Heliyon 10 (2024) e35627

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

The evolution of simulation-based medical education research: From traditional to virtual simulations

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ARTICLE INFO

Keywords:
Medical education
Simulation
Bibliometrics
Visualization analysis
Clinical training

ABSTRACT

Background: Simulation-based medical education (SBME) is a widely used method in medical education. This study aims to analyze publications on SBME in terms of countries, institutions, journals, authors, and keyword co-occurrence, as well as to identify trends in SBME research.
Methods: We retrieved the Publications on SBME from the Web of Science Core Collection (WoSCC) database from its inception to January 27, 2024. Microsoft Excel 2019, CiteSpace, and VOSviewer were used to identify the distribution of countries, journals, and authors, as well as to determine the research hotspots.
Results: We retrieved a total of 11272 publications from WoSCC. The number of documents published in 2022 was the highest in the last few decades. The USA, the UK, and Canada were three key contributors to this field. The University of Toronto, Stanford University, and Harvard Medical School were the top major institutions with a larger number of publications. Konge, Lars was the most productive author, while McGaghie, William C was the highest cited author. BMC Medical Education has the highest number of publications among journals. The foundational themes of SBME are "Patient simulation," "extending reality," and "surgical skills."
Conclusions: SBME has attracted considerable attention in medical education. The research hotspot is gradually shifting from traditional simulations with real people or mannequins to virtual, digitally-based simulations and online education. Further studies will be conducted to elucidate the mechanisms of SBME. The utilization of SBME will be more rationalized.

1. Introduction

Simulation-Based medical education (SBME) is an educational method that utilizes medical simulation technology to create simulated patients and clinical scenarios for teaching and practice, rather than using real patients [1]. Simulation offers a secure

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https://doi.org/10.1016/j.heliyon.2024.e35627
Received 30 March 2024; Received in revised form 4 June 2024; Accepted 31 July 2024
Available online 3 August 2024

setting for students to acquire and hone a variety of clinically relevant skills without any risk of harm to patients. McGaghie et al. proposed this approach, conceptualizing simulation as part of medical education, which they called SBME [2]. SBME is widely used to acquire technical skills in various medical fields, including internal medicine, surgery, nursing, and rehabilitation, due to the demand for improved basic clinical skills training [3,4]. This significantly reduces the risks of teaching medicine and allows for more focused experiential education, resulting in learning benefits superior to traditional clinical medical education. Non-technical skills such as decision-making and communication can also be effectively developed through SBME training [5,6]. SBME has become a popular and important part of medical education for both medical students and clinicians. Additionally, SBME offers a high degree of flexibility, enabling the integration of other highly effective methods and tools. In recent years, the incorporation of high technology has enabled SBME to adapt to the development of the intelligent age. Virtual reality (VR), also referred to as virtual simulation, is a fully synthetic and immersive environment that can be used for patient simulation, surgical simulation, and various medical teaching scenarios [7]. This has provided efficient and diverse options for medical education, facilitating clinical learning in the age of intelligence. The incorporation of artificial intelligence (AI) has created an effect where "1 + 1 is greater than 2."

SBME has attracted many scholars due to its uniqueness and superiority. However, no scholars have conducted a visual bibliometric analysis of SBME yet, and the overall research trends in the field remain unclear. Bibliometric Analysis is a widely used method for presenting the research base and hotspots of a research topic or field by statistically evaluating and quantifying large amounts of bibliometric data [8]. It examines the distribution of research components such as countries, institutions, and authors, as well as the relationships between them [8,9]. This study aims to fill the gap in bibliometric analysis in this research area by conducting a bibliometric study on the current status of global medical simulation education research and the trend of research topics through visual analysis.

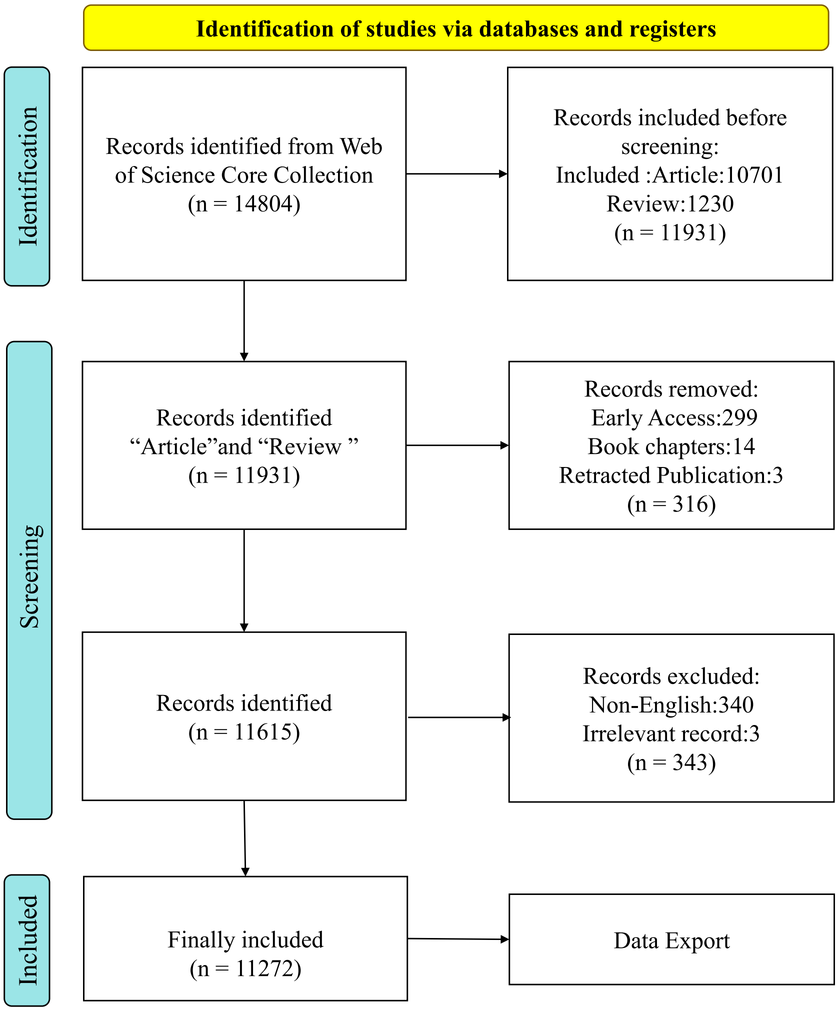

Fig. 1. Flow diagram of the included articles.

2. Methods

2.1. Data acquisition and methods

2.1.1. Search strategy

The bibliometric analysis is based on literature databases. So we utilized the Web of Science Core Collection (WoSCC) because of its comprehensive coverage of high-impact, multidisciplinary international journals. We retrieve relevant literature on SBME since the database establishment. We retrieved all articles on the same day to prevent confusion from partial results due to subsequent publications. The final retrieval strategies are integrated as follows:

TS= (medicine OR medical) AND TS= (education OR educate OR training OR teaching) AND TS= (virtual OR “virtual reality” OR VR OR simulation-based OR simulated).

2.1.2. Data processing

We selected English-language articles and reviews, excluding early access, book chapters, retracted publications, and irrelevant records. This resulted in a dataset of 11,272 records. Fig. 1 shows the specific literature screening process. We exported the resulting data as plain text, including the full record and references.

2.2. Data analysis

The data that has been exported, labeled as “download _XX,” is stored in the “Input” folder. Three additional folders have been created to streamline data preparation: “Output,” “Data,” and “Project.”

For visual analysis, we loaded the final selected publications into CiteSpace (6.2.R4) and Microsoft Excel. The volume of papers produced each year was trended using Microsoft Office Excel. CiteSpace is a powerful tool for the visualization and analysis of academic literature data. It identifies citations and collaborations, visualizes the evolution of research networks, and aids in discovering hot spots and trends within the research field [10]. The CiteSpace default settings include time slices from 1964 to 2024, with one year per slice, as well as options for selecting keywords, countries, institutions, authors, references, cited authors, and cited journals. VOSviewer, introduced by Van Eck and Waltman in 2010, is a valuable tool for constructing visual knowledge graphs and illustrating how knowledge gets structured, evolves, and collaborates [11]. Additionally, other visualization tools, such as Scimago Graphica, are utilized to analyze the data.

3. Results

3.1. Publication trend analysis

Based on the inclusion and exclusion criteria, 11,272 publications were obtained after removing 3532 ineligible records. Fig. 2 shows a global trend in the number of publications related to SBME, with a steady increase each year. The number of documents published in 2022 was the highest in the last few decades, with over 100 publications per year since 2004. It is estimated that the number of books published will gradually increase in the coming years based on the trend of articles over time.

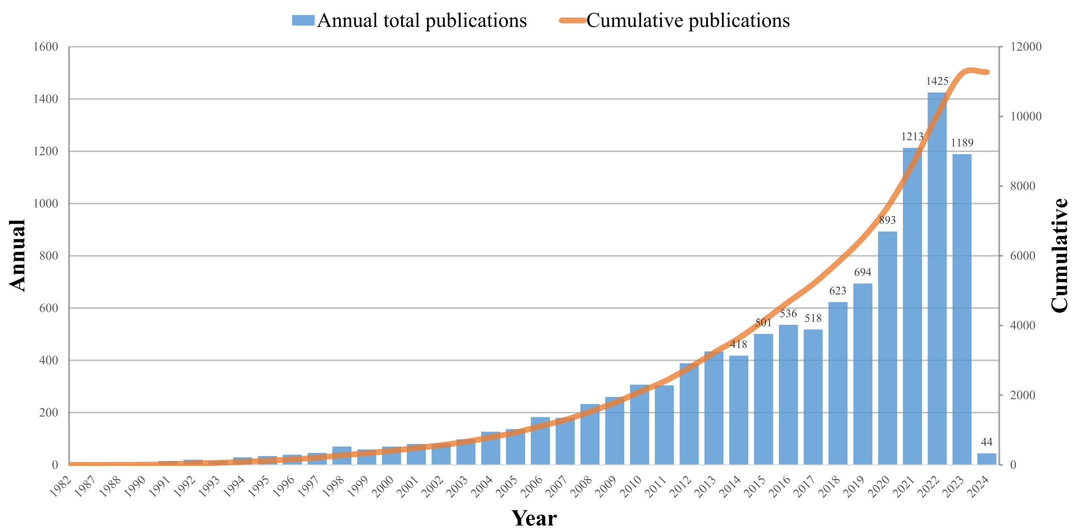

Fig. 2. Annual trend of publications.

3.2. Countries or regions analysis

The citations mention a total of 143 nations or territories. The colored area in Fig. 3 represents the number of documents issued, while the colored connecting lines indicate cooperation between regions. Table 1 presents the top 10 nations or regions based on their publications and total link strength.

The USA, the UK, Canada, China, and Australia were the top five countries in terms of paper counts, while the top five nations in terms of total link strength were the USA, the UK, Canada, Germany, and Australia. The UK was the second most prolific nation, with 1253 papers, behind the USA with 4839. The significant disparity in the number of publications highlights the dominant position of the United States in this field. High link strength indicates that the USA collaborates more with other countries, followed by the UK and Canada.

3.3. Distribution by institutions

We selected the top 30 institutions with the highest number of documents out of more than 10,000 involved for visualization and analysis. Fig. 4A displays the collaborative network between institutions, revealing strong collaborative relationships between Univ Toronto, Univ British Columbia, and Univ Ottawa. Fig. 4B shows the number of publications and citation frequency of the institutions,

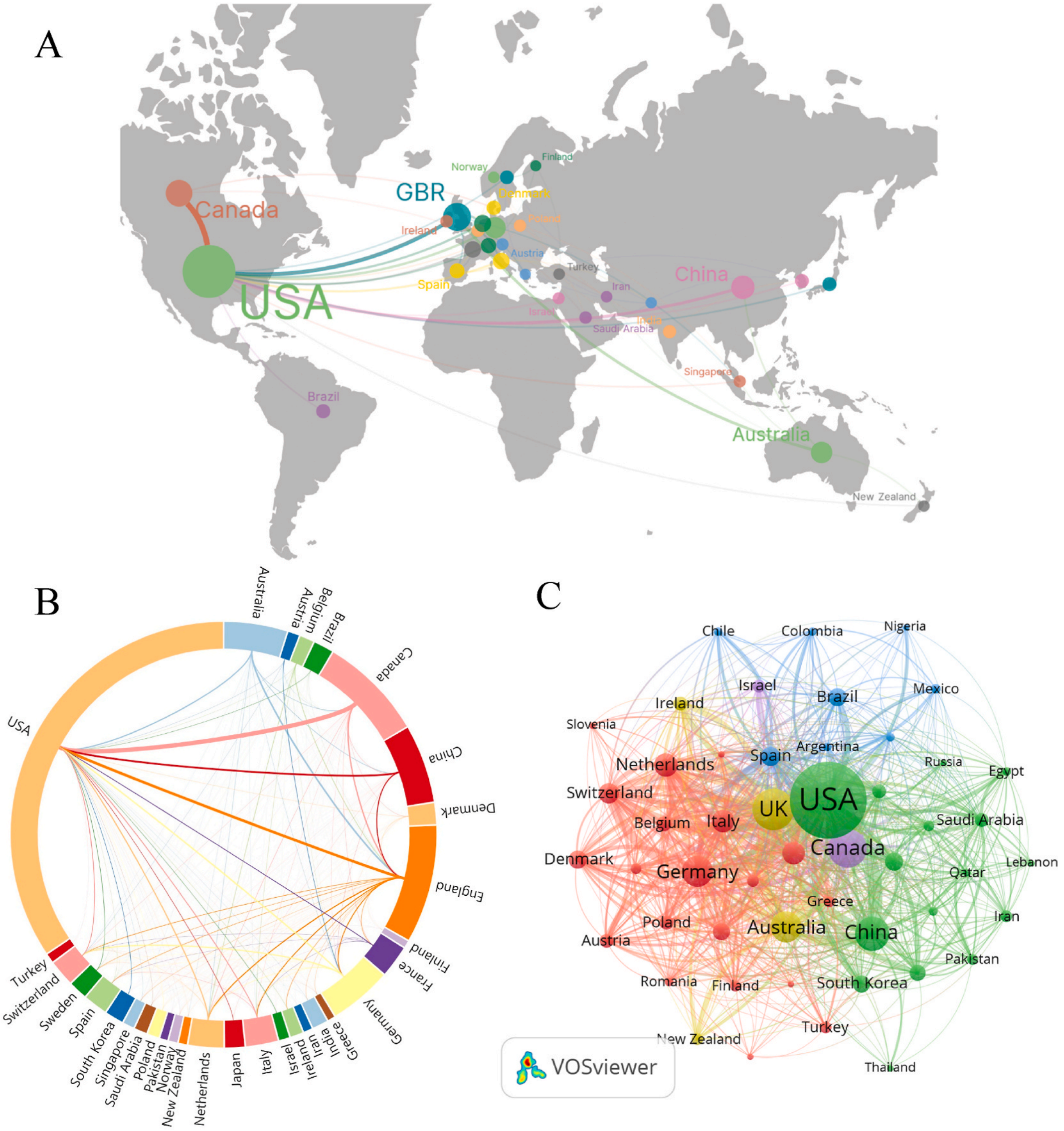

Fig. 3. (A) Visualization map of countries or regions. (B) Collaborative research between countries or regions. (C) Network visualization map of countries or regions.

Table 1
Top 10 countries/regions with highest publications on SBME.

Rank	Country	Documents	Rank	Country	Total link strength
1	USA	4839	1	USA	899
2	UK	1253	2	UK	634
3	Canada	1108	3	Canada	527
4	China	828	4	Germany	354
5	Australia	669	5	Australia	352
6	Germany	664	6	Netherlands	290
7	Netherlands	370	7	China	284
8	Italy	338	8	Switzerland	261
9	France	335	9	Italy	246
10	Switzerland	271	10	France	203

with the majority of these institutions located in the United States.

Table 2 lists the top ten countries. The University of Toronto occupies first place with 351 publications, followed by Stanford University and Harvard Medical School with 200 and 196 publications, respectively. Northwestern University is the most cited institution with 12,835 citations, followed by the University of Toronto and Mayo Clinic with 12,234 and 9788 citations, respectively. The "Total Link Strength" is the total number of co-occurrences of a term with other terms. In the visualization network of institutional partnerships, it is possible to indicate the degree of close cooperation between different institutions. Taking into account the factors of "Documents," "Citations," and "Total Link Strength" collectively, it can be concluded that the University of Toronto holds a significant position in this field.

3.4. *Author-related analysis*

Fig. 5 presents an analysis of author relationships through visualization. Specifically, Fig. 5A displays a network of collaborations among authors, which highlights close collaborations between McGaghie, William C., Cohen, Elaine R., and Barsuk, Jeffrey H. Table 3 ranks the top 30 authors based on the number of publications and citations, while Fig. 5B visualizes the number of citations and temporal distribution of these authors. Lars Konge is ranked first with 74 publications, followed by William C. McGaghie and David A. Cook with 51 and 45 publications, respectively. William C. McGaghie has the highest number of citations with 6,674, followed by David A. Cook and Diane B. Wayne. It is noteworthy that McGaghie, William C., Cook, David A., and Wayne, Diane B. have shown high strength in terms of both the number of publications and collaborations, and have had significant impact in the field. Specifically, Konge, Lars has shown great potential in the field with a high number of publications.

3.5. *Journals-related analysis*

A total of 11,272 articles were published in 2132 journals. Fig. 6 displays the visualization results: Fig. 6A shows the collaborative network of the journals, with node size indicating the number of documents. Notably, BMC Medical Education contributes a large

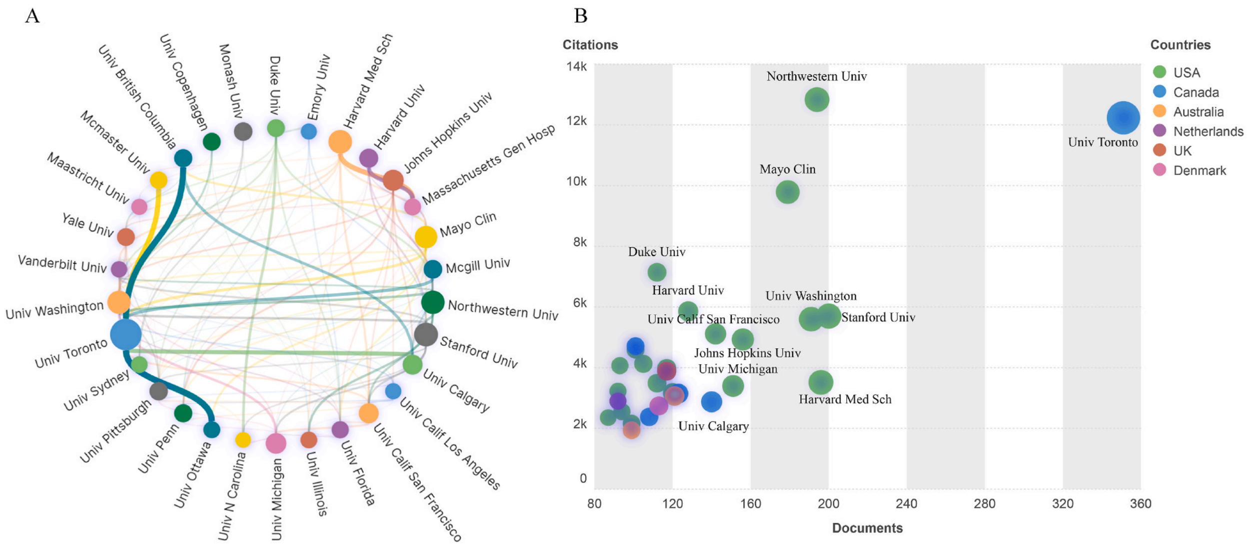

Fig. 4. (A)Institutional collaboration network. The size of the circle representing the quantity, the lines indicate the cooperative relationships between the institutions. (B)Distribution map of publications and citations of institutions.

Table 2
Top 10 institutions related to SBME.

Rank	Institutions	Documents	Total link strength	Countries	Institutions	Citations
1	Univ Toronto	351	248	Canada	Northwestern Univ	12835
2	Stanford Univ	200	143	USA	Univ Toronto	12234
3	Harvard Med Sch	196	151	USA	Mayo Clin	9788
4	Northwestern Univ	194	153	USA	Duke Univ	7143
5	Univ Washington	191	153	USA	Harvard Univ	5858
6	Mayo Clin	179	134	USA	Stanford Univ	5700
7	Johns Hopkins Univ	156	99	USA	Univ Washington	5598
8	Univ Michigan	151	111	USA	Univ Calif San Francisco	5115
9	Univ Calif San Francisco	142	127	USA	Johns Hopkins Univ	4930
10	Univ Calgary	140	116	Canada	Univ Ottawa	4709

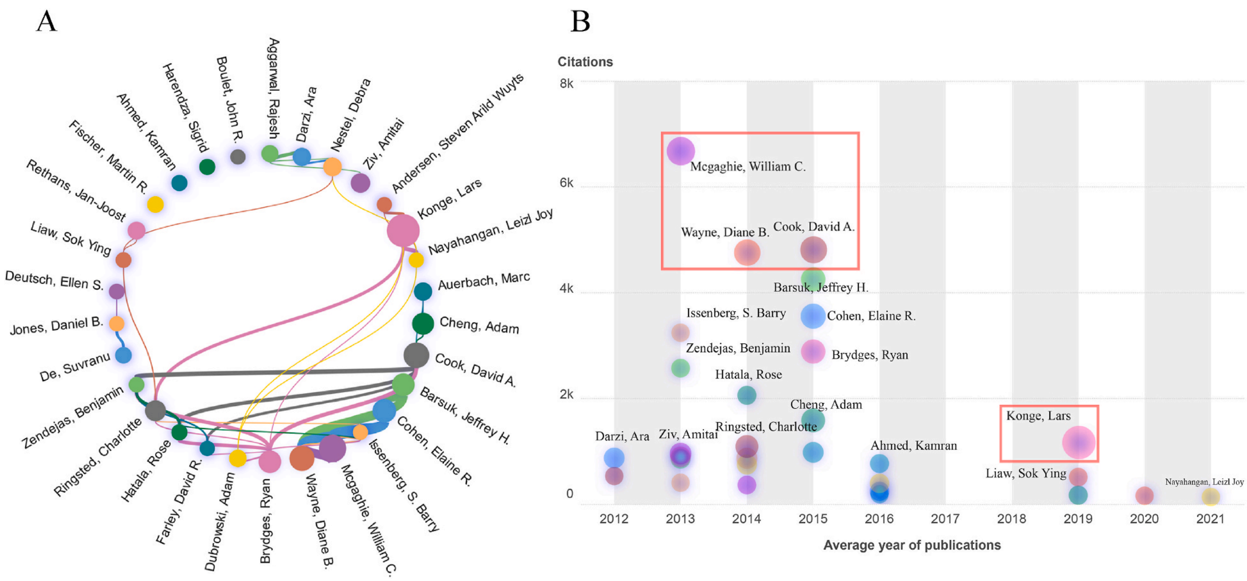

Fig. 5. (A)Visualization map of author collaboration. (B)Analysis of cited authors.

Table 3
Top 30 authors in SBME based on publications and citations.

Rank	Authors	Documents	Total link strength	Authors	Citations
1	Konge, Lars	74	34	McGaghie, William C.	6674
2	McGaghie, William C.	51	88	Cook, David A.	4814
3	Cook, David A.	45	53	Wayne, Diane B.	4760
4	Wayne, Diane B.	43	99	Barsuk, Jeffrey H.	4254
5	Cohen, Elaine R.	38	92	Cohen, Elaine R.	3556
6	Barsuk, Jeffrey H.	35	87	Issenberg, S. Barry	3244
7	Brydges, Ryan	35	46	Brydges, Ryan	2888
8	Cheng, Adam	33	5	Zendejas, Benjamin	2574
9	Ringsted, Charlotte	30	15	Hatala, Rose	2061
10	Ziv, Amitai	26	1	Cheng, Adam	1587

number of articles to the field. Fig. 6B shows the distribution graph of the journals in terms of the number of publications and citations. The majority of the journals are based in the USA. Table 4 displays the top ten journals with the highest number of documents. *BMC MEDICAL EDUCATION* (IF = 3.6/Q2), *SIMULATION IN HEALTHCARE-JOURNAL OF THE SOCIETY FOR SIMULATION IN HEALTHCARE* (IF = 2.4/Q3), and *MEDICAL TEACHER* (IF = 4.7/Q1) occupied the top three positions with 495, 284, and 259 articles, respectively.

Table 5 lists the top ten cited journals. *MEDICAL EDUCATION* (IF = 6.0/Q1) ranked first with 13225 citations, followed by *MEDICAL TEACHER* (IF = 4.7/Q1) and *ACADEMIC MEDICINE* (IF = 7.4/Q1) with 1537 and 9468 citations, respectively. Scholars tend to cite *MEDICAL EDUCATION* more often due to its authority.

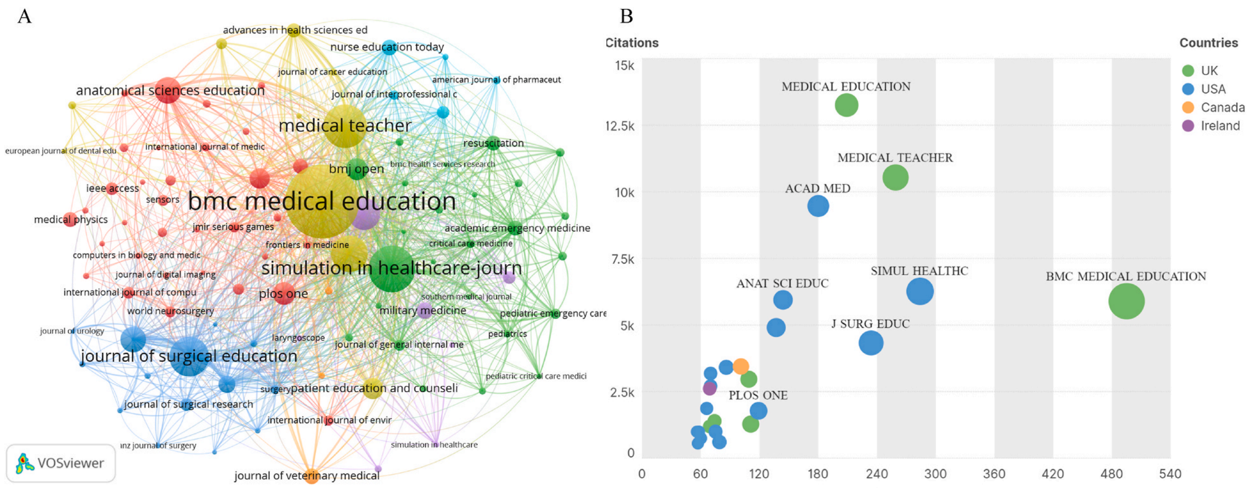

Fig. 6. (A) Visualizations of cited journals. (B) Distribution map of cited journals. Some of the labels have been abbreviated for display effectiveness.

Table 4
Top 10 institutions related to SBME by number of documents.

Rank	Journal	Citations	IF/JCR(2022)	Countries
1	MEDICAL EDUCATION	13255	6.0/Q1	UK
2	MEDICAL TEACHER	10537	4.7/Q1	UK
3	ACADEMIC MEDICINE	9468	7.4/Q1	USA
4	SIMULATION IN HEALTHCARE-JOURNAL OF THE SOCIETY FOR SIMULATION IN HEALTHCARE	6264	2.4/Q3	USA
5	ANATOMICAL SCIENCES EDUCATION	5944	7.3/Q1	USA
6	BMC MEDICAL EDUCATION	5894	3.6/Q2	UK
7	SURGICAL ENDOSCOPY AND OTHER INTERVENTIONAL TECHNIQUES	4905	3.1/Q2	USA
8	JOURNAL OF SURGICAL EDUCATION	4327	2.9/Q1	USA
9	JOURNAL OF MEDICAL INTERNET RESEARCH	3444	7.4/Q1	Canada
10	AMERICAN JOURNAL OF SURGERY	3411	3.0/Q2	USA

3.6. Analysis of Co-cited reference

Fig. 7A displays the clustering of co-cited references based on keywords. The results of the clustering showed Q > 0.3 and S > 0.7, which were deemed significant [12]. The most significant cluster is labeled as “web-based learning,” (cluster#0) followed by “surgical training,” (cluster #1) and “COVID-19.” (cluster#2) The citation hotspots have evolved from the earliest clinical skills training to online learning and VR. It is noteworthy that the outbreaks of the last few years have also made them hotspots for citations, which has certainly boosted the development of medical simulation education research. Additionally, there is a network of relationships between co-cited literature (Fig. 7B).

Table 6 displays the top five cited references. The top-ranked article with 572 citations is “Features and uses of high-fidelity medical simulations that lead to effective learning: a BEME systematic review” published in 2005 (This article analyzes the characteristics of high-fidelity medical simulations and how they can lead to effective learning by reviewing and synthesizing available evidence in education science) [13], followed by “Virtual reality training improves operating room performance: results of a randomized,

Table 5
Top 10 cited journals related to SBME.

Rank	Journal	Documents	IF/JCR (2022)	Countries
1	BMC MEDICAL EDUCATION	495	3.6/Q2	UK
2	SIMULATION IN HEALTHCARE-JOURNAL OF THE SOCIETY FOR SIMULATION IN HEALTHCARE	284	2.4/Q3	USA
3	MEDICAL TEACHER	259	4.7/Q1	UK
4	JOURNAL OF SURGICAL EDUCATION	234	2.9/Q1	USA
5	MEDICAL EDUCATION	209	6.0/Q1	UK
6	ACADEMIC MEDICINE	180	7.4/Q1	USA
7	ANATOMICAL SCIENCES EDUCATION	144	7.3/Q1	USA
8	SURGICAL ENDOSCOPY AND OTHER INTERVENTIONAL TECHNIQUES	137	3.1/Q2	USA
9	PLOS ONE	119	3.7/Q2	USA
10	BMJ OPEN	111	2.9/Q2	UK

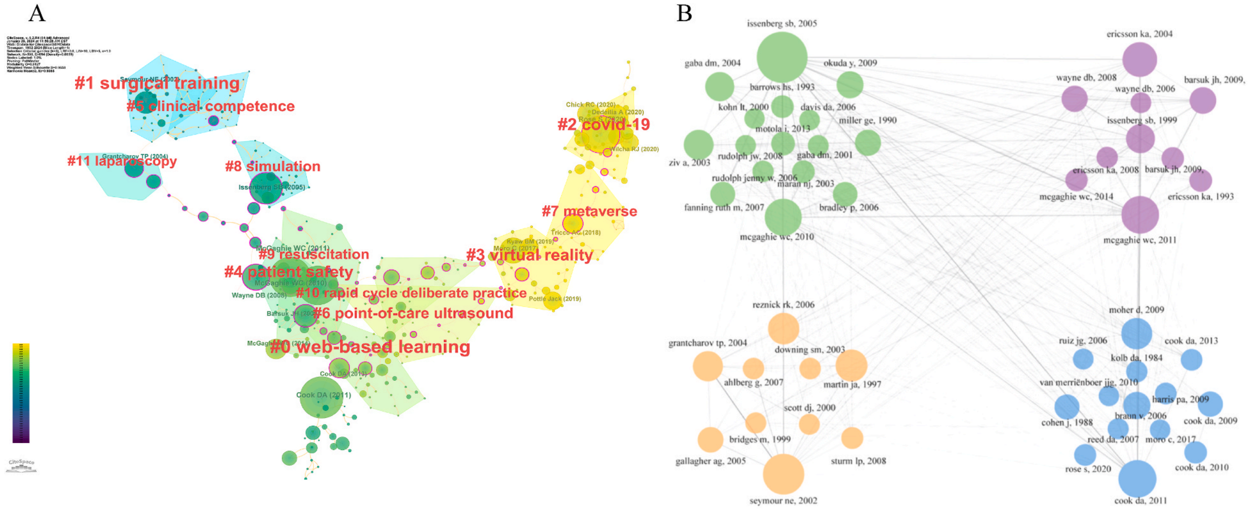

Fig. 7. (A) Visualizations of co-citated references clustering. (B) Co-citated references network.

double-blinded study" [14] and "Technology-enhanced simulation for health professions education: a systematic review and meta-analysis" [15].

3.7. Analysis of keywords

To analyze the temporal distribution of keywords, we formed a temporal heat map of the author keywords (Fig. 8A) and a time zone view of all keywords (Fig. 8B) with R4.3.2 and CiteSpace, respectively. It is evident that "virtual reality" was one of the initial research hotspots in this field and still holds a certain degree of popularity today.

Additionally, we clustered the keywords and labeled clusters with title terms. The parameters were set as follows: Years PerSlice = 1, g-index K = 25, and the clipping method selected were pathfinder and Pruning sliced networks. Fig. 8C shows a keyword co-occurrence clustering map with 1080 nodes and 5454 lines. The clustering shows $Q > 0.3$ and $S > 0.7$, indicating its significance. A total of 9 clusters were formed, the first 7 clusters are shown in Table 7. The most significant cluster was labeled as "standardized patient," (cluster #0) followed by "cardiopulmonary resuscitation," (cluster #1) and "laparoscopic skill" (cluster #2). Meanwhile, Table 8 presents the top ten keywords with the highest frequency. After excluding subject words related to retrieval, the most frequently occurring words were "performance," "skills," and "care". The keyword burst term map (Fig. 8D) reflects the emergence and progress of frontier research themes. The term "clinical competence," which first appeared in 1991, is the most significant keyword, followed by "augmented reality" and "artificial intelligence". "Deep learning," "COVID-19," and "mixed reality" are the terms that have appeared most frequently in the last five years.

4. Discussion

This study comprehensively analyzed 11,272 documents from WoSCC using visualization tools to explore the current research status, hotspots, and future trends of medical simulation education.

4.1. Research status

The number of publications in this field has been increasing each year. Notably, there has been a substantial increase in the number of publications after 2019, which may be attributed to the COVID-19 pandemic. The pandemic has brought virtual web-based learning

Table 6
Top 5 most cited references in the field of SBME.

Rank	Article Title	First Author	Year	Citations
1	Features and uses of high-fidelity medical simulations that lead to effective learning: a BEME systematic review	S Barry Issenberg	2005	572
2	Virtual reality training improves operating room performance: results of a randomized, double-blinded stud	Neal E Seymour	2002	378
3	Technology-enhanced simulation for health professions education: a systematic review and meta-analysis	David A Cook	2011	321
4	Does simulation-based medical education with deliberate practice yield better results than traditional clinical education? A meta-analytic comparative review of the evidence	William C McGaghie	2011	313
5	A critical review of simulation-based medical education research: 2003–2009	William C McGaghie	2010	304

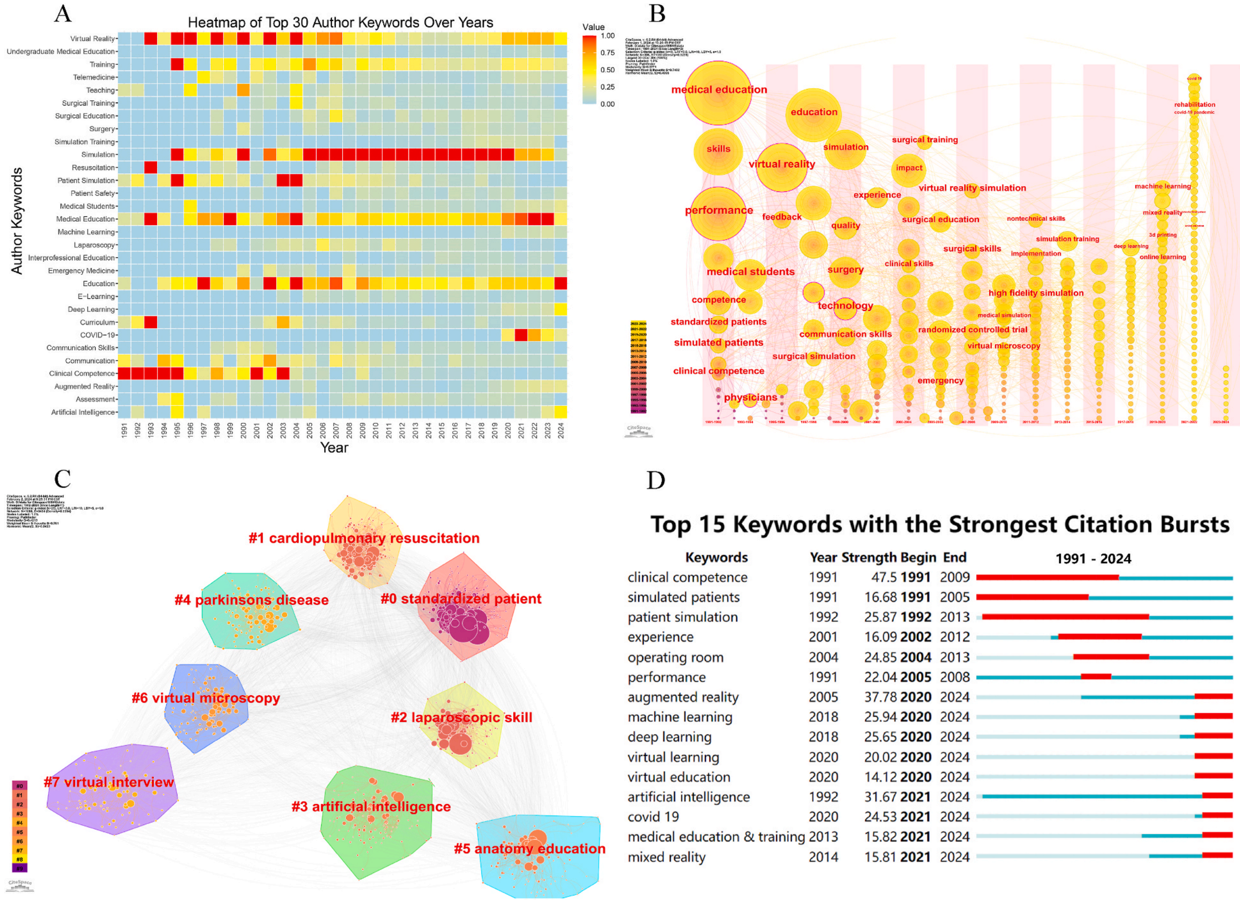

Fig. 8. (A) The heat map of author keywords. (B) The time zone view of keywords. (C) The cluster of keywords. (D) Top 15 keywords with the strongest citation bursts.

Table 7
Keywords clusters in SBME (the silhouette value is over 0.7).

Cluster ID	Size	Silhouette	Label (LLR)	Average Year	Principal Members
0	202	0.794	Standardized patient	2002	medical education; education; performance
1	156	0.773	cardiopulmonary resuscitation	2009	management; health care; patient safety
2	121	0.767	laparoscopic skill	2008	virtual reality; surgery; validation
3	120	0.821	artificial intelligence	2009	system; deep learning; machine learning
4	111	0.703	Parkinsons disease	2013	health; randomized controlled trial; medical student
5	107	0.724	anatomy education	2009	simulation; impact; technology
6	105	0.748	virtual microscopy	2014	undergraduate medical education; virtual microscopy; virtual patients

Table 8
Top 10 keywords related to SBME.

Rank	Keywords	Frequency	Year
1	medical education	1974	1991
2	education	1431	1998
3	performance	1414	1991
4	virtual reality	1239	1995
5	skills	1069	1991
6	simulation	797	2001
7	care	659	1997
8	impact	487	2013
9	medical students	446	1995
10	surgery	352	2000

to the forefront of medical education, adapting to physical distance constraints while maintaining rigorous standards for medical training [16]. This made it a focus of educational research at that time.

The field of SBME is dominated by a few countries, including the United States, the United Kingdom, Canada, China, Australia, Germany, Italy, and France. Notably, China is the only Asian country with a prominent contribution, as shown in Table 1. This highlights the geographical imbalance in SBME research, particularly in developing countries. One possible reason for this imbalance is that scholars may not have given enough attention to research on this topic. This imbalance is also reflected in the institutions conducting research. The top ten institutions with the highest number of publications, as shown in Table 2, are overwhelmingly located in the United States. Only two institutions are located in Canada, with the University of Toronto being the most influential in the field. Regrettably, apart from China, almost no other Asian or African countries made the list. This may be due to the fact that SBME research requires a significant investment, which has led to the emergence of developed countries as the primary locus of research. Still, many non-developed regions, including Asian and African countries, are accepting and exploring SBME. It is evident that SBME is garnering increasing attention on a global scale. The most influential author in the field is William C. McGaghie, an expert in medical education and clinical skills training whose research interests include simulation teaching, clinical skills assessment, and medical professional education. Simulation is important in medical education as it provides a safe environment for students to practice and develop critical medical skills before real-life situations [2].

The most prestigious journal in the field is MEDICAL EDUCATION, which focuses on medical curricula, educational methods, and policies. As a leading medical education journal, it is highly cited. This indicates that MEDICAL EDUCATION is highly recognized among scholars in the field, and scholars are proud to publish in the journal.

4.2. Research hotspots and prospects

The top-referenced references in Table 6 form the basis for research in the area. Highly cited articles reflect valuable and influential research of the time that can set the direction of research in a particular field. Notably, in Fig. 8B, the keywords related to “surgical” and “skill” appear more frequently, indicating that the focus of simulation teaching is on surgical skills training. Additionally, the terms “deep learning,” “machine learning,” “3D painting,” and “online learning” were also mentioned. It appears that AI has played a significant role in the development of 3D printing and online learning. The keywords analysis indicates the significance of standardized patients in the preliminary stages of SBME research. However, these hotspots were later replaced by more advanced simulation techniques. In Fig. 8D, the citation bursts of “deep learning” and “machine learning” in 2020 have had a significant impact, causing a citation explosion in AI. Meanwhile, they promoted the development of virtual education based on augmented reality and mixed reality. It is evident that research is increasingly focused on advancing simulation technology in the service of medical education.

4.2.1. Research hotspots overview

4.2.1.1. Simulated patients. Standardized Patients (SP) is a widely utilized educational tool and assessment method in the field of medical education and clinical skills training, first used by Barrows in the 1960s for psychiatric clinical aptitude tests [17]. SP simulation enables high-fidelity communication skills training and assessment in low-risk environments by simulating real conditions and symptoms, making it the most widely used simulation method in medical simulation education [18]. The use of SP can provide a diverse range of clinical scenarios for training medical students and continuing education of clinicians, including history taking [19], genitourinary examination, and even conversations with a simulated psychopath [20]. Clinical simulation has been shown to improve medical students’ communication skills and self-confidence [6,21]. SP is also used to assess clinical performance, including medical interviewing, differential diagnosis, and decision-making skills [22,23], and with good performance. The purpose of clinical performance assessment is to ensure that the subject has become proficient in these skills. However, due to the increasing cost and increased patient awareness of their rights, identifying an appropriate standardized patient can be challenging. A study conducted through a randomized controlled trial demonstrated that virtual patients can be utilized by students to learn clinical reasoning skills in a safe environment, with the same effectiveness as SP [24]. In the future, it is anticipated that SP will be integrated with digital technology in order to overcome the limitations currently associated with it. Additionally, further research is necessary to demonstrate the transferability of students’ skills.

4.2.1.2. Three-dimensional printing. As a nascent technology that is garnering global interest, 3D printing technology forms highly accurate objects by building them layer by layer based on digital models, which allows for the direct manufacturing of complex objects and improves the fidelity of models used in medical training [25]. With the advent of 3D printing, medical education has seen significant advancements in surgical and anatomical training, shifting from heavy reliance on cadaver dissection and 2D imaging to more realistic and interactive approaches. 3D printing technology has a significant impact on both skill transfer and academic performance of learners. Shen et al. compared the effectiveness of 3D printing techniques for laparoscopic bilioenteric anastomosis simulation training and showed that the use of 3D printed models better facilitated the acquisition and transfer of skills to animal models compared to traditional training techniques [26]. The study by Hojo et al. demonstrated that participants who utilized 3D models exhibited higher ratings than those who utilized textbooks at the outset of their anatomy education. The 3D model-based education was widely accepted by the learners and received positive feedback through questionnaires [27]. Furthermore, By utilizing patient-specific data, 3D printing can create detailed anatomical models, these models were demonstrated to markedly enhance learners’ performance in preoperative planning and intraoperative decision-making [28,29]. Novice students can utilize this to acquire experience in responding to a diverse array of clinical issues. Meanwhile, there is some controversy surrounding the technology of 3D printing. In a study by Cheung et al. [30], 3D models were found to be effective in demonstrating spatial relationships between anatomical structures. However, they were less successful in correctly identifying structures. This discrepancy is likely attributable to the inherent constraints of 3D printing materials. It is therefore imperative to strike a balance between the simplicity of use and the complexity required.

4.2.1.3. Digital-based simulation. Immersive technologies like VR, augmented reality (AR), and mixed reality (MR) provide interactive and realistic simulations for medical education [31]. VR offers full immersion in a digital environment, whereas AR enhances real-world visuals with digital elements, and MR combines both to interact with both real and virtual settings [32,33],. These technologies are increasingly used in medical training for risk-free clinical simulations and surgical training, improving learning experiences by providing realistic scenarios for procedures such as laparoscopic surgery, cardiac surgery, and orthopedic surgery [7,34,35]. A study has shown that VR is more beneficial for novice skill acquisition. Compared to no training or traditional training methods, VR training shows a steeper learning curve, indicating that novices can enhance their skills at a faster rate [34]. It means that medical education resources can be allocated and used more appropriately. VR is also used in anatomy education and has significant advantages. It avoids the ethical concerns of traditional cadaver dissection and the risk of formaldehyde poisoning in dissection laboratories [36]. VR has been shown to enhance long-term retention of anatomical knowledge compared to traditional learning methods [37,38]. However, studies have shown that there is no significant difference in the effectiveness of training clinical skills using VR or AR compared to traditional training methods [39]. There was no real evidence that VR simulation training offered a greater benefit than conventional training. The utility of VR-based medical education remains controversial and more research is needed to prove this.

During the COVID-19 global pandemic, medical education underwent a transition towards distance learning, with the aim of reducing risk for doctors and students. Medical schools launched online platforms with video lectures and conferences, offering flexible and self-organized learning [40,41]. At the same time, online learning posed challenges for teaching clinical skills due to the lack of hands-on opportunities and difficulty in maintaining focus while studying at home [42]. Although virtual dissection tables and mobile VR could provide hands-on experience, they are not yet widely available, in part due to cost and limited research in remote areas [43]. The pandemic has highlighted the value of distance learning, which can extend learning opportunities beyond traditional settings and address the lack of educational resources [42,44]. The epidemic provides an opportunity for the development of distance learning. Instead of debating whether telelearning should or should not be used for medical education, we should consider using it as a complementary method, rather than a replacement, that enhances the overall educational experience [44,45].

4.2.2. Research trend prediction

Artificial intelligence, a key area in computer science, aims to build systems capable of tasks requiring human intelligence, such as learning, reasoning, and problem-solving. AI algorithms, powered by machine learning and deep learning, can handle vast data sets, recognize patterns, and make decisions. With the rise of machine learning and deep learning, AI technology has grown significantly [46,47]. In terms of medical education, the potential for AI to transform traditional learning methods is immense, offering tools for simulation, diagnostics, and personalized learning - redefining the way we train for the challenges of modern medical education.

Through sophisticated algorithms and data processing, AI facilitates the creation of highly realistic simulations. Some advanced VR scenarios, such as the interaction of virtual characters and the generation of natural scenes, need to achieve realistic images and sounds, complex interactions, and natural language, all of which require the use of AI technologies such as machine learning and computer vision [48]. Artificial Intelligence significantly enhances the fidelity of VR and improves the VR-based training experience. It is already being applied in various fields, including ophthalmology, and creating numerous possibilities [49].

With superior model analysis and data processing capabilities, AI significantly optimizes 3D printing technology. Accurate identification of the internal structure of the organ can be achieved through AI, generating highly accurate 3D models [50]. In addition, by analyzing data, AI can determine the optimal ink formulation, accelerating the development of new printing materials [51].

Advanced data processing capabilities have enabled the use of AI for surgical skills training. Mirchi et al. describe a method for training in surgical simulation through the creation of virtual surgical assistants [52]. The use of an AI surgical assistant provides automated educational feedback, allowing students to better understand their skill mastery [52]. A study by Fazlollahi et al. [53]. Showed that performing surgeries with the guidance of an AI tutor is more effective than guidance from a remote expert. This demonstrates the potential of AI in surgical skills training.

4.3. Limitations

There are limitations to our study. Firstly, we restricted our search to the WoSCC database, as different databases use different citation counting methods, which may lead to the exclusion of some literature data. Secondly, we only included English articles and reviews, which may improve the quality of the data. However, the excluded data may provide further insights into the study. Thirdly, we analyzed our data using computer tools, failing to identify all relevant segments. This issue may be resolved in the future with the development of software updates. Nevertheless, we believe that the results are sufficient to reflect the general situation in the industry.

5. Conclusion

This study presents a bibliometric analysis of the distribution of publications, countries, institutions, authors, and journals in the field of SBME research. Additionally, a knowledge map of the SBME research field was created. It can be concluded that the United States has the highest number of publications in this field. The University of Toronto is the institution with the most publications. Konge, Lars is the author with the highest number of publications, while William C. McGaghie is the most influential author. *BMC MEDICAL EDUCATION* is the journal with the most publications. Due to the rapid development of computer technology, the research hotspot is gradually shifting from traditional simulations with real people or mannequins to virtual, digitally-based simulations and online education. In our view, there should be more collaboration between authors in this area in the future. In addition, future research directions are likely to focus on exploring more effective and intelligent simulation technologies, finding a balance in the use of simulation technology to maximize the effectiveness of simulation in teaching and learning, and developing reasonable criteria for evaluating the effectiveness of simulation instruction.

Financial support

The work was supported in part by grants from the Jiangxi Natural Science Foundation (20232BAB216090), Ministry of Education's Project for Demand-Supply Matching in Employment Education (2024011771046) and Ministry of Education's Industry-Academia Cooperation and Collaborative Education Project (231107585221715).

Data availability statement

Data will be made available on request.

Ethics statement

Review and/or approval by an ethics committee was not needed for this study because the research did not involve experimentation on animals or include human subjects.

Informed consent was not required for this study because the research did not involve experimentation on animals or include human subjects.

CRediT authorship contribution statement

Weiming Sun: Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Conceptualization. **Xing Jiang:** Writing – review & editing, Writing – original draft, Formal analysis, Data curation. **Xiangli Dong:** Validation, Software, Methodology, Investigation. **Guohua Yu:** Visualization, Validation, Software, Data curation. **Zhen Feng:** Writing – review & editing, Supervision, Project administration, Conceptualization. **Lang Shuai:** Writing – review & editing, Visualization, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We would like to express our appreciation to all the researchers who have contributed to the field of Simulation-Based Medical Education by providing subjects for our study.

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