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Trends and Impact in Virtual Science Lab: A Bibliometric Analysis

Trend dan Kesan dalam Makmal Sains Maya: Analisis Bibliometrik

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ABSTRACT

This paper presents a bibliometric analysis overview of virtual science laboratories, focusing on 1393 articles published between 1990 and 2024 from the SCOPUS database. The main aim of this study was to identify the growth trend, key collaborations between authors, institutions, and countries and identify prominent themes and keyword in the field. Based on the findings, an increasing trend in the number of publications related to virtual science laboratories was found for the last thirty years with Achutan, K. as the most prominent author, and the United States as leading contributor. In addition, the Amrita University (India), Massachusetts Institute of Technology (US) and University of Patras (Greece) were among the top universities to have contributed to publications. Furthermore, Computer Science, Social Sciences and Engineering feature most prominently in virtual science laboratories. Four major thematic focus emerge: laboratory, virtual, education, and student. The authors recommend future research exploring artificial intelligence in virtual science labs, enhancing accessibility for students with disabilities, infrastructure and training improvements in school and understanding the impact of digitalisation on teachers and student's well-being. Additionally, they suggest studying ethical issue and gaining qualitative insights into students' experiences and satisfaction with virtual science labs are essential.

Keywords: trends; virtual lab; science; bibliometric; analysis

ABSTRAK

Artikel ini melaporkan gambaran keseluruhan analisis bibliometrik tentang makmal sains maya dengan memberi fokus pada 1393 artikel yang diterbitkan antara tahun 1990 hingga 2024 daripada pangkalan data SCOPUS. Matlamat utama kajian ini adalah untuk mengenal pasti perkembangan, kerjasama utama antara pengarang, institusi dan negara serta mengenal pasti tema dan kata kunci yang menonjol dalam bidang tersebut. Berdasarkan penemuan penyelidik, terdapat peningkatan dalam bilangan penerbitan yang berkaitan dengan makmal sains maya sejak tiga puluh tahun yang lalu dengan Achutan, K. sebagai pengarang paling terkemuka, dan Amerika Syarikat, Jerman dan China sebagai penyumbang utama. Selain itu, Universiti Amrita (India), Institut Teknologi Massachusetts (AS) dan Universiti Patras (Greece) adalah antara universiti terkemuka yang menyumbang kepada penerbitan artikel dalam bidang ini. Tambahan pula, kajian dalam bidang Sains Komputer, Sains Sosial dan Kejuruteraan paling menonjol dalam makmal sains maya. Empat fokus tematik utama muncul iaitu: makmal, maya, pendidikan dan pelajar. Penyelidik mencadangkan supaya penyelidikan masa depan meneroka tentang kecerdasan buatan dalam makmal sains maya, kebolehcapaian untuk pelajar kurang upaya, penambahbaikan infrastruktur dan latihan di sekolah dan memahami kesan pendigitalan terhadap kesejahteraan guru dan pelajar. Selain itu, penyelidik juga mencadangkan agar kajian seterusnya mengkaji isu etika dengan mendapatkan data kualitatif tentang pengalaman pelajar dan kepuasan mereka apabila menggunakan makmal sains maya.

Kata kunci: trend; makmal maya; sains; bibliometrik; analisis

INTRODUCTION

In the last few decades, technology has changed the system of education drastically, especially the ways science education is taught (Kiong, 2023). Remarkably, in higher education, educators have ground-breaking scope to improve learning and teaching through the virtual tools and e-learning platforms' (Mashau & Nyawo, 2021; Naim, 2021; Ouadoud et al., 2021; Veeramanickam & Ramesh, 2022) extensive applications, as in this stage of higher education, achieving a strong knowledge foundation is necessary. Significantly, according to Heradio et al. (2016), among these advances, virtual science labs serve as an effective way to increase conventional interactive laboratory experiences, particularly in the face of difficulties illustrated by safety issues, time limits and scarce resources associated with physical laboratories (Raman et al., 2021). At the same time, the rise in the applications of combined learning strategies that centers on traditional face-to-face training and incorporates online components has changed the ways of teaching science. Moreover, as technological innovations shape educational practices, therefore, the integrated laboratory technique becomes popular as an appropriate model of pedagogy (Radhamani et al., 2021). The researchers' discussion in this article is concentrated on the five most recent publications that have been cited the most for their theoretical, methodological, and practical contributions. The results of this bibliometric analysis provide knowledge about the following research questions:

RQ1. What were the growth trends and influences in virtual science labs research?
RQ2. Who were the most productive authors, institutions and countries in these domains (virtual science lab)?
RQ3. What were the dominant themes and keywords in virtual science lab research?
RQ4. Which article had made the most significant impact in this field?

METHODOLOGY

The research problem addressed in this paper focused on analysing and understanding the growth, development, and impact of virtual science laboratories in education. To retrieve and analyse 1393 articles related to the virtual lab approach, a comprehensive Scopus database search was conducted from 1986 to 2024 by two reviewers. The Scopus database was selected as a primary source for this bibliometric study because it offered extensive multidisciplinary coverage and adhered to strict inclusion criteria that ensured data consistency and quality for standardised results (Pirri et al., 2020). Ultimately, only 1387 articles were analysed after 6 were removed due to errors and database record corrections.

The researchers have retrieved and analysed electronically accessible data retrospectively for this bibliometric analysis, as illustrated in Figure 1. Importantly, every selected journal and article was relevant to the subject matter, language, and document type. Interestingly, the researchers did not restrict the analysis of 1387 papers to social science genre because virtual science laboratory research was highly multidisciplinary, encompassing education, STEM, engineering, computer science, medical and health sciences. Restricting the anlysis to a single field would have distorted the findings and weakened the predictive value of publication trends. In addition, journals of mathematics, medicines, economics, engineering and computer sciences were evaluated to ensure that no articles associated with the term “virtual science lab” were overlooked.

The search fields included keywords, abstracts and article titles. Furthermore, the 1387 articles were examined based on publication year, affiliated institutions, authors, geographical distribution, and source journal. Articles lacking essential details, such as authorship, publication date, errata or those with restricted access, were excluded.

From the 1387 records used to evaluate bibliographical information, two analytical techniques were applied. These widely used methods included performance analysis using Publish or Perish and Science Mapping via VOSviewer. Performance analysis, by measuring the frequency with which specific works were cited, assessed the influence of scientific contributors (e.g., journals and researchers) on the topic. The H-index was the most commonly used citation metric for determining the impact of these publications. Meanwhile, science mapping described the research landscape and visually represented its thematic structure, helping to illustrate the dynamic and structural features of the field (Eugenio Petrovich, 2022). Additionally, this bibliometric analysis applied co-word analysis which measured the conceptual relationships between published terms to outline the domain of virtual science laboratory research (Heradio et al., 2016). Citation reports were also generated to evaluate whether the selected articles were indexed in the "Science Citation Index Expanded" or the "Science Citation Index (SCI)". Simultaneously, several influencing factors associated with publication year were collected, including publication growth, source titles, authorship patterns, keyword trends, citation metrics, institutional affiliations and country contributions.

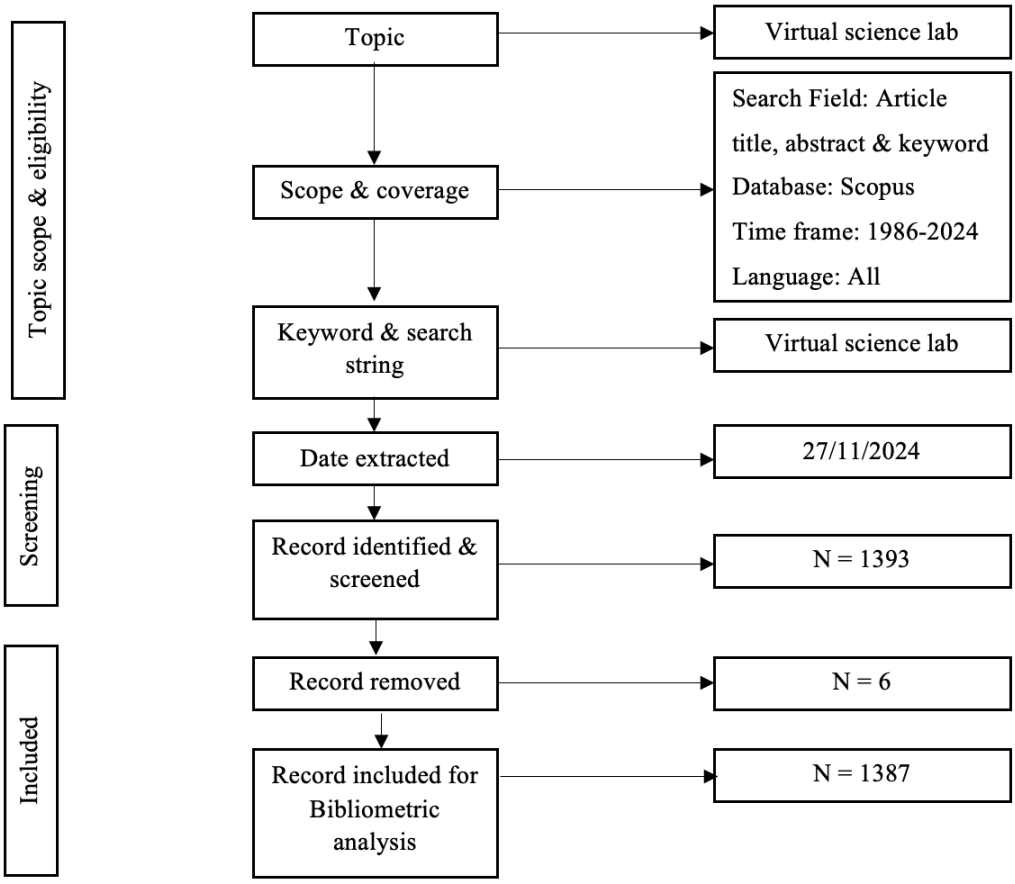

FIGURE 1. Bibliometric data collection process (PRISMA protocols).

RESULTS AND DISCUSSION

PUBLICATION'S GROWTH BY YEAR

To address RQ1 (What were the growth trends and influences in virtual science labs research?), the 1393 publications and their citations for the period 1986 to November 2024 were ranked, as shown in Table 1 and Figure 2. It was noted that scholars began paying attention to studies related to online laboratories as early as 1986. However, from 1986 to 2000, only an average of one to two publications per year were produced. From 2001 to 2010, research activity remained limited, with an average of five to ten publications annually. A marked increase occurred between 2011 and 2020, with more than 50 publications per year. This upward trajectory continued from 2021 to 2024, during which annual publications exceeded 100. Over the decades, the total number of publications increased steadily, with a particularly notable rise in recent years. This pattern was consistent with earlier bibliometric studies by Heradio et al. (2016) and Raman et al. (2022), which also reported growth in virtual laboratory research. The surge particularly aligned with the global shift toward online education during the COVID-19 pandemic. Notably, 2021 recorded the highest number of publications (122) and citations, marking the pandemic's strong influence on research priorities. The same year also showed the highest number of citations for publications (NCP:99).

On the other hand, 2016 recorded the highest total citations (TC:1627), the highest average citations per publications (C/CP:27.12) and the highest average citations per cited publication (C/CP:33.20), as well as the highest g index of 40. Additionally, both the average citations per publication (C/CP) and citations per publication (C/P) exhibited a year-by-year increase, suggesting that higher quality publications were receiving more citations. Similarly, total citations and the number of cited publications also rose, indicating an expanding influence of research outputs in this domain. Furthermore, the H-index, which measured impact and productivity, increased steadily over time, reflecting growing scholarly influence in virtual science laboratory research. Although the annual growth rate of publications fluctuated due to factors such as international collaboration, shifting research trends and varying funding availability, the overall trend remained strongly positive.

TABLE 1. Growth of publication by year

Year	TP	%	NCP	TC	C/P	C/CP	h	g
2024	105	5.24%	2	5	0.07	2.50	2	2
2023	107	1.48%	28	79	0.72	2.82	5	6
2022	106	1.43%	68	275	2.59	4.04	7	11
2021	122	1.65%	99	981	8.04	9.91	16	26
2020	81	1.09%	66	712	8.79	10.79	15	23
2019	89	1.20%	73	1461	16.42	20.01	14	36
2018	68	0.92%	54	1147	16.87	21.24	14	33
2017	57	0.77%	46	602	10.56	13.09	13	23
2016	60	0.81%	49	1627	27.12	33.20	15	40
2015	61	0.82%	47	1155	18.93	24.57	18	33
2014	67	0.90%	51	872	13.01	17.10	13	28
2013	54	0.73%	41	617	11.43	15.05	12	23
2012	64	0.86%	51	722	11.28	14.16	13	25
2011	51	0.69%	40	517	10.14	12.93	11	21
2010	39	0.53%	27	607	15.56	22.48	9	24
2009	50	0.67%	34	618	12.36	18.18	14	24
2008	34	0.46%	28	821	24.15	29.32	11	28
2007	26	0.35%	22	621	23.88	28.23	8	22

2006	24	0.32%	19	410	17.08	21.58	9	19
2005	31	0.42%	21	261	8.42	12.43	8	15
2004	19	0.26%	15	380	20.00	25.33	8	15
2003	16	0.22%	13	285	17.81	21.92	7	13
2002	17	0.23%	14	282	16.59	20.14	5	14
2001	14	0.19%	12	151	10.79	12.58	5	12
2000	7	0.09%	7	111	15.86	15.86	5	7
1999	5	0.07%	5	35	7.00	7.00	4	5
1998	5	0.07%	5	36	7.20	7.20	4	5
1997	4	0.05%	3	19	4.75	6.33	2	3
1996	1	0.01%	0	0	0.00	0	0	0
1995	2	0.03%	1	6	3.00	6.00	1	1
1990	1	0.01%	1	8	8.00	8.00	1	1
1986	1	0.01%	0	0	0.00	0	0	0

Notes: TP = total number of publications; NCP = number of cited publications; TC = total citations; C/P = average citations per publication; C/CP = average citations per cited publication; h = h-index; g = g-index

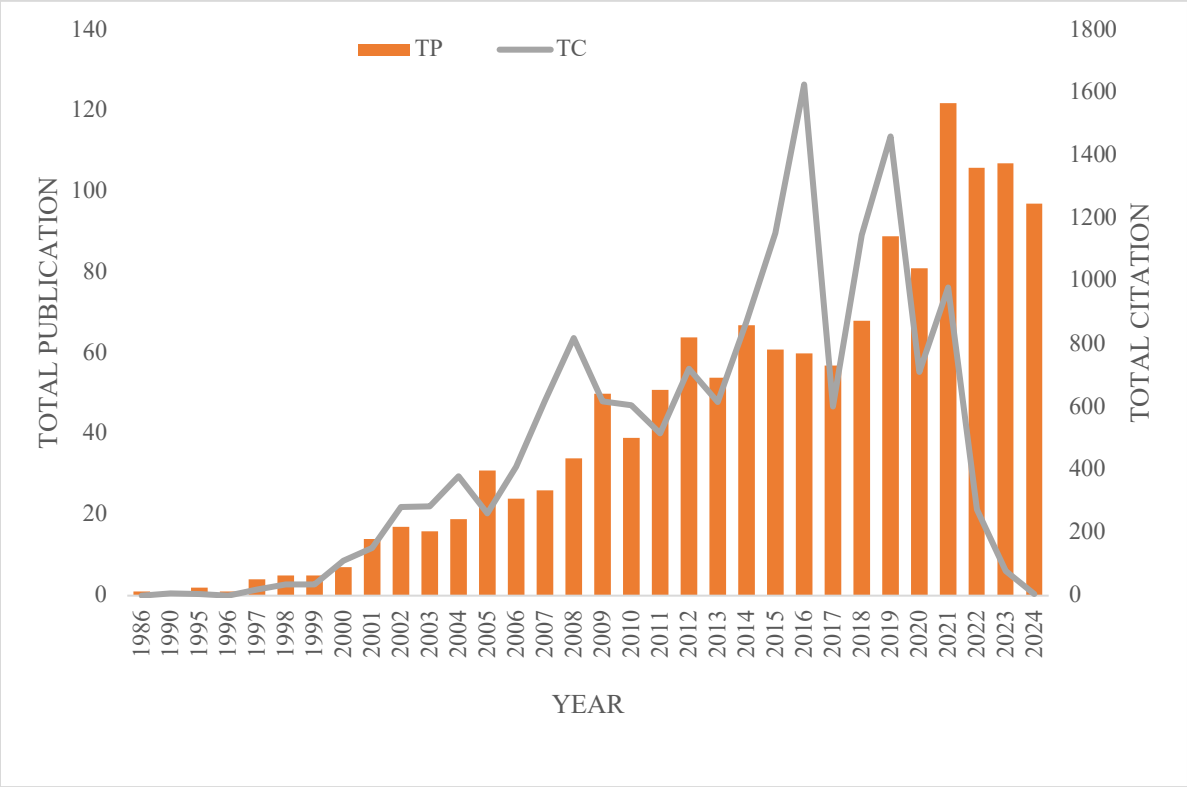

FIGURE 2. Total publications and citations by year

An examination of journal development over time revealed a consistent trend towards amplified research outputs in terms of impact, quality, and quantity. These outputs indicated a robust and expanding body of work in virtual science laboratory research. Virtual scientific laboratories emerged as one of the most effective methods for teaching and learning science topics, as demonstrated by the steady growth of related journal publications, particularly the notable increase in recent years. From 1991 to 2000, research primarily focused on computer-aided instruction and simulation. However, between 2001 and 2010, the focus shifted towards remote access to engineering laboratory equipment. Virtual reality then became increasingly prominent in computer programming, virtualization, and virtual laboratories from 2010 to 2021 (Raman et al.,

2022). By 2023 and 2024, researchers directed greater attention to blended laboratory approaches (Agustina & Putra, 2022; Dirgantara et al., 2024; Mihret et al., 2022), resulting in a temporary decline in research volume. Continued investigation and deeper analysis remained essential to fully comprehend the potential for future advancements and contributions to the scientific community.

PUBLICATIONS BY COUNTRIES, INSTITUTION AND AUTHOR

Publishing analysis was used to identify the major countries that contributed to virtual science laboratory research in order to address RQ2 (Who were the most productive authors, institutions and countries in the domains?). The United States emerged as the foremost contributor to entire publications, accounting for 450 of the overall outputs, as shown in Table 2. This finding was consistent with the result reported by Raman et al. (2022). Such dominance reflected the country's strong research ecosystem, its emphasis on innovation, and the availability of extensive funding opportunities across multiple fields. The top ten countries represented diverse geographical regions, with contributions from Asia, Europe, and North America. This distribution highlighted the global landscape of knowledge exchange and scientific collaboration, with research impacts dispersed across both developed and developing nations. Several countries, including Germany (TP:102), China (TP:83), India (TP:81), the United Kingdom (TP:69), Spain (TP:58), Italy (TP:46), Greece (TP:41), Netherlands (TP:34) and Canada (TP:29) featured prominently in the top ten list. These countries show comparatively high average citations per cited publication (C/CP) and average citation per publication (C/P), reflecting active research environments and strong support for academic activities.

TABLE 2. Total Publication by Country Top 10

Country	TP	%	NCP	TC	C/P	C/CP	h	g	Continent
United States	450	32.89%	429	6900	15.47	16.08	41	74	North America
Germany	102	7.45%	101	1268	12.55	12.55	18	33	Europe
China	83	6.12%	82	516	6.22	6.29	12	20	Asia
India	81	5.75%	75	499	6.40	6.65	12	19	Asia
United Kingdom	69	5.09%	66	1908	27.65	28.91	20	43	Europe
Spain	58	4.28%	56	1012	17.45	18.07	12	31	Europe
Italy	46	3.32%	45	365	8.11	8.11	10	18	Europe
Greece	41	2.95%	40	622	15.55	15.55	11	24	Europe
Netherlands	34	2.43%	33	879	26.64	26.64	15	29	Europe
Canada	29	2.06%	27	379	13.54	14.04	10	19	North America

Notes: TP = total number of publications; NCP = number of cited publications; TC = total citations; C/P = average citations per publication; C/CP = average citations per cited publication; h = h-index; g = g-index

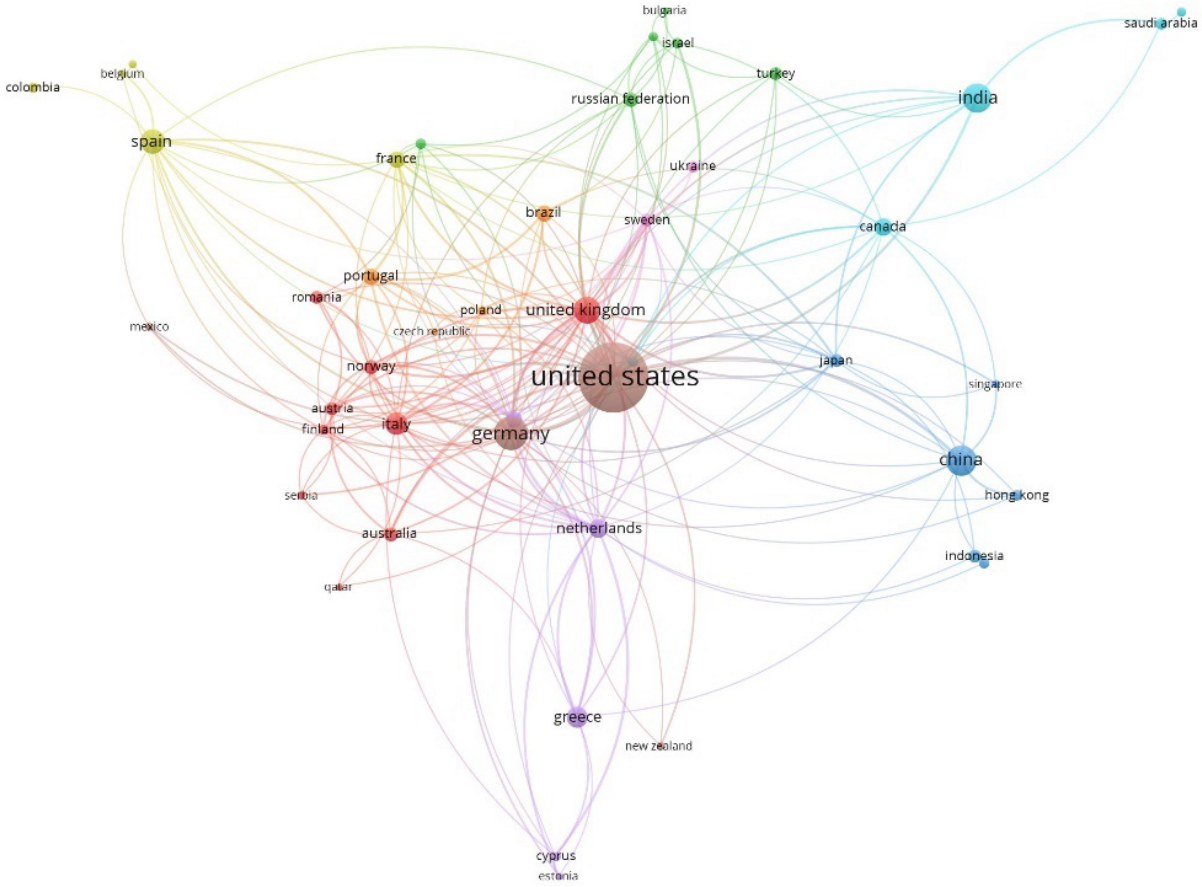

FIGURE 3. Network visualisation map of the co-authorship based on countries that have a minimum of five number of citations and five number of documents (full counting)

The United States led the world in journals publications, with a total of 450 publications, representing the nation's substantial contribution to international research, as shown in Figure 3. Achuthan, K. from the Amrita University (India) had notably high journal counts (13 publications) and citation rates (NCP:145), reflecting the significant impact of the research produced. The facts that research communities collaborate to generate scholarly work, exchange data, and operate across institutional and disciplinary boundaries demonstrated that these communities were part of a broad international network. This investigation also highlighted an important finding: the existence of a "North-South gap." A deeper understanding of research needs was required, as it was found that countries located north of the equator contributed far more research outputs than those in the south. Additionally, attention was drawn to the limited volume of research originating from African countries (Shambare & Jita, 2025).

Authorship analysis was used to identify key institutions and authors to address RQ2 (Who were the most productive authors, institutions and countries in these domains (virtual science lab)?). The findings of the investigation revealed a diverse set of affiliation involving academic institutions from countries such as the US, Greece, India, Germany and Austria, as shown in Table 3. This diversity highlighted the global collaboration and information exchange that occurred among scholars from different institutions and regions. Numerous authors contributed significantly to the literature, with notable citation impacts and high publication counts. For

example, Raman, R. affiliated with the Massachusetts Institute of Technology (US) and Achuthan, K. from Amrita University (India), recorded particularly high publication numbers and citation rates, demonstrating the influence of their research outputs. Authors such as Nedungadi, P. affiliated with University of Patras (Greece) and Diwakar, S. affiliated with the Rutgers University–New Brunswick (US) also established collaborations across international borders, contributing to the global dissemination of knowledge. Achuthan, K. recorded an approximate 46.3% open access rate compared with Raman, R. and Vavougios, D. who recorded approximately 1.4%, while Nedungadi, P. and Diwakar, S recorded approximately 0.4%.

TABLE 3. Authorship Analysis

Author Name	TP	%	Affiliation	Country	NCP	TC	C/P	C/CP	h	g
Achuthan, K.	13	0.96%	Amrita University, Amritapuri Campus	INDIA	12	145	11.15	12.08	6	12
Raman, R.	11	0.81%	Massachusetts Institute of Technology	US	11	135	12.27	12.27	6	11
Nedungadi, P.	10	0.74%	University of Patras	GREECE	10	135	13.50	13.50	6	10
Diwakar, S.	9	0.66%	Rutgers University–New Brunswick	US	9	139	15.44	15.44	5	9
Vavougios, D.	9	0.66%	Purdue University	US	9	29	3.22	3.22	3	4
Kalles, D.	8	0.59%	Rheinisch-Westfälische Technische Hochschule Aachen	GERMANY	8	47	5.88	5.88	4	6
Gobert, J.	7	0.52%	University of Thessaly	GREECE	7	24	3.43	3.43	3	4
Zutin, D.G.	7	0.52%	Carinthia University of Applied Sciences	AUSTRIA	7	56	8.00	8.00	5	7
Auer, M.E.	6	0.44%	University of Wisconsin-Madison	US	6	55	9.17	9.17	5	6
Ioannidis, G.S.	6	0.44%	Pennsylvania State University	US	6	23	3.83	3.83	3	4

Authors differ significantly in terms of the number of documents they supported and the citations their work received, as shown in Figure 4 below. Among the researchers listed, several notable findings emerged. Achuthan, K. (13 documents and 145 citations) demonstrated a considerable level of productivity and impact. Nedungadi, P. showed a strong presence with 10 documents and 135 citations, indicating sustained influence and scholarly output. The total link strength represented the degree of collaborative co-authorship or the strength connections between authors. Research collaboration was observed between Achutan, K., Nair, B. and Diwakar, S. reflecting strong teamwork and impactful research result. Similarly, collaborative links existed between Raman, R. and Nedungadi, P., although to a lesser extent. Overall, these researchers displayed notable connection strength, signifying dynamic partnerships within the academic community.

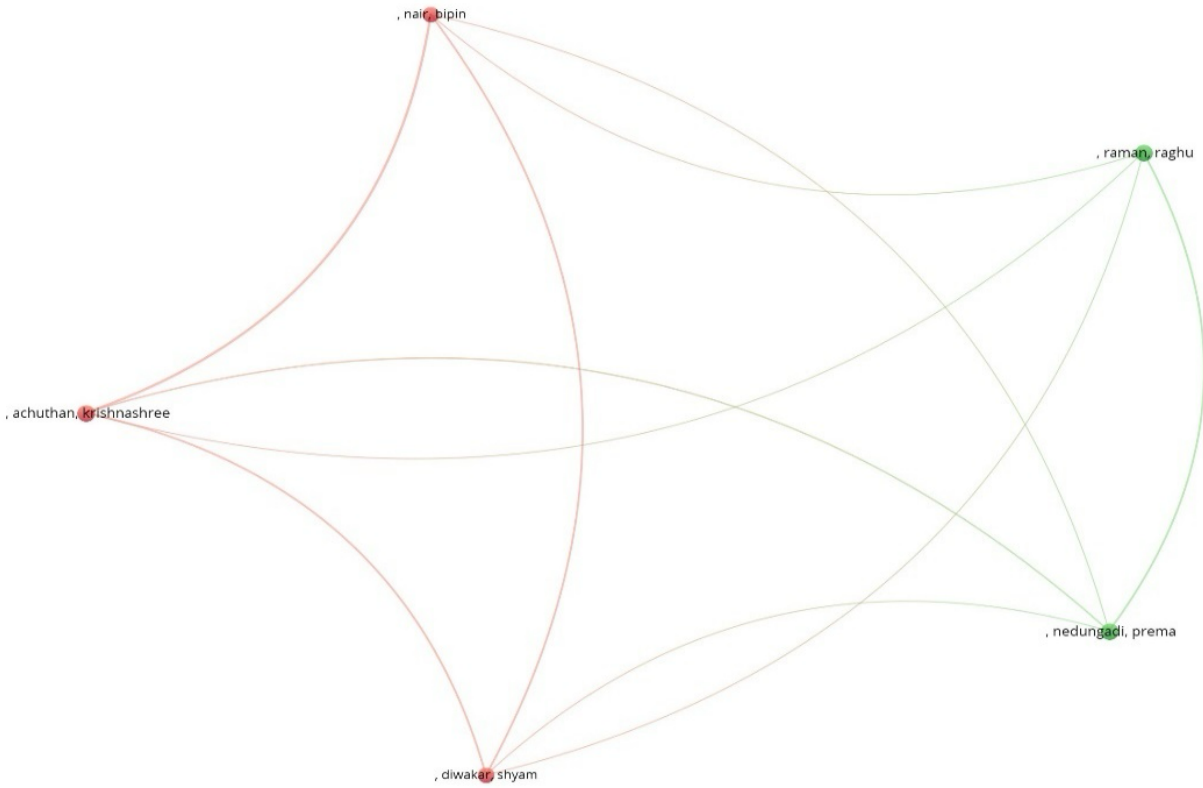

FIGURE 4. Network visualisation map of the co-authorship based on authors that have a minimum of five number of citations (full counting)

KEYWORDS ANALYSIS

To gain insight into RQ3 (What were the dominant themes and keywords in virtual science lab research?), co-word analysis was conducted using VOSviewer. The primary keywords largely revolved around technology and education-related themes, reflecting the strong connection between these two domains across the research landscape, as shown in Figure 5 and Table 4. Based on Figure 5, keywords such as "Virtual Reality (34 occurrences)," "laboratories (26 occurrences)," "Engineering Education (19 occurrences)" and "E-learning (20 occurrences)," indicated a clear emphasis on leveraging technological tools to enhance educational practices and learning outcomes. The prominence of virtual laboratory-related terms including "Virtual Laboratory (13 occurrences)," "Virtual Laboratories (14 occurrences)," and "Virtual Lab (15 occurrences)," demonstrated growing interest in the development and utilisation of virtual laboratory environments as educational tools, particularly within engineering and science education. Furthermore, the impact of COVID-19 was evident through the presence of keywords such as “Remote Learning”, “Pandemic”, and “COVID-19”, which highlighted how the pandemic reshaped educational priorities and research directions. The global shift to remote and online learning modalities intensified interest and investment in technologies that supported distance education.

The keyword "virtual reality" was consistently mentioned in articles from 2001 to 2024, highlighting its ongoing importance in the field. Terms such as laboratories, e-learning, engineering education, and teaching emphasized the key role of lab-based learning in virtual

settings, particularly within educational practices such as engineering education. The emphasis on technology and education replicates the continuous development of educational practices in response to technological advancement and changing societal needs. Educators and researchers increasingly explored advanced approaches to teaching and learning, utilizing tools such as online systems, e-learning platforms, and virtual reality to improve educational experiences and outcomes (Kerimbayev et al., 2023). The emphasis on virtual laboratories underscored the potential of interactive and immersive learning environments to enrich traditional laboratory experiences, especially in situations where access to physical laboratories was limited. Virtual laboratories offered opportunities for hands-on experimentation (Ford et al., 2023; Nzabahimana et al., 2024; Reyes et al., 2024), simulation-based learning, and collaborative problem-solving, thereby strengthening the educational experience for students across multiple disciplines (Errabo et al., 2024).

The influence of the COVID-19 pandemic on education was evident through the emergence of keywords associated with pandemic response strategies, online learning, and remote instruction. The global shift to emergency remote teaching significantly accelerated the adoption of technology-enabled educational solutions and highlighted the need for adaptability and resilience within educational systems. Although “COVID-19” itself did not appear among the top twenty most frequent keywords, its impact on virtual and online learning research is unmistakable. The pandemic compelled institutions worldwide to integrate virtual laboratories, online platforms, and simulation-based systems at an unprecedented scale, driving rapid innovation in digital pedagogies and contributing to a notable increase in publications between 2020 and 2024. Its absence from the most frequent keywords could be explained by the varied terminology used by authors—such as “remote teaching,” “online learning,” and “distance education”—and by its relatively recent emergence compared with two decades of data. Despite this, the pandemic remained a decisive catalyst in the expansion and advancement of virtual learning research, reinforcing the need to continue exploring innovative, technology-integrated teaching approaches that respond effectively to evolving educational demands.

Some of these keywords had not been used or had not appeared in recent years. Terms such as remote laboratories, computer aided instruction, augmented reality, experiments, visualization, were popular in the earlier years but experienced a marked decline, with little recent literature focusing on them. This trend indicated that the field had shifted its priorities from older teaching terminologies to newer, more relevant issues such as virtual reality and e-learning. Over time, the scholarly community adopted standardized terminology, and many variations of a keyword cease to exist. For example, "computer-aided instruction" was gradually replaced by broader terms such as "digital learning" or "online education". It was important to note that the disappearance of certain keywords did not imply that the concept behind them had become obsolete. Rather, it reflected changes in research focus and terminology over the years. Older terms were often overshadowed by more general ideas or phased out in favour technologically advanced terminology. In summary, compared with Biology and Chemistry, most research had been conducted in Physics and robotics, while the application of this knowledge in secondary and primary school education remain limited. This finding was consistent with the findings of previous bibliometric analyses by Heradio et al. (2016).

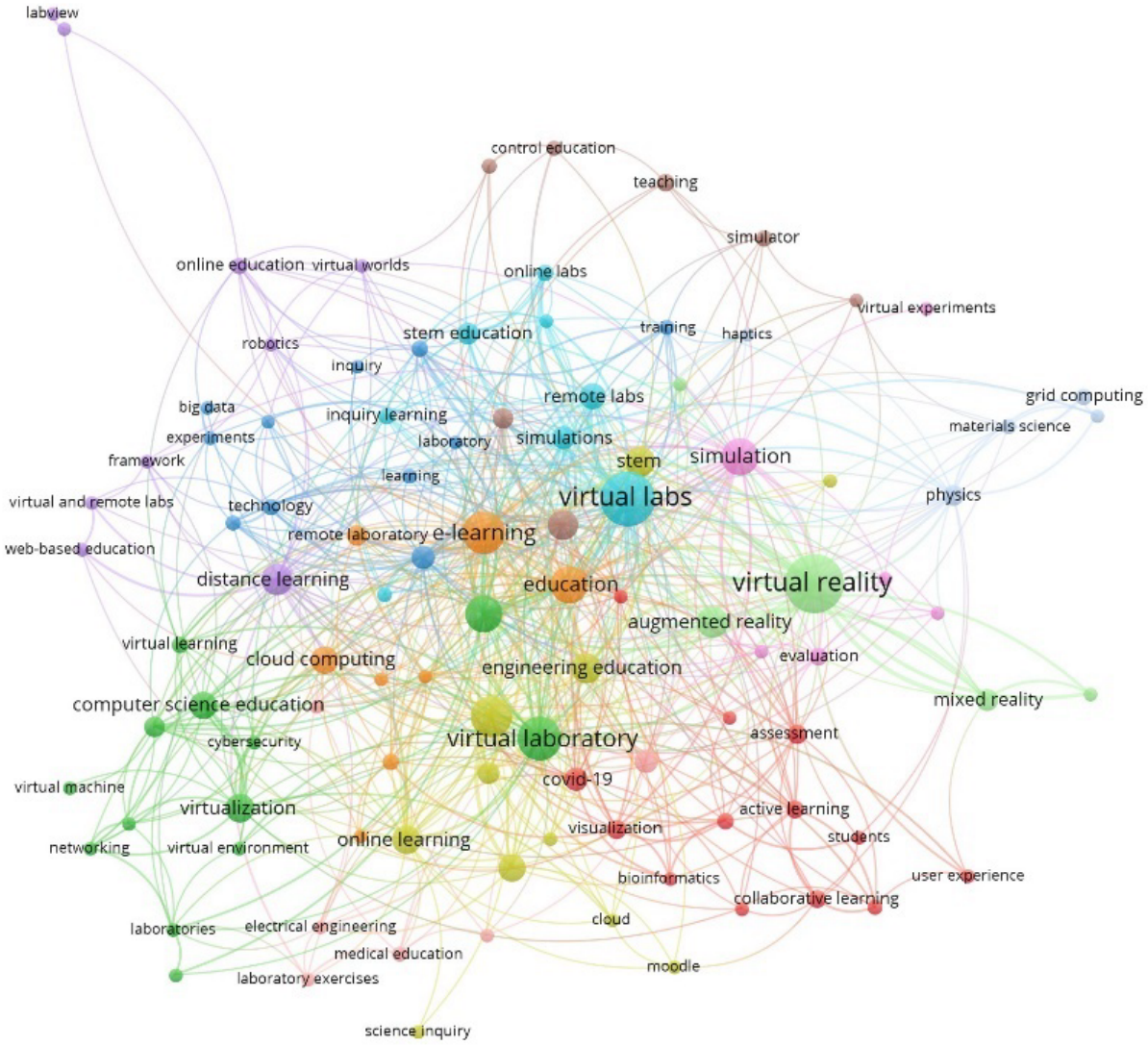

FIGURE 5. Network visualisation map of the author keywords

TABLE 4. Top 20 keywords

Author Keyword	Frequency	(%)
Students	374	27.36%
Virtual Reality	336	24.34%
Laboratories	314	23.16%
E-learning	286	21.09%
Engineering Education	245	18.07%
Teaching	197	14.38%
Education	173	12.76%
Virtual Lab	169	12.46%
Curricula	135	9.96%
Virtual Laboratories	123	9.07%
Distance Education	121	8.92%
Education Computing	114	8.41%
Computer Aided Instruction	98	7.23%
Human	95	7.01%
Virtual Labs	90	6.64%

Computer Science	77	5.68%
Humans	70	5.16%
Learning Systems	69	5.09%
Article	60	4.42%
Virtual Laboratory	59	4.35%

The most frequently occurring terms in the dataset were related to scientific research, teacher, and education as shown in Figure 6. The top keywords included "research" (358), "laboratory" (232), "virtual" (466), "education" (114), and "student" (454). This suggested that the dataset is primarily focused on topics related to technology-enhanced education, particularly in the context of virtual and remote laboratories within educational settings. Some of the related and highly co-occurring terms included "virtual experiment" (468), "remote lab" (353), "virtual reality technology" (474), "active learning", and "virtual learning environment" (471). These findings highlighted a strong emphasis on advanced educational approaches and technologies aimed at enhancing laboratory-based learning experiences.

Several prominent findings involved the occurrence of terms related to STEM education, such as "bioinformatics (15)", "engineering" (12), "chemistry (13)", and "computer science (76)". This suggested that the dataset likely covered research on technology-enhanced learning environment across multiple discipline. The dataset also included terms related to research methodology, such as "experimental group" (136), "questionnaire" (337), "pre-test" (323), and "case study (126)". Many of the abstracts described the use of quantitative data to analyse student learning outcomes and performance. The abstracts frequently reported positive findings associated with the use of virtual science laboratories, including improved student understanding, increased motivation, and enhanced collaborative learning experiences. Educational implications were often discussed, emphasising the need to integrate virtual laboratories into the curriculum.

Overall, the key insights from the analysis indicated a strong emphasis on technology-enhanced, laboratory-based STEM teaching, with a specific focus on active learning, remote and virtual approaches. The study appeared to include empirical evaluation of these instructional innovations. The analysis of term occurrence and significance scores provided valuable understandings in the thematic focus, main topics, and areas of attention within the examined corpus. These findings informed potential future research directions, contributed to academic discourse, and enhanced comprehension of the research landscape under investigation.

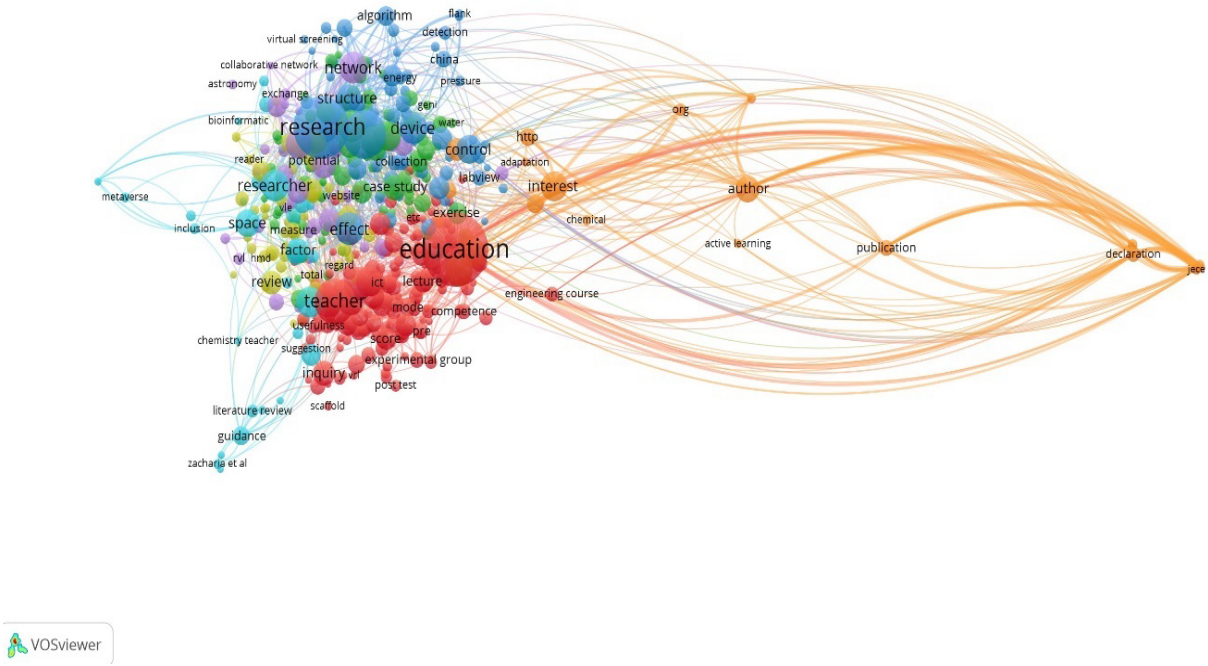

FIGURE 6. VOSviewer visualisation of a term co-occurrence network based on title and abstract fields

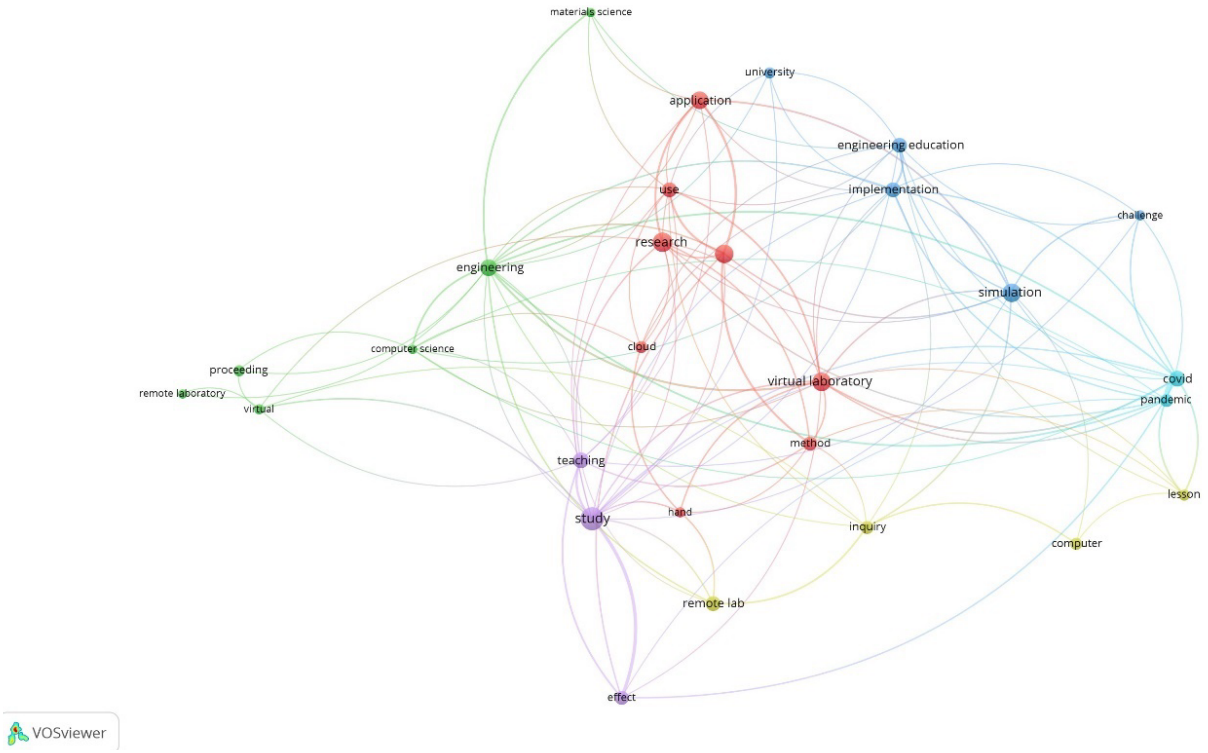

FIGURE 7. VOS viewer visualisation of a Term co-occurrence network based on title fields

The most notable finding was the strong emphasis on virtual or remote laboratories, reflected in the high significance scores for terms such as "remote laboratory", "simulation", "virtual laboratory", and "remote lab", as shown in Figure 7. This indicated that the dataset was focused on research and applications related to technology-enhanced laboratory experiences, particularly in virtual and remote settings. Another key finding was presence of terms associated with STEM education, such as “engineering", "materials science", "engineering education" and "computer science". This suggested that the research encompassed the integration of educational practices and innovations across a range of scientific disciplines. The dataset also included a substantial number of terms related to research evaluation and methodology, such as "study", "effect", "method", and "inquiry". This implied that the research likely involved empirical investigations and assessments of educational interventions and technologies.

The strong emphasis on remote and virtual laboratories, together with the importance placed on STEM education, suggested that the dataset likely reflected the evaluation, implementation, and design of technology-enhanced laboratory experiences intended to support learning in technical disciplines. The studies collectively examined the effectiveness of these innovative approaches in improving student learning outcomes, understanding and engagement (Krishnan, 2025). The methodological terms indicated a rigorous, empirical approach to assessing the impact of these instructional interventions and technologies. Overall, the pattern of co-occurrence network analysis showed that the dataset was heavily focused on the design, operation, and assessment of technology-enhanced learning experiences, particularly within the context of remote and virtual laboratories across various STEM fields. The studies appeared to employment systematic and empirical methods to measure the effect of these instructional innovations on student learning outcomes, comprehension, and engagement while also exploring student-centered pedagogical approaches that leveraged technology to promote active learning and critical thinking (Kerimbayev et al., 2023).

The high occurrence of phrases related to "research" and "education” indicated that these were primary themes in the corpus. The investigation appeared to employ active learning approaches and rigorous, empirical methods to evaluate the effectiveness of technology-enhanced learning strategies in improving student learning, understanding, and engagement across various scientific disciplines such as physical education (Syed Yahya et al, 2024). The strong emphasis on immersive technologies, such as virtual reality, suggested a focus on creating innovative and interactive learning environments to support student mastery of laboratory-related content. These findings highlighted the increasing prominence and acceptance of Virtual Reality (VR) technology in engineering education (Ding et al., 2024; Kim et al., 2023), with a strong emphasis on student-centered e-learning and virtual labs approaches (Srivathsa et al., 2025). The occurrence of terms such as "Distance Education” “Curricula" and "Teaching," indicated a broader exploration of how VR could reshape educational practices and program delivery within engineering programs. Since these developments aligned with United Nations Sustainable Development Goal 4 (UN SDG 4), on ensuring quality education, the majority of the research involves higher education institutions especially those that offers physics. By contrast, considerably fewer studies focused in Biology (Azizah & Aloysius, 2021; Paxinou et al., 2022; Reeves et al., 2024; Thi & Thuy, 2020) and Chemistry (Broyer et al., 2021; Reeves et al., 2021; Sreekanth et al., 2022), and their application within secondary and primary education context remained an area requiring further investigation.

CITATION ANALYSIS

Citation analysis was used to identify the most influential articles to address RQ4 (Which article had made the most significant impact in this field?), as shown in Table 5 below.

TABLE 5. Top cited articles in blended lab research (POP)

No	Authors	Title	TC	C/Y
1.	Makransky, Terkildsen & Mayer (2019)	Adding immersive virtual reality to a science lab simulation causes more presence but less learning	713	142.6
2.	Potkonjak et al. (2016)	Virtual laboratories for education in science, technology, and engineering: A review	599	74.88
3.	Heradio et al. (2016)	Virtual and remote labs in education: A bibliometric analysis	394	49.25
4.	Morton & Williams (2010)	Experimental political science and the study of causality: From nature to the lab	373	26.64
5.	Steinkuehler & Duncan (2008)	Scientific habits of mind in virtual worlds	343	21.44
6.	Portman, Natapov & Fisher-Gewirtzman (2015)	To go where no man has gone before: Virtual reality in architecture, landscape architecture and environmental planning	305	33.89
7.	Lewandowski & Beyenal (2007)	Fundamentals of biofilm research	274	16.12
8.	Markowitz et al. (2018)	Immersive Virtual Reality field trips facilitate learning about climate change	270	45
9.	Haghani & Sarvi (2018)	Crowd behaviour and motion: Empirical methods	223	37.17
10.	de Jong, Sotiriou & Gillet (2014)	Innovations in STEM education: The Go-Lab federation of online labs	215	21.5

In 2016, the highest total number of citations was recorded, due to two most influential papers published that year. The most frequently cited articles in virtual science laboratory research covered a wide range of topics, including virtual reality (VR) in education, biofilm research, crowd behaviour analysis, climate change education, and virtual laboratories. This diversity reflected the multidisciplinary nature of virtual science laboratory field and the intersection of technology, social sciences, science, and education within in the research landscape. Several articles highlighted on the application of virtual laboratories and virtual reality in teaching (Srivathsa et al., 2025). These included studies that examined the impact of immersive VR experiences on learning outcomes, the effectiveness of virtual laboratories in engineering and science education, and the integration of online research facilities into STEM education initiatives (Rahman & Morgan, 2021). Additionally, articles such as "Adding immersive virtual reality to a science lab imitation reasons more occurrence but less education" and "Immersive Virtual Reality research trips make easy for knowledge about climate change" highlighted the significance of immersive experiences in educational settings. These studies demonstrated the potential of VR technologies to enhance learning outcomes, presence, and engagement through interactive and experiential learning environments.

Collectively, these studies demonstrate that although virtual and immersive laboratory research is expanding, much of the literature still lacks a comprehensive theoretical foundation (Heradio et al., 2016). Existing works either provide partial frameworks or overlook key constructs such as presence–learning trade-offs (Makransky et al., 2019), user interaction mechanisms, cognitive load dynamics, and behavioural modelling in immersive environments. This absence of strong theoretical grounding makes it difficult to interpret empirical results and hinders the development of coherent models for designing effective virtual learning experiences.

Research on virtual, immersive, and hybrid laboratory environments is limited by several persistent methodological weaknesses. Many studies rely on short-term learning assessments and examine only a narrow range of learner characteristics, offering little insight into long-term or diverse learning outcomes (Makransky et al., 2019). Experimental setups that lack real-world authenticity further contribute to inconsistent evaluation metrics (Griffin et al., 2025; Potkonjak et al., 2016). Analytical approaches remain underdeveloped, with minimal use of advanced methods such as artificial intelligence-based interaction tracking and insufficient attention to control-group design or trial replication (Heradio et al., 2016). Work on behavioural modelling also lacks tools for realistic validation (Haghani & Sarvi, 2018), while some studies continue to depend heavily on self-reported metrics instead of more reliable performance-based measures (Markowitz et al., 2018). These weaknesses highlight the need for far more rigorous and empirically grounded research designs in this field.

Individual articles are the primary units of scientific communication and knowledge dissemination. Analysing the most influential articles allows researchers to identify seminal works that have shaped the theoretical, methodological, and practical development of the field. Articles such as "Immersive Virtual Reality field trips facilitate learning about climate change" (Markowitz et al., 2018) and "Adding immersive virtual reality to a science lab simulation causes more presence but less learning" (Makransky et al., 2019) emphasised the importance of immersive experiences in educational settings. The focus on instructional applications of virtual laboratories and virtual reality reflected a growing interest in leveraging technology to transform teaching and learning practices. The most influential papers were published in 2019, indicating that existing literature continued to evolve and need to be examined to attain the most current information.

CONCLUSION

This bibliometric study provided a comprehensive overview of the research landscape surrounding virtual science laboratories, highlighting key trends, contributors, and thematic development. Although the analysis generated valuable insights, it was essential to acknowledge its limitations. Notably, the study did not include major databases such as Web of Science, which may have resulted in the omission of significant works. In addition, the search strategy relied on single keyword—"virtual science lab"—which, although intentionally selected to simplify the analysis, excluded other relevant terms such as "AI lab" and "mobile lab". Future research should therefore expand both the keyword scope and the range of data sources to ensure a more holistic and inclusive understanding of the field. Despite these contraints, the findings offered several significant contributions to academic discourse. The study identified a growing emphasis on immersive technologies, particularly virtual reality, as a means of enhancing science education. It also captured an increasing shift toward remote and blended laboratory models. These trends underscored the pedagogical shift toward student-centered, technology-enhanced learning environments, as reflected by the frequent appearance of keywords such as "students," "virtual reality," and "e-learning". Importantly, the analysis highlighted the potential of virtual laboratories to bridge geographical and logistical barriers, particularly in underserved or remote areas. This suggests their potential to reduce educational inequality by providing broader access to high-quality science experiments in supporting the Sustainable Development Goals (SDGs), especially in the quality of education, and reducing disparities.

Furthermore, the study illustrated the interdisciplinary nature of virtual laboratory research, showing its expansion beyond engineering and computer science into discipline such as biology and chemistry. However, these areas remained underexplored, especially in the context of primary and secondary education, and should be prioritised in future research. The study also descriptively outlined emerging themes and illustrated how bibliometric indicators can guide future theoretical and empirical inquiry. Future research should also explore the integration of artificial intelligence and big data analytics in virtual laboratory environments, potentially reshaping the delivery and assessment of science education. In conclusion, while this study had its limitations, it served as a foundational reference for further exploration. Identifying current gaps and emerging directions provides both scholars and practitioners with a clearer understanding of how virtual science laboratories may continue to evolve to meet the needs of 21st-century learners.

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REFERENCES

Agustina, R. D., & Putra, R. P. (2022). Sophisticated Thinking Blended Laboratory (Stb-Lab) Learning Model: Implications on Virtual and Real Laboratories for Increasing Undergraduate Student's Argumentation Skills. *Jurnal Pendidikan IPA Indonesia*, *11*(4), 657–671. https://doi.org/10.15294/jpii.v11i4.38772

Azizah, N., & Aloysius, S. (2021). The Effects of Virtual Laboratory on Biology Learning Achievement: A Literature Review. *Advances in Social Science, Education and Humanities Research*, *541*. 107-116. https://doi.org/10.2991/assehr.k.210326.015

Broyer, R. M., Miller, K., Ramachandran, S., Fu, S., Howell, K., & Cutchin, S. (2021). Using Virtual Reality to Demonstrate Glove Hygiene in Introductory Chemistry Laboratories. *Journal of Chemical Education*, *98*(1), 224–229. https://doi.org/10.1021/acs.jchemed.0c00137

Ding, A.C. E., Huang, K.T. T., DuBois, J., & Fu, H. (2024). Integrating immersive virtual reality technology in scaffolded game-based learning to enhance low motivation students' multimodal science learning. *Educational Technology Research and Development*. https://doi.org/10.1007/s11423-024-10369-7

Dirgantara, Y., Agustina, R. D., Putra, R. P., & Indrawan, I. S. (2024). Sophisticated Thinking Blended Laboratory for Increasing Physics Education Students' Understanding of GIS. *Jurnal Pendidikan IPA Indonesia*, *13*(4), 572–582. https://doi.org/10.15294/c6ddb997

Errabo, D. D., Paguio, A. J., & Enriquez, P. A. (2024). Epistemic fluency in virtual laboratories as flipped classroom's innovative learning delivery. *Journal of Research in Innovative Teaching and Learning*, *17*(2), 256–281. https://doi.org/10.1108/JRIT-03-2024-0052

Eugenio Petrovich. (2022). Science mapping and science maps. *Knowledge Organization*, *48*(7–8), 535-562. https://doi.org/10.5771/0943-7444-2021-7-8

Ford, M. J., Fatehiboroujeni, S., Fisher, E. M., & Ritz, H. (2023). A Hands-on Guided-inquiry Materials Laboratory that Supports Student Agency. *Advances in Engineering Education*, *11*(1), 77–104. https://doi.org/10.18260/3-1-1153-36041

Griffin, C. S., Loughran, S., Kelly, B., Healy, E., Lambe, G., van Rossum, A., Murphy, B., Moore, E., Burke, C., Morrin, A., Breslin, C., Heaney, F., Rooney, D., Bree, R., & Drumm, B. T. (2025). Virtual laboratories complement but should not replace face-to-face classes: perceptions of life science students at Dundalk Institute of Technology, Ireland. *Advances in Physiology Education*, *49*(2), 314–330. https://doi.org/10.1152/advan.00227.2024

Haghani, M., & Sarvi, M. (2018). Crowd behaviour and motion: Empirical methods. *Transportation Research Part B: Methodological*, *107*, 253–294. https://doi.org/10.1016/j.trb.2017.06.017

Heradio, R., De La Torre, L., Galan, D., Cabrerizo, F. J., Herrera-Viedma, E., & Dormido, S. (2016). Virtual and remote labs in education: A bibliometric analysis. *Computers and Education*, *98*, 14–38. https://doi.org/10.1016/j.compedu.2016.03.010

Kerimbayev, N., Umirzakova, Z., Shadiev, R., & Jotsov, V. (2023). A student-centered approach using modern technologies in distance learning: a systematic review of the literature. *Smart Learning Environments*, *10*(1). https://doi.org/10.1186/s40561-023-00280-8

Kim, T., Planey, J., & Lindgren, R. (2023). Theory-Driven Design in Metaverse Virtual Reality Learning Environments: Two Illustrative Cases. *IEEE Transactions on Learning Technologies*, *16*(6), 1141–1153. https://doi.org/10.1109/TLT.2023.3307211

Kiong, J. F. (2023). The Impact of Technology on Education: A Case Study of Schools. *Journal of Education Review Provision*, *2*(2), 43–47. https://doi.org/10.55885/jerp.v2i2.153

Krishnan, S (2025). Ethnic Disparities and Socioeconomic Factors in STEM Education in Malaysia: Towards Inclusive Practice. Akademika 95(2), 279-298. https://doi.org/10.17576/akad-2025-9502-16

Makransky, G., Terkildsen, T. S., & Mayer, R. E. (2019). Adding immersive virtual reality to a science lab simulation causes more presence but less learning. *Learning and Instruction*, *60*, 225–236. https://doi.org/10.1016/j.learninstruc.2017.12.007

Malya, R. M., Mahande, M. J., Urstad, K. H., Rogathi, J. J., & Bø, B. (2025). Perception of simulation-based education among nursing and midwifery students in Tanzania: a qualitative study. *Advances in Simulation*, *10*(1). https://doi.org/10.1186/s41077-025-00339-1

Markowitz, D. M., Laha, R., Perone, B. P., Pea, R. D., & Bailenson, J. N. (2018). Immersive Virtual Reality field trips facilitate learning about climate change. *Frontiers in Psychology*, *9*(NOV). https://doi.org/10.3389/fpsyg.2018.02364

Mashau, P., & Nyawo, J. (2021). the Use of an Online Learning Platform: a Step Towards E-Learning. *South African Journal of Higher Education*, *35*(2), 123–143. https://doi.org/10.20853/35-2-3985

Mihret, Z., Alemu, M., & Assefa, S. (2022). Effects of Blending Virtual and Real Laboratory Experimentation on Pre-Service Physics Teachers' Attitudes Toward Physics Electricity

and Magnetism Laboratories. *Science Education International*, *33*(3), 313–322. https://doi.org/10.33828/sei.v33.i3.7

Naim, A. (2021). Applications of E-Learning Tools for Achieving Students Learning Outcomes. *Journal of Pedagogical Inventions and Practices*, *2*(1), 125–135. https://zienjournals.com/index.php/jpip/article/view/320

Nzabahimana, J., Ndihokubwayo, K., & Mugabo, L. R. (2024). Teachers' Experiences with the Use of Virtual Laboratories in the Teaching of Physics in Rwandan Secondary Schools: A Survey Design. *African Journal of Research in Mathematics, Science and Technology Education*, *28*(2), 196–209. https://doi.org/10.1080/18117295.2024.2361546

Ouadoud, M., Rida, N., & Chafiq, T. (2021). Overview of E-learning Platforms for Teaching and Learning. *International Journal of Recent Contributions from Engineering, Science & IT (IJES)*, *9*(1), 50. https://doi.org/10.3991/ijes.v9i1.21111

Paxinou, E., Mitropoulos, K., Tsalapatas, H., & Kalles, D. (2022). A Distance Learning VR Technology Tool for Science Labs. *13th International Conference on Information, Intelligence, Systems and Applications, IISA 2022*. https://doi.org/10.1109/IISA56318.2022.9904341

Potkonjak, V., Gardner, M., Callaghan, V., Mattila, P., Guetl, C., Petrović, V. M., & Jovanović, K. (2016). Virtual laboratories for education in science, technology, and engineering: A review. *Computers and Education*, *95*, 309–327. https://doi.org/10.1016/j.compedu.2016.02.002

Radhamani, R., Kumar, D., Nizar, N., Achuthan, K., Nair, B., & Diwakar, S. (2021). What virtual laboratory usage tells us about laboratory skill education pre- and post-COVID-19: Focus on usage, behavior, intention and adoption. *Education and Information Technologies*, *26*(6), 7477–7495. https://doi.org/10.1007/s10639-021-10583-3

Rahman, M. M., & Morgan, R. P. (2021). A Remote Instructional Approach with Interactive and Collaborative Learning to Teach an Introductory Programming Course during COVID-19 Pandemic. *Proceedings - 2021 International Conference on Computational Science and Computational Intelligence, CSCI 2021*, 940–946. https://doi.org/10.1109/CSCI54926.2021.00210

Raman, R., Achuthan, K., Nair, V. K., & Nedungadi, P. (2022). Virtual Laboratories- A historical review and bibliometric analysis of the past three decades. In *Education and Information Technologies*, *27*(8). https://doi.org/10.1007/s10639-022-11058-9

Reeves, S. M., Bolch, C. A., Bex, R. T., & Crippen, K. J. (2024). Learner experience and motivational beliefs for a VR Lab in advanced undergraduate biology. *Interactive Learning Environments*. https://doi.org/10.1080/10494820.2024.2307601

Reeves, S. M., Crippen, K. J., & McCray, E. D. (2021). The varied experience of undergraduate students learning chemistry in virtual reality laboratories. *Computers and Education*, *175*. https://doi.org/10.1016/j.compedu.2021.104320

Reyes, R. L., Isleta, K. P., Regala, J. D., & Bialba, D. M. R. (2024). Enhancing experiential science learning with virtual labs: A narrative account of merits, challenges, and implementation strategies. *Journal of Computer Assisted Learning*, *40*(6), 3167–3186. https://doi.org/10.1111/jcal.13061

Shambare, B., & Jita, T. (2025). Factors influencing virtual lab adoption in marginalized rural schools: insights from South Africa. *Smart Learning Environments*, *12*(1). https://doi.org/10.1186/s40561-025-00369-2

Sreekanth, N. S., Varghese, N., & Babu, N. S. C. (2022). Virtual Chemistry Lab to Virtual Reality Chemistry Lab. *Resonance*, *27*(8), 1371–1385. https://doi.org/10.1007/s12045-022-1432-0

Srivathsa, B. S., Pandey, H., & Naganandini, G. (2025). Future trends in education: The impact of AI, data science, and immersive technologies. In *Driving Quality Education Through AI and Data Science*,139–164. IGI Global. https://doi.org/10.4018/979-8-3693-8292-9.ch007

Syed Mohd Najib Syed Yahya, Nur Shakila Mazalan, Khairul Azhar Jamaludin (2024). The Impact of Integrating Technology on Teaching and Learning in Physical Education Curriculum. *Malaysia Journal of Education, 49*(1). Special Issue (Dicember 2024). https://ejournal.ukm.my/jpend/article/view/82031

Thi, P. L., & Thuy, L. D. (2020). Applying Virtual Reality Technology to Biology Education: The Experience of Vietnam. In *Learning and Analytics in Intelligent Systems*, *9*. https://doi.org/10.1007/978-3-030-38501-9_44

Veeramanickam, M. R. M., & Ramesh, P. (2022). Analysis on quality of learning in e-Learning platforms. *Advances in Engineering Software*, *172*, 103168. https://doi.org/https://doi.org/10.1016/j.advengsoft.2022.103168

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