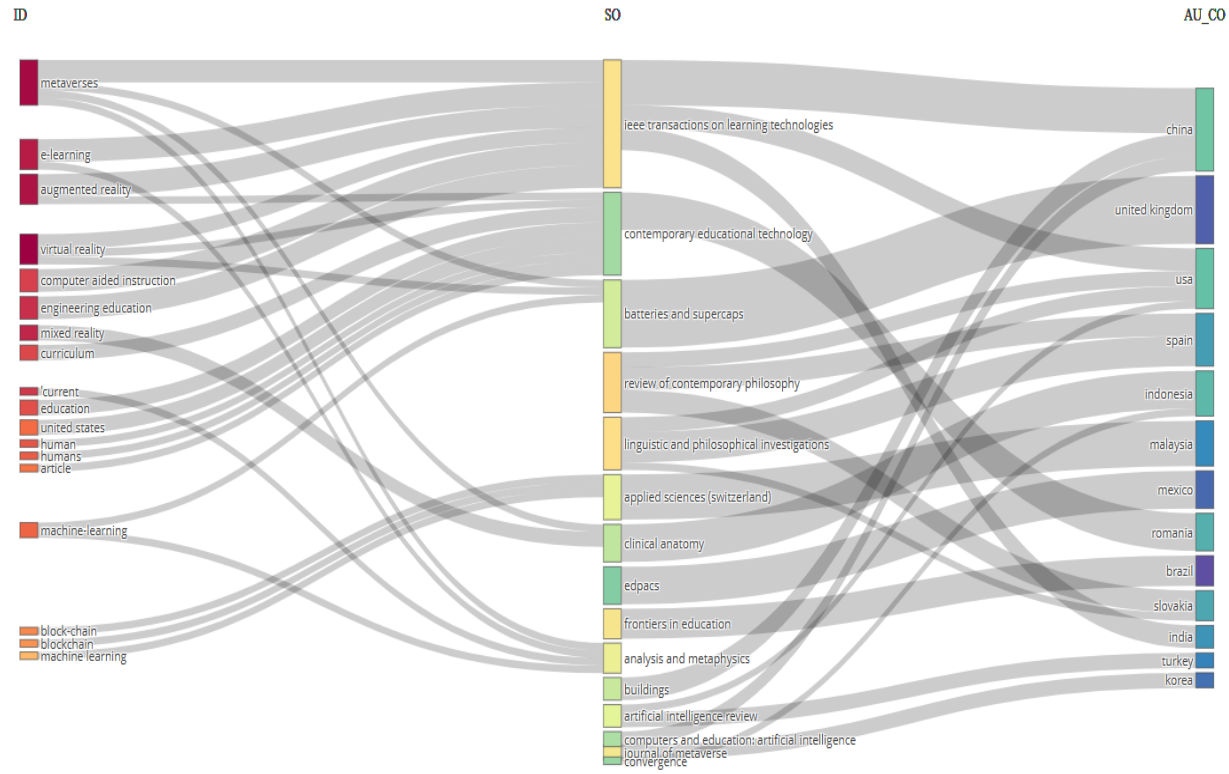

Figure 7. Three-field plot (left field: keywords plus; middle field: sources; right field: countries)

The Review of Top-Cited Articles of Metaverse

Table 5 presents a list of publications related to the topics of educational technology and the metaverse, detailing information such as DOI or links, total citations (TC), citations per year (TCPY), and normalized total citations (NTC). From the table, it is evident that the paper with the highest number of citations is *HWANG G-J, 2022, COMPUT EDUC*, with 420 citations and a TCPY of 105, indicating a significant impact within the academic community. Additionally, the papers *DAMAR M, 2021, J METAVERSE* and *NARIN NG, 2021, J METAVERSE* also exhibit substantial citation counts, with 180 and 155 citations respectively, suggesting that research on the metaverse has begun to garner significant attention in recent years.

Tabel 5. Top cited paper

Paper	DOI/Link	TC	TCPY	NTC
HWANG G-J, 2022, COMPUT EDUC	10.1016/j.caeai.2022.100082	420	105.00	6.57
DAMAR M, 2021, J METAVERSE	https://dergipark.org.tr/en/pub/jmv/issue/67581/1051371	180	36.00	1.07
NARIN NG, 2021, J METAVERSE	https://dergipark.org.tr/en/pub/jmv/issue/67581/1051382	155	31.00	0.93
KADDOURA S, 2023, PEERJ COMPUT SCI	10.7717/peerj-cs.1252	116	38.67	10.28
NG DTK, 2022, AUSTRALAS J EDUC TECHNOL	10.14742/ajet.7945	90	22.50	1.41
MARINI A, 2022, INT J INTERACT MOB TECHNOL	10.3991/ijim.v16i07.25727	50	12.50	0.78
ZHAO J, 2022, FRONT PUBLIC HEALTH	10.3389/fpubh.2022.906715	38	9.50	0.59
ZVARIKOVA K, 2022, REV CONTEMP PHILOS	10.22381/RCP21202211	37	9.25	0.58
LI H, 2024, WIRELESS NETWORKS	10.1007/s11276-022-03000-1	34	17.00	4.18
WIDER W, 2024, INT J HUM-COMPUT INTERACT	10.1080/10447318.2023.2227825	32	16.00	3.94

"TC: Total citation, TCPY: Total citation per year, NTC: Normalized total citation"

Further analysis reveals that more recent publications, such as *KADDOURA S, 2023, PEERJ COMPUT SCI*, demonstrate a relatively high TCPY (38.67) and an NTC of 10.28, indicating that despite their recent publication dates, these works have already made a considerable impact compared to older publications. Moreover, papers published in technology-focused journals, such as *AUSTRALAS J EDUC TECHNOL* and *WIRELESS NETWORKS*, show strong citation metrics, reflecting the ongoing growth and development of research in this field. Overall, the data highlight a rapidly expanding research trend in educational technology and the metaverse, with several papers achieving substantial influence within the scientific community, as evidenced by their high citation counts.

Discussion

Staying updated with the latest information in a specific research field or topic is crucial as it provides insights into emerging trends, evolving methodologies, and recent findings that can enrich understanding and support further research (Kumar, 2025; Zhu & Liu, 2020). By keeping abreast of the latest developments, researchers can identify research gaps, update theoretical frameworks, and adopt innovative approaches that have proven effective in previous studies. Additionally, up-to-date information helps avoid duplication of research efforts and ensures that contributions remain highly relevant within the academic community (Longo et al., 2024). Exploring recent advancements in a field also facilitates better collaboration with other researchers and expands opportunities for publication in reputable journals (Akçayır & Akçayır, 2017; Vrontis et al., 2023). By understanding the direction of ongoing research, academics and practitioners can anticipate future challenges and develop more relevant and applicable solutions.

Bibliometric analysis serves as an excellent tool for presenting the main information of a studied topic (see Table 2). The overview of information provided on the topic of the metaverse in education can guide further research and help identify underexplored research gaps. According to Bankins et al. (2022); Schoenfeld (2010), the presented information also plays a role in supporting decision-making, both in academic and practical contexts. One key reference in this regard is the number of annual publications. In this study, annual publications are presented from 2021 to 2024. Research on the metaverse experienced a significant surge in 2023 due to several key factors, including technological advancements and global interest in virtual world concepts such as AI, blockchain, VR, and AR, all of which contribute to the development of the metaverse. Furthermore, following the COVID-19 pandemic, the metaverse has increasingly been viewed as a potential solution for various sectors, including education (Zhang et al., 2022), business (Koohang et al., 2023), and entertainment (Dwivedi et al., 2022). Many educational institutions and companies have begun experimenting with virtual learning and meetings in metaverse environments, prompting increased research into their effectiveness and user impact (Bale et al., 2022; Shu & Gu, 2023). With numerous conferences, publications, and research projects dedicated to exploring the potential and challenges of the metaverse, 2023 marked the peak of academic exploration in this field.

As the metaverse continues to evolve in the context of science education, international collaboration has become a key strategy for advancing this technology collectively (Bibri, 2022). As shown in (see Table 3), China has emerged as the leading contributor in terms of the volume of publications in the field of the metaverse. This dominance underscores the country's significant investment and focus on advancing research and innovation in this cutting-edge domain. The contributions from Chinese researchers and institutions not only drive the global discourse on the metaverse but also position China as a key player in the ongoing development and implementation of metaverse-related technologies (De Masi et al., 2025b, 2025a). However, Romania stands out as the country with the highest number of collaborations. This is attributed to the fact that, as of 2022, only a small percentage of individuals with digital skills in Romania had experimented with metaverse applications, and even fewer had invested in metaverse-related topics (Chinie et al., 2022).

A cornerstone of research lies in the affiliations and the researchers themselves. As academic hubs, universities provide facilities, resources, and supportive environments that enable researchers to conduct scientific exploration (Smith & Bagchi-Sen, 2012; Soetanto & Jack, 2016). Through collaborations among researchers, both within the same institution and across universities, research can progress more rapidly and yield broader impacts. Additionally, university support in the form of funding, laboratory access, and subscriptions to scientific journals significantly contributes to the quality and relevance of the research conducted (McKiernan et al., 2016; Reed et al., 2007). Although China dominates in the field of the metaverse in science education, the University of Zilina in Slovakia has the highest number of publications in this area, followed by Jakarta State University in Indonesia. This highlights their significant contributions to academic publications on this topic, indicating that research on the metaverse in science education is gaining increasing attention worldwide. Furthermore, it reflects a global effort to explore and develop metaverse technology as part of educational innovation.

As illustrated in Figure 5, many authors have contributed a balanced number of publications, suggesting significant potential for further collaboration to strengthen the research network. This reflects that the topic has garnered widespread attention and is continuously evolving across various institutions and countries. With a relatively even distribution of publications among authors, there is substantial opportunity for further collaboration to foster a more robust research network and produce deeper, more impactful studies. Such collaboration could accelerate innovation and expand the global reach of the research (He & Wong, 2012; Srivastav et al., 2024). By combining multidisciplinary perspectives and facilitating access to a broader range of resources and technologies, these partnerships could significantly enhance the quality and scope of research. Therefore, establishing a strong academic network through international collaborations is key to advancing this field, particularly the topic of the metaverse in science education (Singh et al., 2024; Suzuki et al., 2020).

Furthermore, to ensure the credibility of the research outcomes, it is essential to publish in reputable, internationally recognized journals. The top 10 journals publishing research on the metaverse between 2021 and 2024 (see Table 4) are all indexed in Scopus (Q1=8; Q2=2). According to Montoya et al. (2018); Pranckutė (2021), Scopus is considered one of the most trusted indexing databases in the world for scientific research. Scopus covers a wide range of renowned international journals, conference proceedings, and citation data, allowing researchers to track the influence and impact of their work within the global academic community. As a leading platform, Scopus is frequently used by universities, research institutions, and publishers to assess the quality and impact of research (Pranckutė, 2021; Sabah et al., 2019; Schotten et al., 2017). Therefore, publishing research in journals indexed by Scopus provides valuable exposure and establishes it as a reliable reference for researchers worldwide.

In bibliometric studies, network visualization plays a crucial role in predicting and identifying research gaps within a specific topic (Amiruddin et al., 2025). While bibliometric analyses have been conducted on the metaverse, there has yet to be a study that specifically addresses trends in the field of science education. However, research in science education utilizing the metaverse does exist. By mapping the landscape, as shown in Figure 6, it becomes evident that there are opportunities for further exploration of the intersection between the metaverse and science education. For instance, the use of

extended reality (XR) in science education, which currently lacks proper network connectivity, presents a promising area for future research. However, such studies require careful preparation to support the integration of technology into education, particularly in creating efficient and accessible platforms for educators and learners (Haleem et al., 2022; Thomas, 2016). Adequate preparation is also crucial to ensure the availability of the necessary technological infrastructure and the development of curricula that align with XR-based learning needs. Consequently, this area of study holds the potential to make a significant contribution to the future transformation of science education.

In terms of the authors' countries of origin, it is apparent that publications related to educational technology and innovation originate from a wide range of countries, including China, the United States, the United Kingdom, and Indonesia. This suggests that research in this field is global in scope and attracts attention from various regions worldwide. For instance, IEEE Transactions on Learning Technologies appears to be a primary source for research originating from China and the United Kingdom, while journals such as Applied Sciences (Switzerland) are associated with research from Mexico and Brazil. The connections between countries and publication sources reflect patterns of academic collaboration as well as global trends in educational technology research (Bardakci et al., 2022; Hsu et al., 2013). Overall, this diagram provides valuable insights into how key concepts in educational technology are distributed within the scholarly literature and how specific countries contribute to the advancement of this field.

The impact of citations on research is highly significant, as citations reflect the recognition and influence of a scholarly work within the academic community. The article by Hwang and Chien (2022), published in Computers & Education, has an exceptionally high total citation count of 420, with a citations-per-year (CPY) rate of 105, indicating its substantial influence in the field of technology-enhanced education. This work has become a key reference in the development of educational technology, particularly in the application of extended reality (XR) in science education. On the other hand, the article by Damar (2021), with a total citation count of 180 and a CPY of 36, demonstrates that, although relatively recent, this research has garnered significant attention in the field of the metaverse, contributing to advancements in digital education. Similarly, the article by Narin (2021), with a total citation count of 155 and a CPY of 31, reflects a more limited yet still respected relevance within the scientific community. The work by Kaddoura and Al Husseiny (2023), with a total citation count of 116 and a CPY of 38.67, represents a relatively new but increasingly recognized contribution. The variation in citation counts highlights that while newer articles may not yet have achieved the same level of citation as older ones, they are gradually gaining recognition over time. This suggests that relevant and innovative research can rapidly gain traction. Overall, citations serve as a measure of a study's impact, with higher citation counts indicating greater contributions to the advancement of science and technology.

CONCLUSION

Fundamental Finding: The bibliometric analysis of metaverse-related research in science education reveals significant publication growth from 2021 to 2024, with an annual growth rate of 100%. This indicates that the field is evolving rapidly, reflecting growing academic interest in integrating the Metaverse into educational contexts. The United

States and China are the most productive countries, though their research patterns differ significantly, with China focusing on national studies and the U.S. engaging more in international collaborations. Key thematic areas include augmented reality (AR), machine learning, and science education, which strongly emphasize technology-driven learning. The study also identified a notable gap in bibliometric studies focusing specifically on science education within the Metaverse, highlighting an area ripe for further exploration. **Implication:** The findings have important implications for both researchers and educators. As Metaverse technologies continue to shape the future of education, understanding the evolving research landscape can guide future academic inquiries and policy-making. Researchers can build on the identified trends and gaps, particularly in exploring the applications of the Metaverse in science education. Furthermore, the results underline the potential for international collaboration, with countries like the U.S. showing a global research approach. This could foster a more interconnected academic community that accelerates innovation in educational technology. **Limitation:** One limitation of this study is that it only analyzed articles published from 2021 to 2024, potentially excluding valuable early-stage insights. Additionally, the analysis was restricted to published articles, which may not capture the full spectrum of research, including conference papers or grey literature. **Future Research:** Future studies should aim to explore the pedagogical outcomes of Metaverse-based learning environments in science education, assessing their effectiveness in fostering engagement, learning outcomes, and critical thinking. Longitudinal studies could offer deeper insights into how Metaverse technologies evolve and impact educational practices.

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