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THEORETICAL ARTICLE

A bibliometric analysis of metaverse technologies in healthcare services

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Abstract

A bibliometric analysis was conducted to examine healthcare metaverse research using 3721 Web of Science publications covering the period 1994–2022. Using bibliometric and bibliographic link network analyses, this study aimed to uncover emerging trends, country and university contributions, author collaborations, and common metaverse themes. Contrary to expectations, inconsistent correlations between publication volume and citation impact emerged. This pioneering research evaluated empirical bibliometric laws, identified influential entities, and provided a structured thematic categorization for metaverse studies. Serving as the first comprehensive investigation of the healthcare metaverse, this study lays a solid foundation for subsequent research efforts and guides further scholarly research.

Keywords Metaverse · Healthcare services · Bibliometric analysis · Web of science

1 Introduction

He term "metaverse" is derived from the combination of "meta" and "universe," representing the convergence of the internet, virtual worlds, and augmented reality (AR). It encompasses four core elements: virtual world, mirror world, life logging, and AR (Lee et al. 2011). Initially introduced in Neal Stephenson's 1992 science fiction novel, the metaverse concept depicts individuals from the real world using virtual reality (VR) technology and digital avatars to inhabit a parallel virtual universe. Today, driven by advancements in web and mobile internet technologies, the

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metaverse has emerged as the next-generation internet paradigm, offering users the opportunity to lead digital-native lives in VR (Wang et al. 2022).

Over the past decade, online health communities and telemedicine applications have played pivotal roles in advancing the digital health landscape. Digital health innovations benefit various stakeholders, including pharmaceutical companies, internet platforms, healthcare providers, and patients (Chen and Zhang 2022). Wearable health devices, such as smartwatches, seamlessly synchronize with mobile applications to track vital metrics, sleep patterns, caloric consumption, and physical activity (Lee and Lee 2020). In the realm of orthopedic surgery, Oculus, a subsidiary of Meta, contributes significantly. Peer-to-peer support thrives in online health communities, enhancing patient–doctor interactions (Chen and Zhang 2022).

The term "metaverse" gained prominence during the COVID-19 pandemic as face-to-face interactions were restricted, particularly in health education. This limitation affected cross-border medical training and observation of advanced medical procedures. To overcome these challenges, the medical field introduced educational methods such as the "metaverse" to fulfill the increasing demand for remote training (Koo 2021). As the pandemic reshaped lifestyles, the healthcare sector turned to technology to fulfill essential needs. This shift has generated a growing interest in the metaverse as a secure digital realm for remote interactions.

Emerging technologies, such as VR, AR, and mixed reality serve as the foundation for metaverse-related concepts. These technologies offer immersive experiences that can either supplement or entirely replace traditional services. They achieve this by transporting users into alternative environments (Belk et al. 2023). While there exists an extensive body of literature on telemedicine, this study addresses the gap by conducting a comprehensive bibliometric analysis of healthcare metaverse development. Our approach involves categorizing studies into 12 thematic clusters, with a detailed examination of the top five most cited clusters and a summarization of the remainder. To achieve this, we analyzed 3721 healthcare metaverse publications up to April 28, 2022. Our analysis applies Zipf's Law, Bradford's Law, and Lotka's Law to enhance our understanding. The research questions (RQs) guiding our study are as follows:

RQ1: What are the top publishing countries, authors, universities, and journals?
RQ2: How are publications distributed by language, document type, and research area?
RQ3: Does the distribution of publications among authors adhere to Lotka's Law?
RQ4: Does the distribution of publications among journals fit Bradford's Law?
RQ5: Does the distribution of keywords fit Zipf's Law?
RQ6: Who are the most influential researchers?
RQ7: Which journals have the greatest impact?
RQ8: Which countries and universities have the greatest impact?

This study makes important contributions to the existing literature on the healthcare metaverse in many ways. Through a rigorous bibliometric analysis covering nearly five decades, our research provides a comprehensive overview of the scientific landscape in this emerging field. Categorizing studies into thematic clusters, our research provides nuanced insights into specific subtopics and research areas and guides future research. The assessment of bibliometric laws adds empirical rigor to the findings and serves as a reference for future research. Furthermore, the identification of influential universities, authors and countries stimulates opportunities for collaboration and resource allocation strategies. By directly addressing relevant research questions, it provides clarity on the study's objectives and conclusions. Finally, this study pioneers a relatively understudied area, laying a solid foundation for future research efforts. It makes a significant contribution to the existing literature by being the first study in this field to seamlessly combine bibliometric analysis, bibliometric laws, and bibliometric network analysis.

The remainder of the paper is organized as follows. Section 2 examines prior research on the bibliometric analysis of metaverse. Section 3 outlines the methodologies used in this research, including the data collection procedure, and the analytical techniques applied. The results, including key trends, patterns, and relationships identified in the literature, as well as a detailed analysis of the bibliographic coupling network, are presented in Sect. 4. Section 5 is dedicated to a comprehensive discussion of the results. The paper concludes with Sect. 6, which covers "Theoretical Implications," "Practical Implications," and "Limitations and Future Research."

2 Literature review

2.1 Metaverse technologies in healthcare

In the realm of metaverse services, four fundamental technologies have emerged: VR, AR, mixed reality (MR), and extended reality (XR). VR is a graphical interface that enables users to engage width a simulated virtual world through a range of VR equipment, such as VR headsets, motion trackers, gloves, and body suits (Bale et al. 2022). AR technology operates on a location-aware platform that can integrate digital graphics into the physical world. Utilizing devices such as glasses, smartphones, and lenses, an AR system aligns with the actual surroundings, overlaying supplementary information onto it (Gandi et al. 2023). MR integrates data from both the physical and virtual worlds, merging them into a unified virtual space. XR embodies a comprehensive concept encompassing VR, AR, MR, and potential future realities (Lee 2022).

Metaverse technologies are revolutionizing healthcare with their versatile applications. These technologies play a pivotal role in healthcare, spanning medical training, surgical procedures, and patient care, providing a virtualized perspective of patients' conditions for precise surgical targeting (Lee 2022). In addition, XR technologies are transforming surgical broadcasts, as demonstrated by the smart operating room of Seoul National University (SNU) Bundang Hospital. Equipped with a 360°–8 K-3D camera, this technology offers an immersive experience, making observers feel as though they are present in the actual operating room (Koo 2021). VR; on the other hand, is beneficial for maintaining both physical and mental health. It has been effective in treating mental health issues, such as public speaking anxiety and driving phobias, when integrated with cognitive behavior therapy or exposure therapy (Trappey et al. 2020; Lindner et al. 2021). VR has also been used to improve the emotional well-being of patients with lung disease and reduce anxiety and stress (Rutkowski et al. 2021). AR can streamline medical staff operations and enhance patient health management, aiding in tasks like patient information retrieval and developing surgical support systems (Lee 2022). AR in education is exemplified by Cruscope's Virtuali-Tee, an AR T-shirt allowing students to explore the human body's inner workings as if in an anatomy lab. Moreover, AR technology continues to advance in healthcare, with projects like the spinal surgery platform developed in collaboration with university laboratories, projecting real-time images onto the human body structure for spinal fixation (Kye et al. 2021).

2.2 Previous studies on metaverse services

Previous studies on metaverse services cover a wide range of topics, including bibliometric analyses, healthcare applications, educational perspectives, and the broader implications of the metaverse in various domains. Damar (2021), Rejeb et al. (2023), Verma and Sharma (2023), and Wider et al. (2023) focus on conducting comprehensive bibliometric analyses of the metaverse research landscape. Damar (2021) focuses on metaverse technology trends. Rejeb et al. (2023) conduct a metaverse-related journal article analysis, which is a first in this field. Wider et al. (2023) provide a comprehensive overview, while Verma and Sharma (2023) summarize the available literature. Taken together, these works map the growing landscape of metaverse research.

Bansal et al. (2022), Musamih et al. (2022), Chengoden et al. (2023), and Ullah et al. (2023) investigate various applications of the healthcare metaverse. Bansal et al. (2022) and Musamih et al. (2022) thoroughly delve into applications ranging from telemedicine to healthcare facilities. Chengoden et al. (2023) shed light on how the metaverse could address healthcare challenges, while Ullah et al. (2023) explore ways the metaverse can be used in healthcare settings. Together, they collectively explore the potential of the metaverse and its positive impact on the healthcare sector.

Tas and Bolat (2022) and Tlili et al. (2022), on the other hand, primarily focus on incorporating the metaverse into educational environments. Tas and Bolat (2022) evaluate existing research on using the metaverse in education, while Tlili et al. (2022) examine its use in studies. In relation to education, their studies investigate the opportunities and effects of integrating the metaverse.

The integration of technology in healthcare settings is also explored by Pera (2022), Petrigna and Musumeci (2022), and Chengoden et al. (2023). Pera (2022) specifically looks at how VR technologies can be utilized in treating illnesses, while Petrigna and Musumeci (2022) address how the metaverse can facilitate access to healthcare services. Chengoden et al. (2023) emphasize the incorporation of metaverse technologies into healthcare, emphasizing the potentially groundbreaking impact on the healthcare industry.

Damar (2021), Garavand and Aslani (2022), and Ullah et al. (2023) investigate new developments and future directions in the use of metaverse in healthcare.

Damar (2021) addresses the implications of the growth of metaverse technology for everyday life. Garavand and Aslani (2022) explore the increasing use of metaverse in healthcare domains, while Ullah et al. (2023) speculate on future research prospects involving AR/VR technology, especially in remote medical consultations. They provide insight into the emerging models and future outlooks of the role of the metaverse in healthcare.

The metaverse is extensively examined by Bansal et al. (2022), Musamih et al. (2022), and Chengoden et al. (2023). Bansal et al. (2022) provide a comprehensive review of the metaverse focusing on collaboration mechanisms, implementation standards, and potential directions for future research. Musamih et al. (2022) also provide a detailed review in the areas of metaverse covering system architecture, enabling technologies and potential challenges. In their research, Chengoden et al. (2023) thoroughly investigate the applications of the healthcare metaverse. They provide an overview by examining examples and presenting case studies that offer valuable insights into the potential of the metaverse in various fields.

Works such as Ullah et al. (2023) and Damar (2021) represent the nature of research in healthcare showcasing a diverse range of knowledge and perspectives that contribute to its development. Moreover, Bansal et al. (2022), Musamih et al. (2022), and Chengoden et al. (2023) delve into themes related to the role of the metaverse in healthcare making them valuable resources, for readers seeking an understanding.

3 Methods

3.1 Research design

This paper performs a bibliometric analysis to determine the current state of research on metaverse in the field of healthcare. The study consists of two primary components: First, a comprehensive bibliometric analysis examines patterns and advancements in healthcare metaverse research. Second, a bibliographic coupling network analysis is conducted to identify research themes associated with the healthcare metaverse.

3.2 Data collection

Data were collected from the web of science (WoS) database from 1994 to 2022, which is one of the most comprehensive databases. We used a 28 year time span because the first healthcare metaverse-related paper was appeared in 1994, and we would like to review all the publications related to the topic as of April 28, 2022. A total of 3721 publications have been found in this database, which is the main data source of this study. As mentioned in the earlier sections, the metaverse is closely related to VR and AR. The metaverse relies significantly on VR and AR technologies, especially in healthcare applications. So, the following search keywords were used in the Web of Science database: “health” "metaverse" (Topic) OR "health metaverse" (Topic) OR "virtual reality in health" (Topic) OR "augmented reality in health" (Topic) OR "healthcare metaverse" (Topic) OR "metaverse health" (Topic) OR "metaverse healthcare" (Topic) OR "metaverse" "health" (Topic) OR "metaverse" "healthcare" (Topic) OR "healthcare" "metaverse" (Topic) OR "AR in health" (Topic) OR "VR in health" (Topic) OR "augmented reality" "health" (Topic) OR "virtual reality" "health" (Topic) OR "health" "virtual reality" (Topic) OR "health" "augmented reality" (Topic). Because WoS lets download up to 500 records simultaneously, the dataset we obtained contains eight different ".text" files. The exported data content included the full records and cited references in a tab-delimited text file format. The flow chart for the bibliometric analysis procedure is given in Fig. 1.

3.3 Data processing and tools

In this study, bibliometric analysis was conducted using VOSviewer and Microsoft Excel. The analysis and visualization of extensive bibliographic datasets were facilitated by VOSviewer through its modularity-based clustering method, which is similar to multidimensional scaling (Damar 2021). Microsoft Excel was employed for the generation of summary tables and graphs and the application of methods such as Zipf's Law, Bradford's Law, and Lotka's Law.

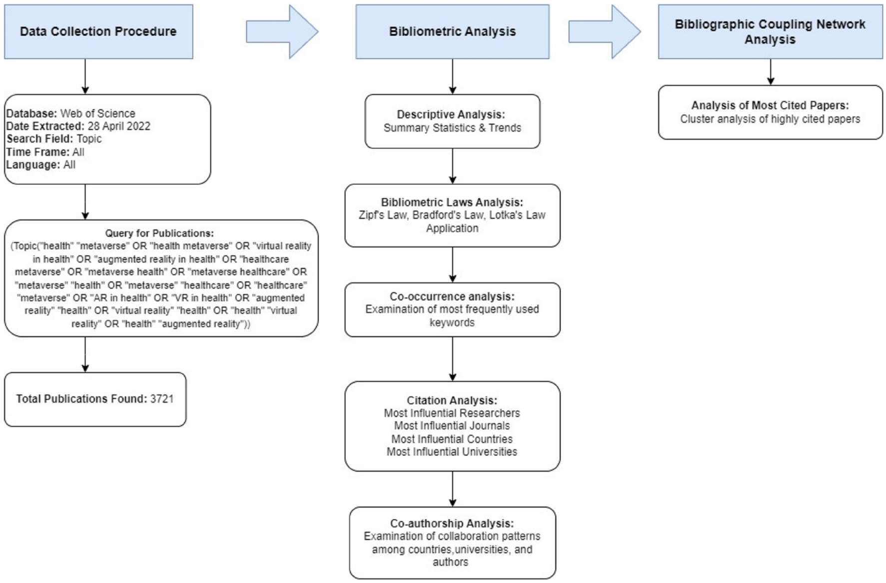

Fig. 1 Flow chart of the bibliometric analysis procedure

4 Results

4.1 Bibliometric analysis

This study analyzed trends in annual publications and citations from 1994 to 2022. It revealed a gradual increase in both publications and citations between 1994 and 2006, followed by relative stability. However, starting in 2007, a substantial and consistent increase occurred. It is important to note that the trend in publications closely mirrored the trend in citations.

In examining healthcare metaverse research in the top three countries, the USA leads with 21.781%, followed by England (7.090%) and Italy (5.705%). Among universities, "Università Cattolica del Sacro Cuore" holds the highest number of publications at 0.624%, followed closely by "University Valencia" (0.535%) and "Istituto Auxologico Italiano" (0.502%). The top contributors to healthcare metaverse research include G. Riva (0.370%), B. K. Wiederhold (0.222%), and C. Botella (0.199%). The leading journals in this field are the "Journal of Medical Internet Research" (1.908%), "International Journal of Environmental Research and Public Health" (1.827%), and "Frontiers in Psychology" (1.371%). Figure 2 shows the top 10 journals. These collective findings address RQ1, showcasing the top contributors across countries, universities, authors, and journals in the healthcare metaverse domain.

The publications were written in 11 different languages. The most common language used was English, accounting for 97.071%, followed by Spanish at 1.021% and Portuguese at 0.699%. The types of publications related to the metaverse in healthcare were also analyzed. It was reported that 58.479% are "Article," 25.020% are "Proceedings Paper," and 15.265% are "Review Article." Regarding research areas, "Computer Science" leads with 26.391%, followed by "Engineering" at 16.958%, and "Psychology" at 11.234%. This paragraph effectively addresses RQ2

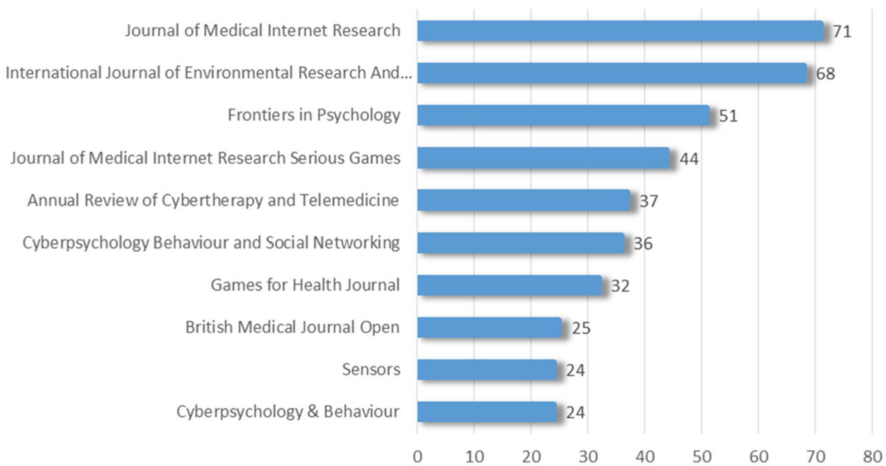

Fig. 2 Publication according to journals

by elucidating publication distribution based on language, document type, and research areas within the healthcare metaverse literature.

Lotka's Law specifies the publication frequency of authors in a particular field of study. It points out that "…the number (of authors) making n contributions is about $1/n^2$ of those making one, and the proportion of all contributors that make a single contribution is about 60 percent." According to the rule, the majority of authors (60 percent) will publish only one work. In contrast, 15 percent will publish two, 7 percent will publish three articles, and so on (Ahmad and Batcha 2020). The formula below may be used to represent this

$$y(x) = \frac{y(1)}{x^2} \tag{1}$$

where $y(1)$ is the number of authors with one paper, and $y(x)$ is the number of authors with x papers (Qiu et al. 2017). Lotka's law, which is characterized by frequency-based author ranking, reveals a square inverse relationship that constrains article concentration and dispersion (Qiu et al. 2017). Concerning RQ3, the study examined authorship distribution employing Lotka's Law. Comparing the observed author distribution to Lotka's law exposes significant disparities. According to Table 1, which shows the application of Lotka's Law up to ten articles, most authors (88.13%) contributed only once, 8.18% making two contributions, 1.97% contributing three times and 0.95% contributing four times, etc. This observed distribution deviates notably from Lotka's equation.

Bradford's Law can be defined as a quantitative relationship between journals and their publications. This law states that only a limited number of core journals will provide the core of articles on a particular topic. This core corresponds to a significant portion, typically one-third, of the total articles. Following this core, there is a second group of journals, larger in number, responsible for another third of the articles. Beyond that, a much larger group of journals contributes to the final third of the articles (Rajeswari et al. 2021). Bradford's multiplier factor is calculated by dividing the journals of a zone by the previous zone. This multiplier factor is expressed as the

Table 1 Lotka's law

No. of articles	Observed no. of authors	Observed %	Expected no. of authors	Expected %
1	12,828	88.13	12,828	62.87
2	1191	8.18	3207	15.72
3	287	1.97	1425	6.99
4	138	0.95	802	3.93
5	44	0.30	513	2.51
6	20	0.14	356	1.75
7	7	0.05	262	1.28
8	6	0.04	200	0.98
9	11	0.08	158	0.78
10	7	0.05	128	0.63

ratio of the number of journals in any zone to the one immediately preceding it. This relationship is expressed as $1{:}n{:}n^2$ (Clarance and Raja 2020).

Table 2 reveals the distribution of journals across different zones. Zone I comprises 110 journals, collectively responsible for 33.3% of the total publications. Zones II and III each encompass 667 and 1241 journals, respectively, contributing to 33.3% of the publications.

Bradford's multiplier factor (k) is calculated by dividing the number of journals in a zone by the number of journals in the previous zone.

$$= \frac{(6.06 + 1.86)}{2} = 3.96 \tag{2}$$

$$= 1 : n : n^2 \tag{3}$$

$$= 110 : 110 * 3.96 : 110 * 3.96^2 \tag{4}$$

$$= 110 : 435.6 : 1724.976 \gg 2270.576 \tag{5}$$

Hence, the percentage of error $= \left[\frac{|2270.576-2018|}{2270.576}\right] * 100 = 11.12\%$, indicating that Bradford's Law does not apply to this study due to the high percentage of error. It directly responds to RQ4 by assessing the relevance of Bradford's Law in describing distribution of publications among journals in healthcare metaverse research.

Zipf's Law refers to a word frequency ranking that is often used to estimate the frequency of word usage within a text. The law states that "list the words occurring within that text in order of decreasing frequency, the rank of a word on that list multiplied by its frequency will equal a constant. The equation for this relationship is: $r \times f = k$, where r is the rank of the word, f is the frequency, and k is the constant" (Lalrempuii et al. 2020).

In Table 3, the application of Zipf's law was examined for the top ten most frequently used keywords. The first position in terms of frequency was taken by the term "virtual reality," which was observed 1391 times. Following closely, "augmented reality" was identified 362 times, while the 3rd position was secured by "rehabilitation" with a frequency of 164. Contrary to expectations, the application of Zipf's Law yielded results that do not align with the findings. This directly addresses RQ5 by investigating the frequency distribution of keywords and their alignment with Zipf's Law.

Table 2 Bradford's law zone

Bradford's zone	No. of journals	% of journals	No. of publications	% of publications	k
Zone 1 (core)	110	5.45	1239	33.30	–
Zone 2	667	33.05	1241	33.35	6.06
Zone 3	1241	61.50	1241	33.35	1.86
Total	2018	100	3721	100	

Table 3 Zipf's law

Rank (*r*)	Keyword	Frequency (*f*)	*r***f*=*k*
1	Virtual reality	1391	1391
2	Augmented reality	362	724
3	Rehabilitation	164	492
4	Mental health	138	552
5	Simulation	120	600
6	Technology	94	564
7	Stroke	85	595
8	Education	83	664
9	Serious games	78	702
10	Telemedicine	75	750

A co-occurrence analysis was conducted for author keywords with at least five occurrences, as shown in Fig. 3. Out of 7694 keywords, 445 were used for the analysis. The keywords were then categorized into 12 clusters. The largest cluster contained 63 items, followed by clusters with 51, 48, and 42 items, respectively.

4.1.1 Most influential researchers

To determine the most influential authors in the field of healthcare metaverse, a citation analysis was conducted on 14,555 authors. The top 10 authors are ranked in Table 4 according to their total link strength (TLS) and citation values. Total link strength refers to the overall strength of the links that exist between a particular item

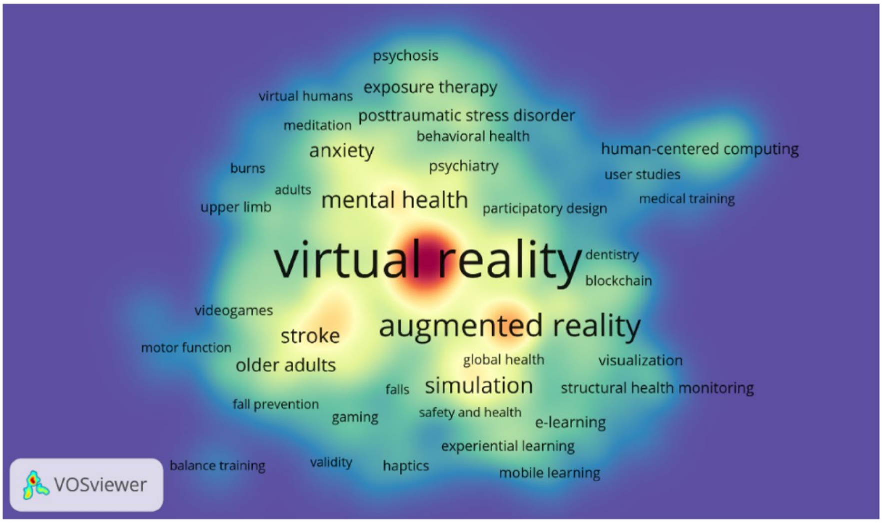

Fig. 3 Co-occurrence analysis of author keywords

Table 4 Most influential authors according to TLS and citation

	According to TLS			According to citation		
Rank	Author	Documents	TLS	Author	Documents	Cites
1	G. Riva	65	2056	G. Riva	65	1768
2	P. Langhorne	35	1044	P. Langhorne	2	1585
3	J. Bernhardt	39	951	J. Bernhardt	1	1226
4	G. Kwakkel	30	776	G. Kwakkel	1	1226
5	Z. Bao	20	711	Z. Bao	1	952
6	J. W. Chung	23	692	J. W. Chung	1	952
7	A. Ehrlich	1	545	A. Ehrlich	1	952
8	V. R. Feig	1	545	V. R. Feig	1	952
9	A. M. Foudeh	1	545	A. M. Foudeh	1	952
10	A. Gasperini	1	545	A. Gasperini	1	952

and other items. For example, when analyzing co-authorship relationships between researchers, the total link strength attribute measures the overall strength of the co-authorship relationships that a given researcher shares with colleagues (Van Eck and Waltman 2018). G. Riva stands out as the most influential author based on TLS values, with C. Botella and B. K. Wiederhold also making significant contributions. Similarly, G. Riva leads the way in terms of citations, followed by P. Langhorne and J. Bernhardt in the second and third positions, respectively. Notably, the top 10 authors based on citations or TLS do not necessarily align with those who have the most publications. This observation underscores that an author's influence is not solely determined by their publication quantity. This analysis comprehensively addresses RQ6, most influential researchers, by examining the relationship between authors' publication volumes and their impact.

4.1.2 Most influential journals

The results of the citation analysis are presented in Table 5, which lists the top 10 journals according to TLS and citation values. The journal "Cyberpsychology Behavior and Social Networking" stands out as the most influential, boasting the highest TLS score. Similarly, "Cyberpsychology and Behavior" and "Journal of Medical Internet Research" emerge as influential journals with notable TLS values. However, it is crucial to highlight that "Journal of Medical Internet Research" not only ranks among the top influential journals but also secures the position of the most impactful journal. It is supported by an impressive citation count, recording 71 publications cited 1851 times and earning a TLS score of 142. In addition to these, "Lancet" and "Cyberpsychology and Behavior" are notable for their high citations, further enriching the landscape of influential journals. In response to RQ7, these findings offer valuable insights into specific journals' influence, with "Journal of Medical Internet Research" clearly holding the greatest impact.

Table 5 Most influential journals according to TLS and citation

Rank	According to TLS			According to citation		
	Journal	Documents	TLS	Journal	Documents	Cites
1	Cyberpsychology behavior and social networking	36	207	Journal of medical internet research	71	1851
2	Cyberpsychology and behavior	24	187	Lancet	2	1385
3	Journal of medical internet research	71	142	Cyberpsychology and behavior	24	1088
4	Psychological medicine	3	135	Nature	2	959
5	International journal of environmental research and public health	68	135	Journal of neuroengineering and rehabilitation	19	920
6	Journal of medical internet research serious games	44	101	Cochrane database of systematic reviews	9	818
7	Games for health journal	32	98	Developmental medicine and child neurology	2	697
8	Computers in human behavior	19	87	Cyberpsychology behavior and social networking	36	646
9	Social psychiatry and psychiatric epidemiology	3	83	Quality and safety in health care	1	597
10	Frontiers in psychiatry	21	82	International journal of medical informatics	5	593

4.1.3 Most influential countries

A citation analysis involving 101 countries was conducted to assess their influence on healthcare metaverse research. Table 6 presents the top 10 countries based on TLS values and citation counts. The USA displayed the highest TLS value, indicating its leading position, followed by England and Italy. Similarly, in terms of citation counts, the USA ranked first, followed by England and Australia. Thus, the most influential countries in healthcare metaverse research, as determined by both TLS values and citations, include the USA, England, and Australia. This analysis effectively addresses RQ8, shedding light on the healthcare metaverse's most influential countries.

4.1.4 Most influential universities

Four thousand, two hundred eighty-two universities were subjected to citation analysis. Table 7 shows the top 10 influential universities according to the highest number of TLS and citations. Università Cattolica del Sacro Cuore is the most influential university with the greatest TLS score. The Istituto Auxologico Italiano and King's College London ranked 2nd and 3rd positions and were influential universities with high TLS values. In terms of citations, the lead is taken by Stanford University, followed by the University of Toronto and the University of Glasgow. Considering the citations and TLS values, it can be claimed that the Istituto Auxologico Italiano is the most influential university. This analysis aligns with RQ8 by evaluating and highlighting the impact of universities in healthcare metaverse research.

Table 6 Most influential countries according to TLS and citation

Rank	According to TLS			According to citation		
	Country	Documents	TLS	Country	Documents	Cites
1	USA	1069	1992	USA	1069	20,511
2	England	348	1194	England	348	8578
3	Italy	280	912	Australia	251	6477
4	Australia	251	831	Canada	217	5124
5	Spain	258	785	Italy	280	4595
6	Canada	217	588	Netherlands	156	4336
7	Netherlands	156	425	Spain	258	3591
8	Peoples Republic of China	221	386	Scotland	59	2973
9	Germany	217	357	Germany	217	2722
10	Sweden	68	309	South Korea	107	2574

Table 7 Most influential universities according to TLS and citation

Rank	According to TLS			According to citation		
	University	Documents	TLS	University	Documents	Cites
1	Università Cattolica del Sacro Cuore	56	976	Stanford University	42	2399
2	Istituto Auxologico Italiano	45	858	University Toronto	34	2274
3	King's College London	29	628	University Glasgow	12	1619
4	University Valencia	48	593	University British Columbia	22	1406
5	University Oxford	20	568	Istituto Auxologico Italiano	45	1381
6	University Washington	41	532	La Trobe University	8	1334
7	Universitat Jaume 1	37	517	University Medical Center Utrecht	6	1291
8	Oxford Health National Health Service Foundation Trust	6	495	Vrije University Amsterdam Medical Center	4	1277
9	University Barcelona	17	495	Florey Neuroscience Institute	1	1226
10	University Southern California	21	444	King's College London	29	1179

4.1.5 Co-authorship analysis

A co-authorship analysis was conducted to evaluate collaboration in healthcare metaverse research among countries. Out of 101 countries, 65 countries met the publication threshold and were included in the analysis. The findings revealed the existence of six distinct clusters, as depicted in Fig. 4. These clusters showcase how all countries are interconnected within the research network. Notably, the analysis identified influential countries based on TLS values. These influential countries include the USA, England, Germany, Canada, Italy, the Netherlands, Australia, Spain, Switzerland, and Belgium. In addition, it was noted that certain countries like the USA, England, Australia along with Spain and Canada share common clusters. This suggests a significant level of international collaboration within this field.

Co-authorship analysis was carried out on universities that had at least five publications. A total of 365 universities met this requirement and were included in the analysis. The analysis resulted in the identification of 31 clusters, with 18 of them displaying connections, as shown in Fig. 5. This interconnectedness highlights the strong collaborative efforts among universities. Notably, the top five universities, based on their TLS values, are Università Cattolica del Sacro Cuore, University Valencia, Istituto Auxologico Italiano, Universitat Jaume 1 and University Washington. It is interesting to note that some of these universities belong to the same cluster.

Co-authorship analysis, focusing on authors with a minimum of 5 publications out of the total 14,555 authors, was undertaken. This threshold was met by 111 authors. The analysis revealed 50 distinct clusters, with some of them interconnected. These clusters varied in size, with Cluster 1 having 11 authors, Cluster 2

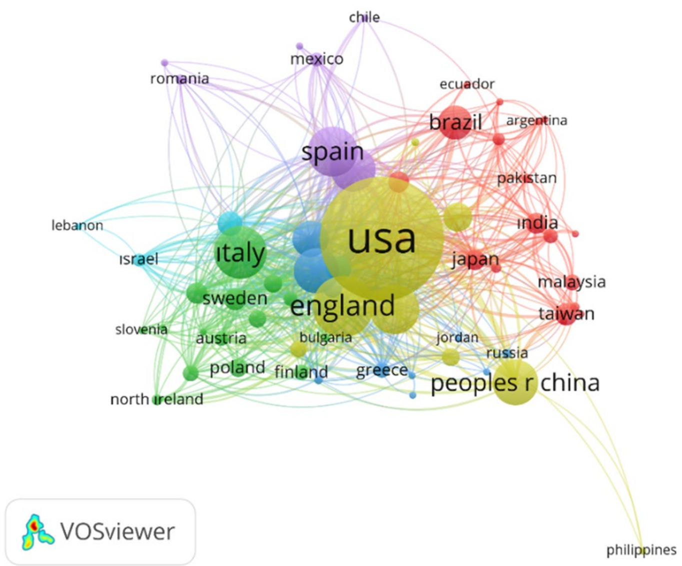

Fig. 4 Co-authorship network map of countries

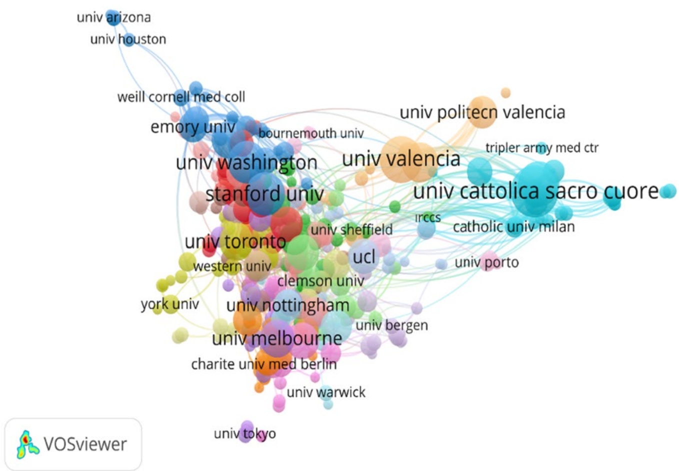

Fig. 5 Co-authorship connected clusters map of universities

having 10, and Cluster 3 consisting of 9 authors. Clusters 4 and 5 each included 5 authors, while Cluster 6 had 4. In addition, there were 8 clusters with 3 authors, 7 clusters with 2 authors, and 29 individual authors. Collaborative author groups are visually represented in different colors in Fig. 6. Overall, it is evident that collaboration among scholars in the field of metaverse in healthcare remains insufficient.

In the connected clusters map, the most significant cluster is represented in red and includes 9 authors. Notably, G. Riva has the highest number of publications in this cluster with 65 publications, followed by A. Gaggioli with 30 publications and P. Cipresso with 17 publications. The second important cluster, highlighted in green, also comprises 9 authors. Within this cluster, C. Botella stands out with 35 publications, accompanied by M. Alcaniz with 17 publications and R. M. Banos with 14

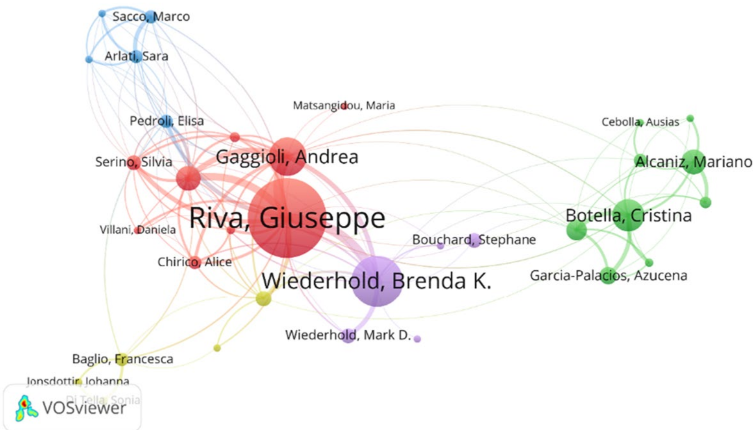

Fig. 6 Co-authorship connected clusters map of authors

publications. The third cluster, depicted in blue, consists of 5 authors. In this cluster, M. Sacco, S. Arlati, and E. Pedroli each have 9 publications, making them the leading authors.

4.2 Bibliographic coupling network analysis

Bibliographic coupling occurs when two documents share one or more references, which indicates that they refer to the same source. This coupling provides insight into the similarity between publications in terms of subject or other characteristics (Kurutkan and Orhan 2018).

In VOSviewer, a bibliographic coupling network analysis was performed. The analysis type selected was “bibliographic coupling,” and the unit of analysis considered was “documents.” A minimum document citation threshold was set at 20. Out of the 3721 documents, 653 met these criteria, resulting in 628 interconnected documents. These interconnected documents were then categorized into 12 thematic clusters by VOSviewer. Figure 7 illustrates the network of interconnected documents, depicting the relationships of bibliographic coupling. Subsequently, a comprehensive review of articles within each cluster was conducted to identify and categorize their respective topics.

(1) Cluster 1: Stroke and rehabilitation after stroke
(2) Cluster 2: Simulation
(3) Cluster 3: Mental health
(4) Cluster 4: Physical health
(5) Cluster 5: Construction health and safety
(6) Cluster 6: Pain management
(7) Cluster 7: Psychotherapy
(8) Cluster 8: VR applications AR games
(9) Cluster 9: Wearables in IoT

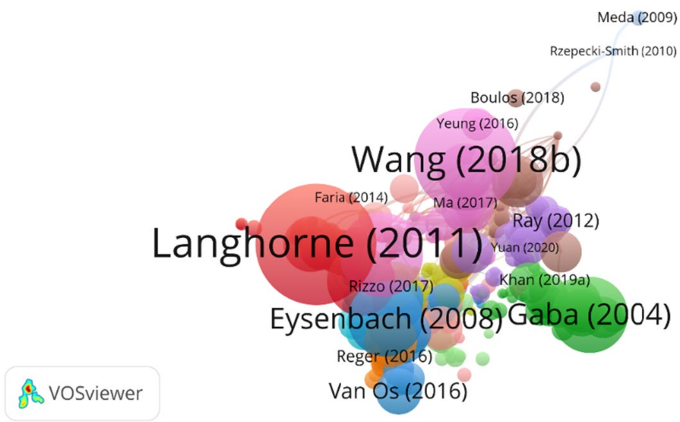

Fig. 7 Bibliographic coupling connected document network map

(10) Cluster 10: Computer-aided treatment and VR
(11) Cluster 11: Environmental perceptions and nature therapy
(12) Cluster 12: Driving behavior

The three most cited papers in the top five large clusters are described in the following sections, and the remaining clusters are summarized.

4.2.1 Cluster 1: stroke and rehabilitation after stroke

Cluster 1 is the largest among the clusters, comprising 125 publications, and it primarily focuses on stroke rehabilitation and post-stroke recovery. Langhorne et al. (2011) conducted an extensive review that encompassed principles of rehabilitation practice, care systems, and specific interventions for stroke rehabilitation. Their study also assessed the effectiveness of interventions addressing stroke-related impairments. Ekeland et al. (2010) performed a systematic review of telemedicine interventions. They evaluated 80 heterogeneous reviews from the EPOC (Cochrane Effective Practice and Care). Out of 1593 identified articles, they selected 80 systematic reviews for quality assessment. The results indicated that 21 reviews reported the effectiveness of telemedicine. Giggins et al. (2013) focused on biofeedback applications in physical rehabilitation. They categorized these applications into physiological and biomechanical groups, with a specific emphasis on real-time biofeedback.

4.2.2 Cluster 2: simulation

Cluster 2 is the second-largest cluster, comprising 102 publications centered on simulation. Gaba (2004) aimed to create a comprehensive framework for understanding various applications of simulation in healthcare. He proposed an 11-dimension classification system to categorize these applications and investigated the advantages of fully integrating simulation into healthcare. He also outlined factors that may determine future publication trends in this field. Larsen et al. (2009) examined the impact of VR simulator training on laparoscopic surgery. They divided patients into two groups: one receiving VR simulator training and the other serving as the control. The study measured technical performance and operating time, revealing that proficiency-based VR simulator training positively impacted laparoscopic surgery skills. In addition, Rosen (2008) provided a detailed historical account of medical simulation's development. He traced its origins as 'an imitation of some real thing, state of affairs, or process' for developing abilities, judgment, and problem-solving.

4.2.3 Cluster 3: mental health

Cluster 3 consists of 74 publications, all centered around the theme of mental health. Eysenbach (2008) introduced the concept of Medicine 2.0, which he defined as: "Medicine 2.0 applications, services, and tools are Web-based services for health care consumers, caregivers, patients, health professionals, and biomedical researchers, that use Web 2.0 technologies and/or semantic web and VR tools, to enable and facilitate specifically social networking, participation, apomediation, collaboration, and openness within and between these user groups." Mohr et al. (2013) investigated behavioral intervention technologies (BITs) in the context of mental health. Their findings indicated that web-based interventions and video conferencing for psychotherapy were effective. However, they also noted that mobile technologies had a limited impact on mental health outcomes. Freeman et al. (2017) highlighted the increasing demand for VR technology among clinicians and researchers in the mental health field. They conducted a comprehensive review of 1096 studies published until the end of 2016. Their focus was on the use of VR in treating major mental health illnesses in adults. For this review, they utilized the PubMed database and included 285 studies that met their criteria.

4.2.4 Cluster 4: physical health

Cluster 4 focuses on physical health and comprises 62 publications. Hershfield et al. (2011) suggested that photorealistic age-progressed depictions could encourage individuals to prioritize their future well-being. In four separate studies, participants used interactive decision tools and immersive VR technology to choose between immediate or delayed consumption. They subsequently engaged with digitally created future self-images. In another study, Muessig et al. (2015) conducted a comprehensive review of research published between 2013 and 2014. They aimed to explore the utilization of eHealth, mHealth, and "Web 2.0" in preventing and treating HIV. Among current trends, they identified 32 funded active initiatives, and 23 published intervention works. These initiatives employed tools such as social networking websites, gamification, and VR. Furthermore, Warburton et al. (2007) investigated whether combining interactive video games with stationary cycling produced more significant improvements in physical fitness compared to traditional stationary cycling alone (control group). Their findings demonstrated that the training program, integrating interactive video games and cycling, indeed yielded substantial enhancements in health-related physical fitness.

4.2.5 Cluster 5: construction health and safety

Cluster 5 comprises 54 publications related to construction health and safety. In one study, Cobb et al. (1999) conducted nine experiments with 148 participants to assess the health and safety impacts of using head-mounted displays (HMDs) in virtual environments (VEs) with different exposure durations and systems. They found that the most significant effects were observed in disease signs and physiological measures. In another study, Sacks et al. (2013) utilized immersive virtual environment (IVE) technology to develop a virtual construction site and conducted experiments to assess several safety activity settings. They discovered a significant benefit of VR training for cast-in-situ concrete work and stone cladding work. However, this benefit was not observed for general site safety. The study showed that VR training improves trainees' attention and concentration. Ray and Teizer (2012) proposed a real-time system to categorize and observe the posture of construction workers using emerging 3D range camera technology. They classified the worker's posture as "standing," "bending," "sitting," or "crawling." This information was then used to categorize tasks as ergonomic or non-ergonomic, with the assistance of OpenNI middleware.

4.2.6 Remaining clusters

Since the clusters that remain are comparatively small, they have not been discussed in detail; nevertheless, they can be summarized as follows.

Cluster 6 consists of 51 publications that primarily focus on pain management. These studies examine the effectiveness of VR technology in alleviating pain and anxiety during medical procedures. In addition, they investigate VR's role in detecting and treating mental illnesses, along with its application in using e-health technology to assist patients dealing with chronic pain.

Cluster 7 is composed of 47 publications related to psychotherapy. The cluster explores the potential of VR and other technologies to enhance psychological treatments, particularly for anxiety and post-traumatic stress disorder (PTSD). Studies within this cluster investigate the efficiency of virtual reality exposure-based therapy (VR-EBT) and virtual reality exposure (VRE) in treating PTSD among active-duty soldiers and highlight the benefits of using affordable consumer VR technology to automate the delivery of psychological interventions. In addition, the cluster discusses the current state of therapy effectiveness for PTSD and emphasizes the importance of understanding its treatment and etiology to deliver influential care to individuals in need.

Cluster 8 comprises 30 publications that center on VR applications and AR games. The publications cover various topics such as the Visible Human Project, simulation as an alternative to traditional learning, accessible therapies for mental health, non-pharmacological strategies for dental patients, peer-to-peer assistance for mental illnesses, and the effects of playing Pokemon GO on cognitive performance and emotional intelligence. Other publications in this cluster discuss advancements in human–computer interaction, the potential uses of AI technology in clinical psychology, and the pleasures associated with playing AR games.

Cluster 9 encompasses 29 publications related to wearables in IoT, covering various topics. These include wearable tactile sensors, consumer trends in wearable technologies, IoT technology, and the evolving 5G-IoT scenario. In addition, there are publications on intelligent systems for tracking neurodegenerative diseases and emerging issues in smarter interactive technologies to meet expanding social requirements.

Cluster 10 highlights the growing interest in utilizing computer-aided treatment and VR in healthcare. This interest is particularly focused on treating mental health disorders, brain injuries, and various medical conditions. Researchers emphasize VR's potential to enhance the therapeutic process, facilitate self-care, and improve illness self-management.

Cluster 11 consists of 24 publications that focus on environmental perceptions and nature therapy. These publications investigate the potential of VR technology to improve the well-being of people who cannot access natural environments like coasts and lakes. The studies also analyze the physiological and psychological advantages of exposure to nature through VR, such as stress reduction, physical activity, and mental health benefits.

Cluster 12 comprises three publications that investigate the relationship between driving behavior and brain function. These studies utilize a VR driving simulator to examine the effects of alcohol on driving, explore the neural bases of speeding behavior, and analyze disruptions in brain networks that occur while driving under the influence. The findings from these studies indicate that alcohol impairs memory-related brain functions and leads to distinct disruptions in brain networks during intoxicated driving. The three most cited publications in each cluster are summarized in the Appendix. In the Appendix, the studies are listed according to their citations.

To sum up, all the RQs stated for our research are solved throughout the paper. The first five RQs (RQ1-RQ5) are addressed in the 4.1 Bibliometric analysis subsection. RQ6 is addressed in the 4.1.1 Most influential researchers subsection. RQ7 is addressed in the 4.1.2 Most influential journals subsection. RQ8 is addressed in the 4.1.3 Most influential countries and 4.1.4 Most influential universities subsections. The results of this research, spanning from 1994 to 2022, reveal significant trends in annual publications and citations. These trends were characterized by a gradual increase up to 2006, followed by a period of relative stability. Subsequently, there was a substantial surge in publications and citations starting in 2007. In the analysis of healthcare metaverse research by country, the USA emerged as the leader, followed by England and Italy. Notable institutions included "Università Cattolica del Sacro Cuore," and influential contributors comprised authors such as G. Riva, B. K. Wiederhold, and C. Botella. The primary language of publication was English, and "Article" was the predominant publication type, primarily within the "Computer Science" field. A departure from Lotka's law was observed in author distribution, and Bradford's Law was found to be inapplicable. Surprisingly, Zipf's Law did not align with keyword frequency. Additional insights were obtained through citation analysis, which highlighted influential authors, journals, countries, and universities. International collaboration was evident among countries, with the USA, England, and Germany at the forefront. Furthermore, the bibliographic coupling analysis categorized research into thematic clusters, revealing the diversity of topics within healthcare metaverse research. These topics encompassed mental health, simulation, and stroke rehabilitation, among others.

5 Discussion

This section describes the main findings from the bibliometric analysis and insights from the reviewed articles based on the clustering approach. It also paves the way for subsequent research directions in the healthcare metaverse.

The study found a significant and consistent increase in both publications and citations since 2007. This upward trend in research outputs indicates a growing interest in the healthcare metaverse. This phenomenon can be attributed to the growing realization of the potential of VR and AR technologies in the field of healthcare. Analyzing the contributions of different countries to healthcare metaverse research revealed the USA as the leading contributor, with 21.781% of the research output, followed by England (7.090%) and Italy (5.705%). This concentration of research in a few countries may reflect the availability of resources, funding, and expertise in these regions. Among universities, the “Università Cattolica del Sacro Cuore” leads in terms of publications, followed closely by “University Valencia” and “Istituto Auxologico Italiano.” The prominence of these institutions emphasizes their pivotal role in advancing healthcare metaverse research. The top contributors in terms of authors are G. Riva, B. K. Wiederhold, and C. Botella, who have played a crucial role in shaping this research landscape.

The predominance of the English language, accounting for 97,071% of publications, emphasizes the international reach and attractiveness of healthcare metaverse research. The analysis of publication types reveals a majority of “Article” publications, reflect the scientific nature of this field. In terms of research fields, “Computer Science” leads, followed by “Engineering” and “Psychology,” indicating the multidisciplinary nature of healthcare metaverse research.

Lotka’s Law, which characterizes author ranking based on frequency, deviates significantly in this area. The majority of authors (88.13%) contributed only once, indicating the presence of a large number of infrequent contributors. Hence, one cannot assert the existence of an intellectual elite accountable for generating scientific material on this subject matter. This may be indicative of the interdisciplinary nature of healthcare metaverse research, with a wide range of experts contributing to the field. Bradford’s Law, which predicts the distribution of journals, was found not to apply to this study. This implies that healthcare metaverse research is in its early stages of development and remains a work in progress within the academic literature, lacking a clearly established core and specific distribution zones among prominent journals. However, the application of Zipf’s Law to the most frequently used keywords in healthcare metaverse research yielded results that do not align with the expectations. This finding calls for further exploration into the patterns of keyword usage and their semantic significance in healthcare metaverse research.

The co-occurrence analysis of author keywords revealed the prevalence of certain keywords, with “virtual reality” and “augmented reality” emerging as the most frequent. This suggests that these concepts are central to the field of healthcare metaverse research. Furthermore, a citation analysis revealed the most influential authors, journals, countries, and universities, showcasing the complex interplay between quantity and impact. Notably, a high publication count does not guarantee a high impact, and some influential figures in the field may have fewer publications but higher citation counts.

Co-authorship analysis reveals the interconnectedness of countries and universities in healthcare metaverse research. Significant international collaboration exists, particularly among the USA, England, Australia, Spain, and Canada. However, it is worth noting that, among authors, collaborative efforts remain limited, suggesting potential room for increased interdisciplinary research.

Finally, the bibliographic coupling network analysis revealed twelve thematic clusters, shedding light on the diverse research topics within healthcare metaverse research. These clusters cover a wide spectrum of themes, including stroke and rehabilitation, simulation, mental health, and physical health. The interdisciplinary nature of these clusters suggests the cross-pollination of ideas and expertise in this multidisciplinary field.

6 Conclusion

The metaverse, a fusion of AR, XR, MR, and VR technologies, is changing our daily lives, especially in healthcare due to the COVID-19 pandemic. This shift towards immersive digital experiences is revolutionizing technology development and integration. Consequently, there is a pressing need for developers, designers, and policymakers to lead these changes.

This work adds significantly to the healthcare metaverse literature by undertaking a complete bibliometric analysis covering nearly five decades. This analysis categorizes research into theme clusters and uses bibliometric laws to ensure empirical rigor, providing significant recommendations for future research. Furthermore, it identifies significant institutions, authors, and governments, encouraging chances for collaboration and efficient resource allocation. By addressing major research problems, this study clarifies its objectives and conclusions. Notably, it is the first study to seamlessly incorporate bibliometric analysis, bibliometric laws, and bibliometric network analysis within this new discipline, creating a solid platform for future research endeavors.

6.1 Theoretical implications

This work has several important theoretical implications for healthcare metaverse development. First, it provides a detailed analysis of the evolving trends in this discipline over nearly three decades, shedding insight into the growth and changes in both publications and citations. This analysis adds to our understanding of how healthcare metaverse research is emerging.

In addition, the study's analysis of geography and institutional factors is highly significant from a standpoint. By showcasing the varying levels of involvement among countries and institutions, it provides insights into global collaboration patterns and the dissemination of knowledge within the healthcare metaverse research field. Consequently, this sheds light on discussions surrounding international research collaboration and the transfer of scientific knowledge across borders. Moreover, the study delves into author productivity and influence as journal contributions within the realm of healthcare metaverse research. This contributes to our understanding of authorship dynamics, the significance of authors, and the prominence of journals in specialized research domains. These findings hold relevance for scholars studying impact, authorship dynamics, and the roles played by journals in scientific disciplines.

This study also contributes by investigating the application of laws such as Lotka's Law, Zipf's Law, and Bradford's Law. The observed distribution deviates from Lotka's equation, implying that the majority of authors contribute just once. This discovery calls into question our understanding of authorship dynamics in healthcare metaverse research and highlights the need for more research into the mechanisms influencing this distribution. In addition, Bradford's Law, which was found to be not applicable, highlights the nature of information dissemination in this field, calling for a reevaluation of publication patterns. The deviation from Zipf's Law in the distribution of keyword frequency indicates a unique landscape within this field and invites further examination of language usage and terminology. Taken together, these findings call for research on how these laws apply to this field.

Finally, identifying influential authors, journals, countries, universities and collaboration clusters contributes to a theoretical understanding of the dynamics in healthcare metaverse research. The fact that the most influential authors do not necessarily have the highest publication volumes underscores that author impact is influenced by factors beyond outputs. These findings warrant further exploration of the factors contributing to research impact and the dynamics of academic collaboration in this field.

6.2 Practical implications

The practical implications of the study are multifaceted and hold relevance for various stakeholders, including researchers, institutions, technology companies, policymakers, and healthcare practitioners. First and foremost, the analysis of the most influential countries, universities, authors, and journals provides valuable insights for researchers and institutions seeking to establish collaborations and partnerships. Identifying influential contributors to the field can guide researchers in building networks, accessing valuable resources, and staying updated with the latest developments. Identifying influential journals and citation models enables researchers to make informed decisions about where to publish their work for maximum visibility and impact. For institutions, understanding the impact of specific journals can inform resource allocation and support decisions for researchers aiming to publish in high-impact venues.

Publication characteristics, such as language use and publication types, offer practical insights for researchers and institutions seeking to disseminate their work effectively. The prevalence of English, for example, highlights the importance of publishing in this language to reach a wider audience. Understanding these characteristics can inform publication strategies and maximize research visibility.

The dynamics of authorship and collaboration have practical implications for supporting interdisciplinary research and encouraging author collaboration. Institutions can use these data to promote interdisciplinary collaborations and increase the impact and reach of research studies. This study offers practical guidance for researchers and institutions aiming to promote collaborative research in the healthcare metaverse. Building a collaborative ecosystem in the healthcare metaverse accelerates knowledge sharing, resource exchange, and expertise sharing, fostering innovation and sustainable growth.

According to the findings, technology companies can profit from the fast-growing healthcare metaverse by investing in VR and AR technologies, with a focus on health simulations. They can also investigate the potential of IoT and wearable health devices, collaborate with influential authors and universities, and collaborate with authors and institutions from other countries, with a focus on international collaboration. These activities can assist technology firms in fostering innovation in healthcare solutions.

This study provides a snapshot of the global landscape of healthcare metaverse research for policymakers and healthcare practitioners. The prominence of the USA, England, and Italy in this field suggests that these countries can serve as potential models for the implementation of healthcare metaverse practices. By reviewing top journals and influential publications, policymakers and practitioners can gain insight into the latest developments potentially informing decisions on health policies, interventions and practices.

Moreover, the identification of thematic clusters through bibliographic coupling network analysis provides a roadmap for future research directions. Researchers and practitioners can focus their efforts on specific areas such as stroke rehabilitation, mental health, pain management, or environmental perceptions, depending on their areas of interest and expertise. This targeted approach can lead to more impactful and relevant contributions to the field.

6.3 Limitations and future research

Despite the valuable insights provided by this study, some limitations should be considered in future research. One of these limitations is the potential bias in the dataset, as bibliometric data may not cover all relevant publications. Future research should aim to expand the dataset by including additional databases, as the study only considers articles published in sources indexed in WoS.

Considering the passage of time is another factor that future studies should take into account. While the study concentrates on trends spanning from 1994 to 2022, it would be prudent for research to incorporate up-to-date data to capture the latest trends and dynamics accurately. This approach will offer an overview of how the field has evolved.

Considering generalizability is also significant. The results pertain to the realm of healthcare metaverse research. It would be worthwhile for future studies to explore if similar patterns exist in emerging fields and if bibliometric laws hold across diverse research domains. Furthermore, while this study offers insights, it would be beneficial for future research to complement these findings with qualitative analysis, allowing for a more thorough examination of the content and impact of publications. Qualitative analysis can provide an understanding of the context and significance of contributions within the field.

Finally, a more in-depth analysis of the factors contributing to author influence and the impact of specific publications on the field will provide valuable information for researchers and institutions aiming to maximize their impact. Understanding the mechanisms that enhance the impact of research in the healthcare metaverse can inform strategies for knowledge dissemination and knowledge translation. This, in turn, can ultimately contribute to the growth and development of the field.

Appendix

See Table 8.

Table 8 The most cited publications

Author's	Title	Publication	Country	Cluster	Total Citations
Langhorne et al. (2011)	Stroke rehabilitation	The Lancet	Scotland	1	1226
Wang et al. (2018)	Skin electronics from scalable fabrication of an intrinsically stretchable transistor array	Nature	USA	9	952
Novak et al. (2013)	A systematic review of interventions for children with cerebral palsy: state of the evidence	Developmental Medicine and Child Neurology	Australia	9	692
Gaba (2004)	The future vision of simulation in health care	British Medical Journal Quality and Safety	USA	2	597
Eysenbach (2008)	Medicine 2.0: social networking, collaboration, participation, apomediation, and openness	Journal of Medical Internet Research	Canada	3	577
Ekeland et al. (2010)	Effectiveness of telemedicine: A systematic review of reviews	International Journal of Medical Informatics	Norway	1	513
Yang et al. (2017)	Recent advances in wearable tactile sensors: Materials, sensing mechanisms, and device performance	Materials Science and Engineering: R: Reports	Peoples Republic of China	9	372
Katzman et al. (2014)	Canadian clinical practice guidelines for the management of anxiety, posttraumatic stress and obsessive–compulsive disorders	British Medical Journal Psychiatry	Canada	7	342
Ackerman (1998)	The visible human project	Proceedings of the IEEE	USA	8	327
Mohr et al. (2013)	Behavioral intervention technologies: evidence review and recommendations for future research in mental health	General Hospital Psychiatry	USA	3	309
Freeman et al. (2017)	Virtual reality in the assessment, understanding, and treatment of mental health disorders	Psychological medicine	England	3	308
Larsen et al. (2009)	Effect of virtual reality training on laparoscopic surgery: randomised controlled trial	British Medical Journal	Denmark	2	285
Hershfield et al. (2011)	Increasing saving behavior through age-progressed renderings of the future self	Journal of Marketing Research	USA	4	270
Giggins et al. (2013)	Biofeedback in rehabilitation	Journal of Neuroengineering and Rehabilitation	Ireland	1	256
Riva (2005)	Virtual reality in psychotherapy	CyberPsychology and Behavior	Italy	10	248

Table 8 (continued)

Author's	Title	Publication	Country	Cluster	Total Citations
Cobb et al. (1999)	Virtual reality-induced symptoms and effects (VRISE)	Presence: Teleoperators Virtual Environments	England	5	233
Kneebone et al. (2004)	Simulation and clinical practice: strengthening the relationship	Medical Education	England	8	230
Rosen (2008)	The history of medical simulation	Journal of Critical Care	USA	2	228
Sacks et al. (2013)	Construction safety training using immersive virtual reality	Construction Management and Economics	Israel	5	211
Kazdin and Rabbitt (2013)	Novel models for delivering mental health services and reducing the burdens of mental illness	Clinical Psychological Science	USA	8	193
Muessig et al. (2015)	A systematic review of recent smartphone, Internet and Web 2.0 interventions to address the HIV continuum of care	Current Hiv/aids Reports	USA	4	187
Gold et al. (2006)	Effectiveness of virtual reality for pediatric pain distraction during IV placement	CyberPsychology and Behavior	USA	6	173
Lewis (1999)	Computer-based approaches to patient education: a review of the literature	Journal of the American Medical Informatics Association	USA	10	167
Koller and Goldman (2012)	Distraction techniques for children undergoing procedures: a critical review of pediatric research	Journal of Pediatric Nursing	Canada	6	164
Warburton et al. (2007)	The health benefits of interactive video game exercise	Applied Physiology, Nutrition, Metabolism	Canada	4	164
Ray and Teizer (2012)	Real-time construction worker posture analysis for ergonomics training	Advanced Engineering Informatics	USA	5	154
Gregg and Tarrier (2007)	Virtual reality in mental health	Social Psychiatry Psychiatric Epidemiology	England	10	141

Table 8 (continued)

Author's	Title	Publication	Country	Cluster	Total Citations
Riva et al. (2016)	Transforming experience: the potential of augmented reality and virtual reality for enhancing personal and clinical change	Frontiers in Psychiatry	Italy	7	129
Riva et al. (2019)	"Neuroscience of virtual reality: from virtual exposure to embodied medicine"	Cyberpsychology Behavior and Social Networking	Italy	6	116
Botella et al. (2015)	Virtual reality exposure-based therapy for the treatment of post-traumatic stress disorder: a review of its efficacy, the adequacy of the treatment protocol, and its acceptability	Neuropsychiatric Disease and Treatment	Spain	7	104
Grellier et al. (2017)	BlueHealth: a study programme protocol for mapping and quantifying the potential benefits to public health and well-being from Europe's blue spaces	British Medical Journal Open	England	11	83
Yin et al. (2018)	Physiological and cognitive performance of exposure to biophilic indoor environment	Building and Environment	USA	11	71
Calogiuri et al. (2018)	Experiencing nature through immersive virtual environments: Environmental perceptions, physical engagement, and affective responses during a simulated nature walk	Frontiers in Psychology	Norway	11	61
Meda et al. (2009)	Alcohol dose effects on brain circuits during simulated driving: an fMRI study	Human brain mapping	USA	12	49
Jäncke et al. (2008)	Brain activation during fast driving in a driving simulator: the role of the lateral prefrontal cortex	Neuroreport	Switzerland	12	34
Rzepecki-Smith et al. (2010)	Disruptions in functional network connectivity during alcohol intoxicated driving	Alcoholism: Clinical Experimental Research	USA	12	20

Author contribution SD carried out the primary literature review, analyzed the data, and reported the findings. SD and GHK were involved in the extraction and verification of individual study data. GHK supervised the process, reviewed the draft manuscript, and provided feedback.

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Data availability Data used for the analysis in this study can be accessed upon request.

Declarations

Conflict of interest The authors have no funding, financial, or non-financial interests in this article.

Ethical approval This article does not contain any studies with human participants or animals performed by any of the authors.

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