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TOPICAL REVIEW

Virtual Reality and User Experience: Current Trends and Future Challenges

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ABSTRACT Virtual reality is an emerging and versatile technology that is gaining increasing interest from the scientific community, particularly regarding user experience. A review of the literature highlights the need for updated analyses that comprehensively address current trends in this field. The objective of this study is to analyze the evolution of scientific publications related to virtual reality and user experience, identifying trends, the most influential authors, relevant journals, and international collaborations, to provide a comprehensive overview. A bibliometric analysis was conducted using the Web of Science Core Collection database, identifying a total of 1,848 relevant publications. Network analysis techniques and Bradford's law were applied, allowing for the examination of the distribution and impact of publications, as well as collaboration between authors and institutions. The results show an exponential growth in scientific output, particularly since 2019. While the United States leads in the number of publications, most of the influential authors are from Europe, with notable scientific output in Spain and Portugal. Current research hotspots include virtual reality applications in education and healthcare (over 70% of the analyzed publications), which align with Sustainable Development Goals, particularly 3 and 4. Trends indicate a shift towards integrating virtual reality with artificial intelligence, adaptive systems, and multisensory interaction to enhance immersion and usability. Challenges include a lack of standardized methodologies to assess immersion, presence, and cognitive load, which limits comparisons across studies and hinders the development of best practices. Future research should focus on refining interaction paradigms, improving accessibility, and developing ethical frameworks that respect data privacy and protect the user from cybersickness and the psychological effects of prolonged virtual reality exposure.

INDEX TERMS Bibliometric analysis, user experience, virtual reality, multisensory interaction.

I. INTRODUCTION

Since its inception, virtual reality (VR) has significantly transformed interaction with technology, and defining it has become a challenge due to the diversity of functions it encompasses. According to Morimoto et al. [1], VR is an immersive, entirely artificial image and environment simulated by a computer with real-time interaction. Bec et al. [2] defined it as a computer-generated simulation of an environment, while Tuena et al. [3] describe it as a system based on an interactive 3D environment that incorporates auditory, visual, and sometimes haptic feedback. While these definitions vary, common elements among them include the generation of a digital environment by a computer, immersion, and human-machine interaction (HCI).

Advances in technology have made VR more affordable, overcoming the cost and development limitations of the past [4]. This has allowed for the expansion of its applications

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in various fields, such as entertainment, simulation, education, and healthcare, which are among the most prominent [5], [6]. This development has increased consumer adoption of VR, thereby accelerating the growth of the industry [7]. With the development of more autonomous head-mounted displays (HMDs), VR has become a promising candidate for the next generation of mobile platforms [8]. This contributes to enhancing the user experience, allowing individuals to feel physically present in the virtual environment, temporarily replacing the physical world [9].

For VR to be effective and widely adopted, it is necessary to understand and optimize several inherent parameters. These parameters include immersion, presence, realism, interactivity, input and output devices, and user experience, among others [10]. Immersion refers to VR's ability to immerse the user in a virtual environment, creating the sensation of being physically present in a non-physical space [11]. This sensation is achieved through sensory stimuli, such as visual, auditory, and tactile, which give the user the perception that the virtual environment resembles the real one [12]. Immersion is reinforced by presence, which is the user's subjective perception of actually being in the virtual environment [13]. High interactivity and low latency help intensify this presence, enabling the user's actions to be immediately and accurately reflected in the virtual world.

Realism also plays a significant role in creating a convincing experience within virtual environments. It is not only about the quality of the graphics and sounds but also the narrative's ability to capture and maintain the user's attention, one of the most important cognitive functions [14]. It is also important to note that input and output devices, such as HMDs and hand controllers, must be intuitive [15]. These devices should facilitate user interaction without introducing additional complexities, allowing for smooth navigation, which encourages new users.

When addressing the design of effective VR environments, user experience (UX) allows for the integration of several factors that influence interaction within these environments [15]. The quality of UX not only enhances the sense of presence but also ensures that users feel safe and comfortable, leading to greater acceptance and long-term use [16]. The perception of a good experience is influenced by several elements, such as the devices used (HMDs, projectors, or monitors), interaction methods, and individual user characteristics [17], [18]. These variables determine how users interact with and perceive the virtual environment, directly affecting their satisfaction and willingness to continue using the technology.

As VR advances, it becomes increasingly relevant to investigate how different hardware configurations and interaction techniques influence UX. In 2019, Kim et al. [10] conducted a systematic review to analyze how different technologies and interaction methods in VR impact UX. However, they identified that UX research had not yet fully addressed how various usage contexts influence user experience, nor the potential adverse effects in unexplored environments. The need to more comprehensively evaluate sensor-generated data in VR systems was presented to expand their applicability in sectors such as education and healthcare.

On the other hand, Voigt-Antons et al. [19] investigated how more natural interactions, such as hand tracking, influence the perception of presence and realism compared to traditional controllers. While they demonstrated that certain interaction modalities enhance immersion, their findings showed that usability varies significantly depending on the task. This reveals a gap in research on how to tailor interactions to specific contexts, an area that remains underexplored.

Ahn et al. [20] explored the influence of visual and interactive elements in VR, showing how interactive experiences can enhance immersion and usability. However, they also identified technical limitations, such as unstable graphics and cybersickness, that limit the effectiveness of VR applications. Similarly, Cheng [21] studied how people can learn better through reading in immersive VR environments. The study also showed that when stories are engaging, students feel more connected to the content, which improves their learning and understanding. However, this focus is on specific educational applications, leaving open the discussion on how these findings apply to other UX domains.

Bu et al. [22] proposed a conceptual framework for developing VR-based smart product and service systems. This framework combined user- and system-generated data to improve UX, demonstrating its effectiveness in a practical case involving an ergonomic rowing machine. However, the authors acknowledged that their framework faces limitations related to the number of tests performed and the accuracy of the physiological data obtained, showing the need for more robust and replicable methodologies.

Based on these studies, it is clear that VR UX research is in a stage of expansion, but lacks a consolidated view on current trends. This bibliometric analysis aims to fill this gap by mapping the landscape of scientific publications in the field of VR and UX. The main contribution of this study lies in the use of bibliometric metrics to trace the connections between authors, institutions, and thematic areas, identifying specific gaps in the literature that require attention. By providing a data-driven framework to guide future research, this analysis facilitates the development of more robust methodologies tailored to the interdisciplinary needs of the field.

II. MATERIALS Y METHODS

A. DATA SOURCES

This study was based on a descriptive bibliometric analysis of scientific production on VR, focusing on publications indexed in the Web of Science. This database is recognized for including high-quality, peer-reviewed research. For this analysis, the Web of Science Core Collection (WoSCC) was used, providing a comprehensive overview of research in this field. However, it is important to recognize that excluding other databases may limit the coverage of the literature

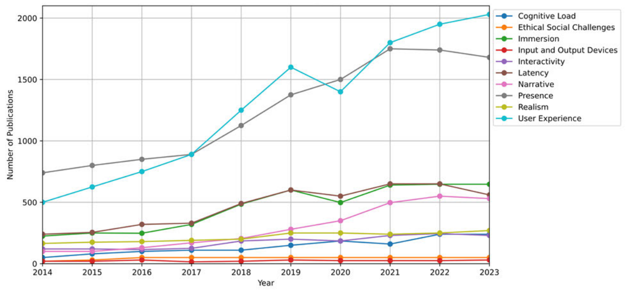

FIGURE 1. Annual publication trends on VR and its inherent parameters.

review. These repositories may contain relevant research that is not indexed in WoSCC.

B. DEFINITION OF THE SCOPE OF THE STUDY

The preliminary analysis focused on ten inherent parameters of VR, including "latency," "interactivity," "realism," "narrative," "cognitive load," "ethical and social challenges," "presence," "user experience," "immersion," and "input and output devices." The selection was based on its recurrent relevance in previous studies and its connection to VR was detailed in the introduction section.

Cognitive load is particularly relevant, as the complexity of visuospatial transformations in certain VR setups can increase mental effort and affect user experience [23]. As Jin [24] highlights, immersion and interactive storytelling enhance engagement and learning, while presence and interactivity significantly contribute to technology acceptance, making users feel more integrated into virtual environments.

The initial research, conducted on May 16, 2024, showed that "user experience" and "immersion" were the most researched topics during the last decade (Fig. 1), the former being the most relevant subject that motivated this bibliometric study.

C. SEARCH STRATEGY

A search was conducted using WoSCC on August 2, 2024. The search strategy included the following keywords: TI = ("VR" OR "virtual environment" OR VR OR "virtual simulation") AND ALL = ("user experience" OR UX OR "user interaction" OR "user engagement" OR "user satisfaction" OR usability OR "user-centered design" OR "user feedback" OR "user interface" OR "user performance" OR "UX design" OR "user acceptance" OR "user adaptability" OR "user preferences" OR "user satisfaction survey" OR "user evaluation" OR "user-centered evaluation"). The UX-related variants were selected to cover the terminological and conceptual diversity present in the scientific literature on UX in virtual environments. The search included the Science Citation Index Expanded (SCI-Expanded), the Social Sciences Citation Index (SSCI), and the Emerging Sources Citation Index (ESCI).

The inclusion criteria were: (i) original research articles and reviews, (ii) studies published in English, and (iii) research directly addressing VR and user experience. Exclusion criteria included proceeding papers, early access articles, and studies unrelated to the defined topics. The search covered documents from the beginning of the database to the search date. The data were exported in. csv format for subsequent analysis.

D. DATA ANALYSIS

The data analysis was based on bibliometric tools to provide a comprehensive view of scientific production. First, a descriptive analysis of annual publications and citations was performed. Price's Law was used to analyze whether the growth of scientific production follows an exponential trend, indicating whether the research area is expanding or reaching saturation. This law is particularly relevant since it allows to identify how technological advances generate a certain amount of publications. An exponential fit was used to model the growth of scientific output, without comparing it with other models, given the focus on its applicability to the field of study.

Bradford's Law was chosen because its practical application provides the mechanisms for selecting the most productive but also the most relevant periodical publications to cover a given area of knowledge. This classification was performed using Bibliometrix R [25], which facilitated the segmentation of journals based on their productivity and impact.

In terms of authorship, Lotka's law was applied to identify the most prolific co-authors, and their citations were also analyzed. This law allows us to understand the distribution of author productivity, helping to identify relevant researchers who contribute significantly to the field, rather than occasional contributors. This ensures that author influence is measured beyond raw publication counts.

To explore collaboration patterns and topic structures, VOSviewer was used to generate co-occurrence maps and network visualizations. This software was selected due to its efficiency in processing large bibliometric data sets and its ability to automatically cluster research topics, authors, and institutions, providing a clear representation of relationships within the field. Furthermore, its integration with Web of Science data enabled a seamless workflow in analyzing citation networks and keyword associations.

A contribution analysis by country and institution was also performed, assessing the number of publications and citations, as well as international collaborations. The combination of these two software tools allowed for a robust and detailed bibliometric analysis. On one hand, Bibliometrix R provided statistical information and bibliometric indicators, while VOSviewer allowed for an effective visualization of the relationships within the dataset. Given the objectives of this study, these tools fully addressed the analytical and graphical needs of the research.

III. RESULTS

A selection process was carried out to ensure that only relevant articles related to the subject were included. From an initial search in WoSCC, a total of 3,923 records were identified. After removing records from other WoS indexes, 2,013 articles remained for further evaluation. At this stage, a manual review of titles and abstracts was carried out to assess relevance and apply the inclusion and exclusion criteria previously presented. As a result, 165 articles were excluded, leading to a final dataset of 1,848 studies included in the bibliometric analysis. The flow of this process is illustrated in Fig. 2.

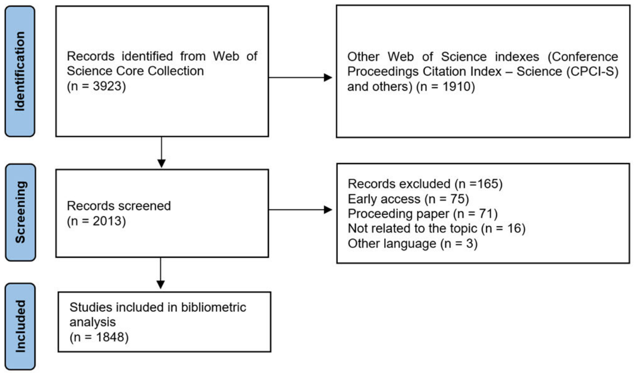

FIGURE 2. Flowchart of literature selection.

A. ANNUAL PUBLICATION TREND

A total of 1,848 publications met the established criteria. Fig. 3 shows the clear growth trend in scientific production. According to Price's Law, exponential growth in a field of research indicates that it is in full expansion, as observed between 2019 and 2023, with a considerable increase in the number of published articles. This analysis was conducted manually. The growth model shows a coefficient of determination (R^2) of 0.83, indicating that 83% of the variation in the number of publications can be explained by the exponential growth model. This strong fit suggests that the observed increase in publications aligns closely with the predicted trend, reducing the likelihood of random variability. Furthermore, the model is supported by a significant p-value ($p<0.001$). This confirms that the growth in publications is not random but follows an exponential trajectory, consistent with the accelerated expansion of the field.

B. DISTRIBUTION OF PUBLICATIONS IN SCIENTIFIC JOURNALS

Bradford's Law divides scientific literature into zones based on productivity and concentration of articles in journals. The central zone includes the most productive and impactful journals, which publish a significant proportion of the total articles. Zone 1 is made up of journals with slightly lower productivity, but which together equal the volume of the central zone. Finally, zone 2 includes a large number of journals with marginal contributions that, when combined, equal the production of the previous zones.

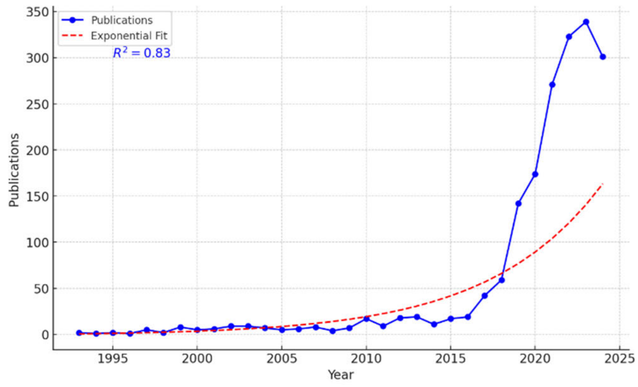

FIGURE 3. Annual scientific production on VR and user experience.

The analyzed publications were distributed across 674 journals, with contributions ranging from 1 to 101 articles per journal. Approximately 50% of all publications are concentrated in 56 journals. Bradford's core consists of 18 journals, each with more than 15 published articles, accounting for 36.2% of the total publications. Among these journals are VR (101 articles), Applied Sciences-Basel (67 articles), and IEEE Transactions on Visualization and Computer Graphics (47 articles). The analysis of Bradford's zones was performed using Bibliometrix R, which divided the journals into three zones: 18 in the core, 133 in Zone 1, and 523 in Zone 2, following a characteristic pattern that reflects their contribution to the field, though with a margin of error of 189.27%, as detailed in Table 1. This error suggests that the distribution of journals in this field does not follow the expected geometric progression, which could be due to the particular nature of the area of study. In highly specialized or interdisciplinary disciplines, it is common for scientific literature to be distributed more evenly or not conform to traditional patterns of knowledge dispersion.

Based on the number of citations, 30 journals account for 50% of the total citations. The most cited journals are VR (1,280 citations), Computers & Education (1,253 citations), and Computers in Human Behavior (1,131 citations). Some journals, such as Computers & Education and IEEE Transactions on Neural Systems and Rehabilitation Engineering, with only 9 publications each, stand out for their high citation counts, reflecting their relevance. Psychological Medicine, with 1 article and 609 citations, demonstrates significant impact. Table 2 highlights the 10 most relevant journals based on the number of citations.

C. MOST PROLIFIC AND INFLUENTIAL CO-AUTHORS

According to Lotka's law, the distribution of authorship was analyzed using Bibliometrix R, identifying 161 co-authors with at least three publications were identified, representing 41.5% of the total production. Table 3 highlights the 10 most relevant authors. Miguel Melo and Maximino Bessa, from the University of Trás-os-Montes and Alto Douro, lead in terms of publications, though with a relatively low average citations

TABLE 1. Distribution of journals according to Bradford's Law.

Zone	No. of Journals	No. of Articles	Cumulative No. of Journals.	Cumulative No. of Articles	Bradford Multipliers	Journals (Theoretical Series)
Core	18 (2.7%)	614 (36.2%)	18 (2.7%)	614 (36.2%)	n0 = 18	18
Zone 1	133 (19.7%)	626 (36.9%)	151 (22.4%)	1240 (73.1%)	7.39 (133/18)	54
Zone 2	523 (77.6%)	609 (26.9%)	674 (100%)	1848 (100%)	3.93 (523/133)	161
Total	674 (100%)	1848 (100%)	-	-	5.66	233
					% Error	189.27 %

TABLE 2. The 10 most relevant journals based on the number of citations.

Journal	Publications	Citations	ACPA	Publisher
Virtual Reality	101	1280	12.67	Springer
Computers & Education	9	1253	139.22	Elsevier
Computers in Human Behavior	13	1131	87	Elsevier
International Journal of Human-Computer Interaction	27	916	33.93	Taylor and Francis
Journal of Neuroengineering and Rehabilitation	21	806	38.38	BioMed Central
Applied Ergonomics	14	790	56.43	Elsevier
IEEE Transactions on Neural Systems and Rehabilitation Engineering	9	690	76.67	IEEE
Journal of Travel Research	3	645	215	SAGE
Automation in Construction	12	612	51	Elsevier
Psychological Medicine	1	609	609	Cambridge

ACPA: average citations per article

TABLE 3. The 10 most relevant authors based on the number of articles.

Author	Publications	Citacions	ACPA	H-index	Institution	Country
Miguel Melo	14	121	8.64	21	University of Trás-os-Montes and Alto Douro	Portugal
Maximino Bessa	13	120	9.23	23	University of Trás-os-Montes and Alto Douro	Portugal
Hai-Ning Liang	11	188	17.09	29	The Hong Kong University of Science and Technology (Guangzhou)	China
Pablo Campo-Prieto	9	82	9.11	8	Universidad de Vigo	Spain
Guilherme Goncalves	9	76	8.44	11	University of Trás-os-Montes and Alto Douro	Portugal
Gustavo Rodriguez-Fuentes	9	82	9.11	9	Universidad de Vigo	Spain
Jinmo Kim	8	105	13.13	14	Hansung University	South Korea
Mariano Alcañiz	7	488	69.71	49	Universidad Politécnica de Valencia	Spain
Mark Billinghurst	7	78	11.14	68	University of South Australia	Australia
Andrés Bustillo	7	77	11	26	Universidad de Burgos	Spain

per article (ACPA). In contrast, Mariano Alcañiz, from the Polytechnic University of Valencia, stands out with the highest ACPA (69.71), despite having fewer publications. Figure 4 shows how these authors' output has increased significantly in recent years, especially since 2019. Spain stands out as the country with the highest number of prominent authors, followed by Portugal, indicating that the southwestern part of Europe has a high level of production in this field.

Fig. 5 presents the co-occurrence map of authors using the ''Association Strength'' method, highlighting collaborations among the most influential researchers. Each color represents a cluster of authors with strong collaboration. For example, Miguel Melo, Maximino Bessa, and Guilherme Goncalves

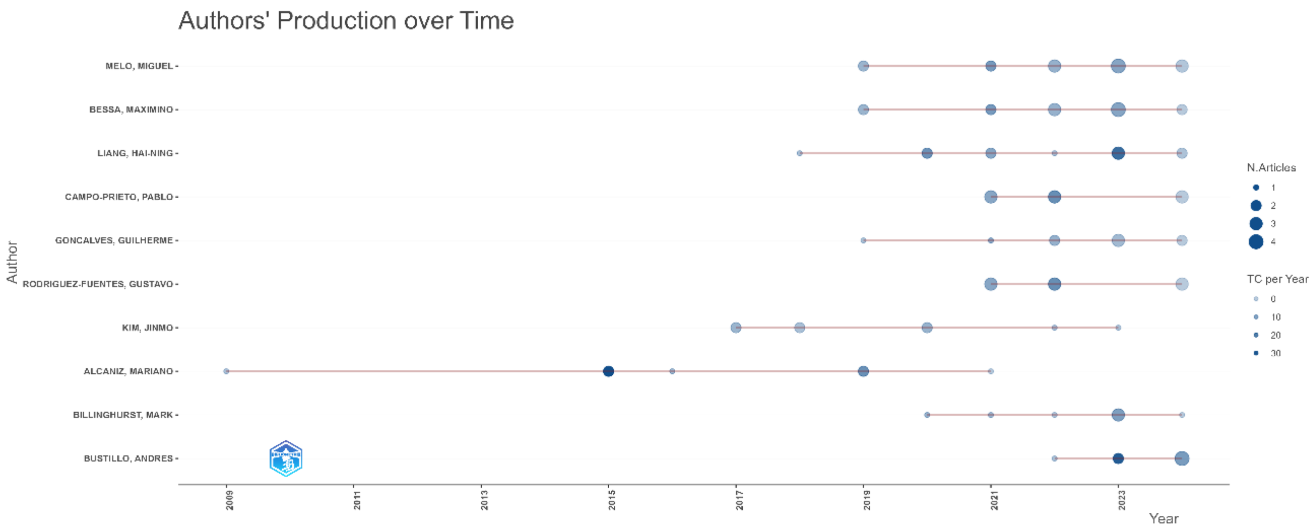

FIGURE 4. Author productivity over time.

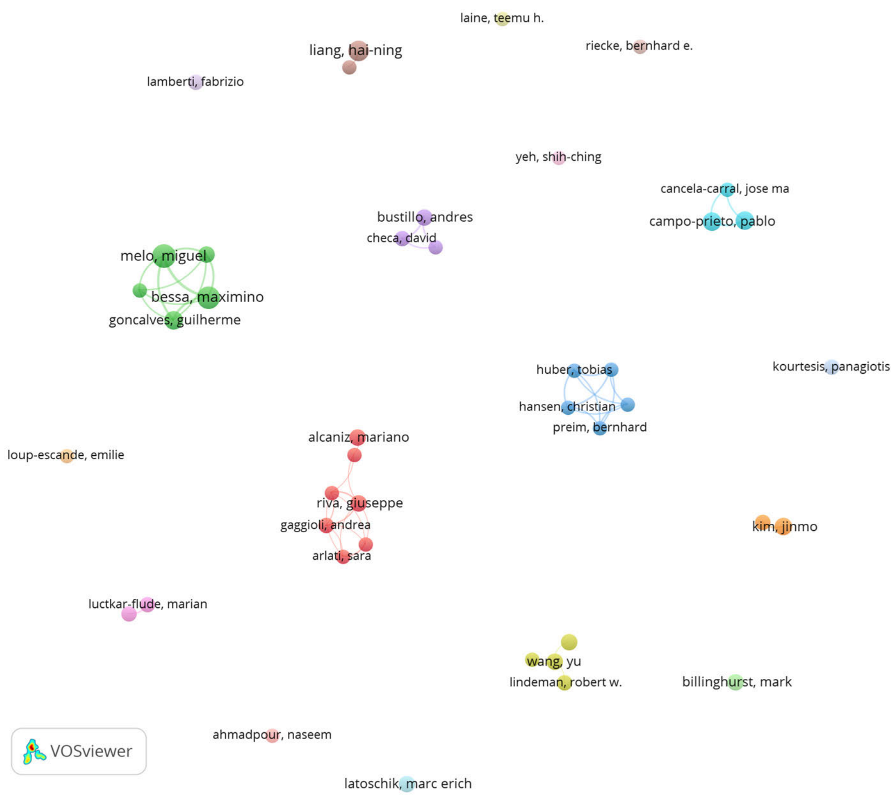

FIGURE 5. Co-occurrence map.

form the green cluster, while Mariano Alcañiz and Giuseppe Riva, in the red cluster, show less connected nodes, reflecting more dispersed collaboration. This suggests that the field could benefit from greater diversification and expansion of collaborative networks. On the other hand, Fig. 6 shows the citation map between authors, highlighting the high impact of researchers such as Miguel Melo and Hai-Ning Liang. As with collaborations, citations are also concentrated in a small group of authors, indicating that knowledge and citations are centralized among certain researchers.

D. CONTRIBUTION BY COUNTRIES AND INSTITUTIONS

The international collaboration analysis presented in Table 4 reveals that the United States (USA) and the People's Republic of China lead with the highest number of generated documents. In terms of total citations, the USA tops the

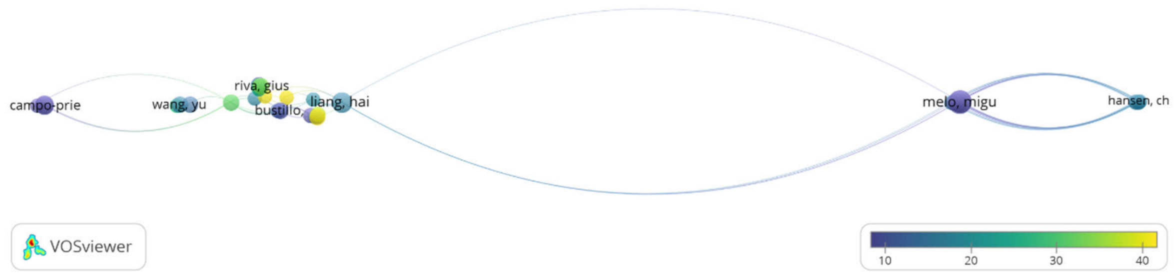

FIGURE 6. Author citations.

TABLE 4. The 10 most relevant countries based on the number of articles.

Country	Publications	Citations	ACPA
USA	355	7896	22.24
Peoples R China	250	3000	12.00
South Korea	154	3920	25.45
England	142	4650	32.75
Germany	139	3027	21.78
Italy	123	2342	19.04
Spain	119	2705	22.73
Australia	108	2325	21.53
Canada	105	1326	12.63
France	62	1115	17.98

list with 7,896 citations. The average citations per article highlight Norway (38.87) and Israel (37.71) as countries with a relatively high impact per publication, despite having fewer documents.

Fig. 7a shows a co-occurrence map of countries, where larger nodes, such as the USA and China, represent a higher number of publications. Several collaborative clusters are identified: the USA leads a large cluster, while China and South Korea are part of another significant cluster. England, Spain, and Italy also play a significant role in scientific collaboration. Additionally, European countries such as Germany and France are part of an interconnected collaborative group involving multiple countries.

In contrast, Fig. 7b presents a citation map between countries, where the node colors vary according to citation impact per country. Here, we observe that some countries with fewer publications, such as Norway and Finland, show a higher relative impact in terms of citations per article. This comparative analysis between publication output and citation impact by country suggests that, while countries with a higher volume of publications lead in collaboration, some countries with fewer publications generate significant academic impact.

Among the 2,326 institutions contributing to this field of research, the State University System of Florida leads the list with 29 publications and an ACPA of 28.28 (Table 5). The Universitat Politècnica de València also stands out with

TABLE 5. The 10 most relevant institutions based on the number of articles.

Affiliations	Publications	Citation	ACPA	Country
State University System of Florida	29	820	28.28	USA
Centre National de la Recherche Scientifique Cnrs	23	400	17.39	France
University System of Ohio	23	495	21.52	USA
University of London	19	390	20.53	UK
University of Toronto	18	245	13.61	Canada
Pennsylvania Commonwealth System of Higher Education Pcshe	17	432	25.41	USA
INESC TEC	16	129	8.06	Portugal
University of Sydney	16	478	29.88	Australia
University of Texas System	16	350	21.88	USA
Universitat Politècnica de València	15	551	36.73	Spain

the highest ACPA of 36.73, establishing itself as one of the most influential institutions. In contrast, INESC TEC from Portugal, despite having 16 publications, shows the lowest ACPA (7.50). In terms of countries, the United States leads with four institutions on the list, reaffirming its global leadership both in production and academic impact.

Table 6 presents the main funding agencies that have supported research in this field. Of a total of 1,413 agencies, the National Natural Science Foundation of China (NSFC) leads with 86 publications, representing 4.65% of the total, along with 929 citations. Although the European Union has fewer publications, its impact is considerable, with 2,350 citations, reflecting strong recognition in the scientific community. South Korea funds 8.01% of the publications, with the National Research Foundation of Korea being particularly prominent. Globally, the agencies from China, the United States, and South Korea account for 19.11% of the total publications, indicating a significant concentration of resources in a small number of countries.

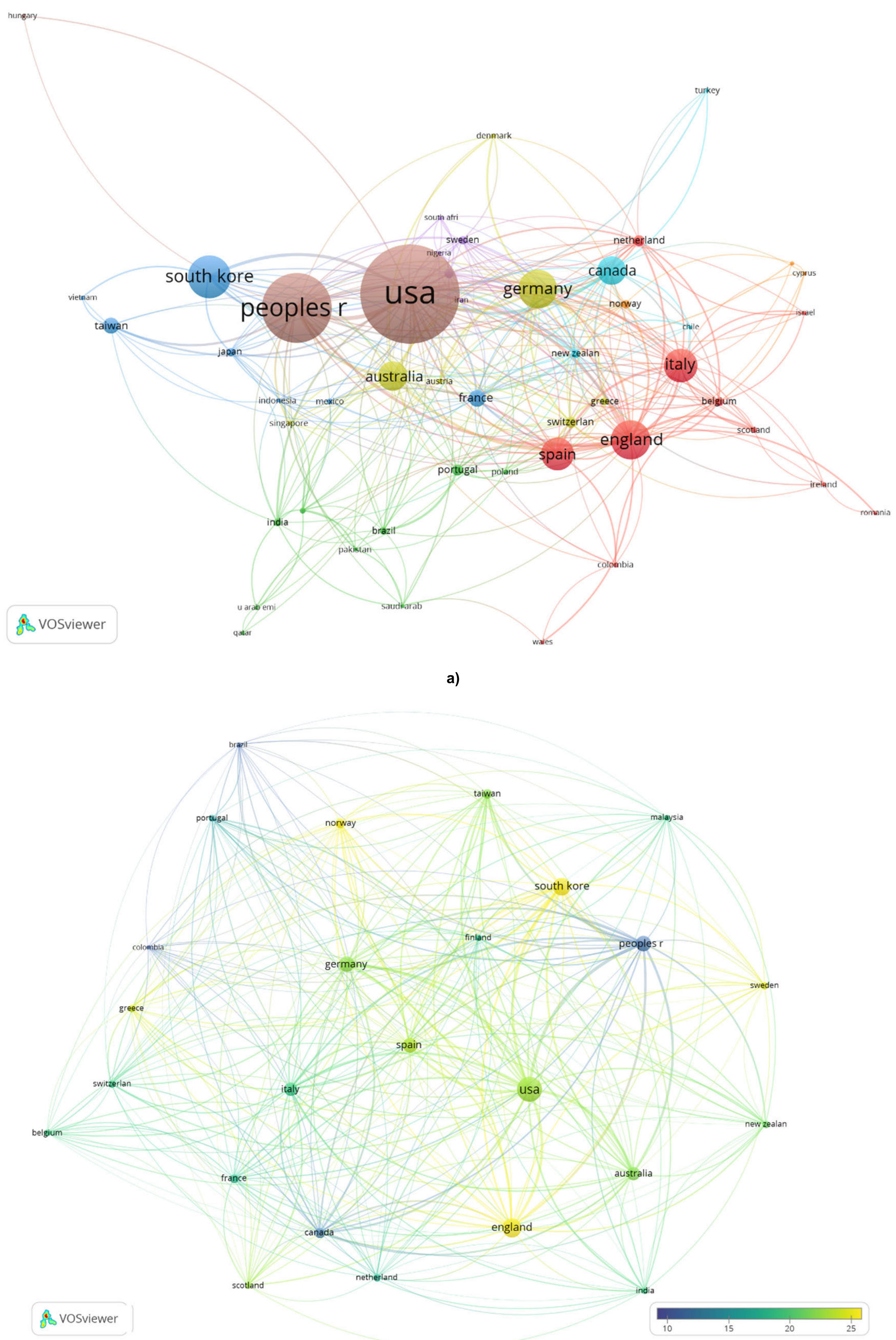

FIGURE 7. a) Co- occurrence; b) Citations by country.

TABLE 6. Main funding agencies based on the number of articles.

Funding Agencies	Publications	Citation	Country
National Natural Science Foundation of China (NSFC)	86	929	China
European Union (EU)	68	2350	European Union
National Research Foundation of Korea	64	2163	South Korea
United States Department of Health and Human Services	44	634	USA
National Institutes of Health (NIH) USA	43	659	USA
National Science Foundation (NSF)	40	550	USA
Ministry Of Science, ICT and Future Planning, Republic of Korea	38	340	South Korea
Ministry of Science and ICT (MSIT), Republic of Korea	38	382	South Korea
UK Research and Innovation (UKRI)	26	604	United Kingdom
Fundação para a Ciência e a Tecnologia (FCT)	25	376	Portugal

E. MOST CITED DOCUMENTS

Table 7 lists the most cited articles, highlighting research in education, mental health, tourism, and rehabilitation. The most cited article, related to VR applications in higher education, has an average annual citation rate of 133.20, calculated by dividing the total number of citations by the number of years since its publication. This is followed by studies on the use of VR in mental health disorders (609 citations) and consumer behavior in virtual tourism (558 citations). South Korea and Australia are notable for their multiple contributions to this list.

F. THEMATIC ANALYSIS AND SUSTAINABILITY

Fig. 8 illustrates a map of key terms used in research on VR and user experience. The red cluster focuses on technology and virtual environments, highlighting terms such as "technology," "environments," and "simulation." This underscores the importance of developing new technologies and systems to improve virtual experiences, as well as perception and usability. The blue cluster focuses on user acceptance and experience, with terms like "user acceptance," "experience," and "model," emphasizing how the technology is perceived and adopted by users, as well as its impact on overall experience.

Finally, the green cluster is oriented towards healthcare, with keywords such as "rehabilitation," "exercise," and "therapy," indicating the growing use of VR in therapeutic interventions to improve physical and mental well-being in

specific groups such as "children" and "older adults."

The thematic evolution (Fig. 9) shows a transition from an initial focus on design, simulation and systems in the 1990s to an expansion into educational, medical and technological applications in the 2000s. Between 2001 and 2010, research diversified with the study of virtual environments, augmented reality, performance and recognition, reflecting a growing interest in human-computer interaction and the integration of emerging technologies. Later, between 2011 and 2015, the field focused on models and performance, consolidating theoretical and methodological frameworks to evaluate the effectiveness of VR. In recent years, from 2016 to 2024, research converges on the development of more sophisticated models and their impact on well-being and medicine, consolidating its role in applied research.

In line with current trends, VR research is increasingly aligning with the Sustainable Development Goals (SDGs), as shown in Fig. 10. SDG 04 "Quality Education" stands out with 46.97% of the publications, demonstrating that VR has significant potential to transform education through immersive experiences that enhance learning and address accessibility challenges. SDG 03 "Good Health and Well-Being" covers 26.46% of the publications, highlighting the use of VR in rehabilitation and mental health. Other SDGs, such as "Sustainable Cities and Communities" (4.83%) and "Industry, Innovation, and Infrastructure" (1.66%), show a growing interest in how VR can support sustainability and urban development.

IV. DISCUSSION

A. GLOBAL IMPACT AND COLLABORATIVE NETWORKS

The use of VR has undergone significant evolution since its early days, when it was primarily limited to flight simulations and military training applications [6]. With technological advancements and reduced costs, its application has expanded considerably, driving a notable growth in scientific publications related to user experience. In the past four years, there has been an increase of nearly 60% in the production of articles, reflecting growing interest in research within this field and demonstrating the relevance of our review. In terms of impact, journals such as VR, IEEE Transactions on Visualization, Computers & Education, and IEEE Transactions on Neural Systems and Rehabilitation Engineering are key sources for disseminating high-quality research, with many publications and citations.

Collaboration networks are well-established in various regions around the world, with notable leadership from Europe and Asia. Portugal and Spain stand out as countries with high scientific output, with authors such as Miguel Melo, Maximino Bessa, and Mariano Alcañiz leading in terms of publications. The latter is particularly distinguished for having a high number of citations per article, suggesting that his work is highly valued within the academic community. Our analysis also revealed a trend toward the concentration of co-authorships within certain geographical groups, as seen in the clusters from Portugal and Spain. This is consistent with other bibliometric reviews showing how

Iberian countries are making significant advances in VR [36]. Additionally, geographical proximity could motivate the consolidation of regional research teams that may

TABLE 7. The 10 most cited articles on VR and user experience.

Reference	Title	Year	Citations	Citation per article	Journal	Country of first author
Radianti et al. [27]	A systematic review of immersive virtual reality applications for higher education: Design elements, lessons learned, and research agenda	2019	666	133.20	Computers & Education	Norway
Freeman et al. [28]	Virtual reality in the assessment, understanding, and treatment of mental health disorders	2017	609	76.13	Psychological Medicine	United Kingdom
Kim et al. [29]	Exploring Consumer Behavior in virtual reality Tourism Using an Extended Stimulus-Organism-Response Model	2018	558	111.60	Journal of Travel Research	Republic of Korea
Jack et al. [30]	Virtual reality -enhanced stroke rehabilitation	2001	444	18.50	IEEE Transactions on Neural Systems and Rehabilitation Engineering	USA
Kim et al. [31]	Virtual reality sickness questionnaire (VRSQ): Motion sickness measurement index in a virtual reality environment	2018	419	59.86	Applied Ergonomics	Republic of Korea
Yung et al. [32]	New realities: a systematic literature review on virtual reality and augmented reality in tourism research	2017	417	69.50	Current Issues in Tourism	Australia
Shin [33]	Empathy and embodied experience in virtual environment: To what extent can virtual reality stimulate empathy and embodied experience?	2017	367	52.43	Computers in Human Behavior	South Korea
Ijaz et al. [34]	Player Experience of Needs Satisfaction (PENS) in an Immersive virtual reality Exercise Platform Describes Motivation and Enjoyment	2020	347	69.40	International Journal of Human-Computer Interaction	Australia
Huang et al. [35]	Exploring the Implications of virtual reality Technology in Tourism Marketing: An Integrated Research Framework	2015	310	34.44	International Journal of Tourism Research	Taiwan
Carrozzino and Bergamasco [36]	Beyond virtual museums: Experiencing immersive virtual reality in real museums	2010	302	20.13	Journal of Cultural Heritage	Italy

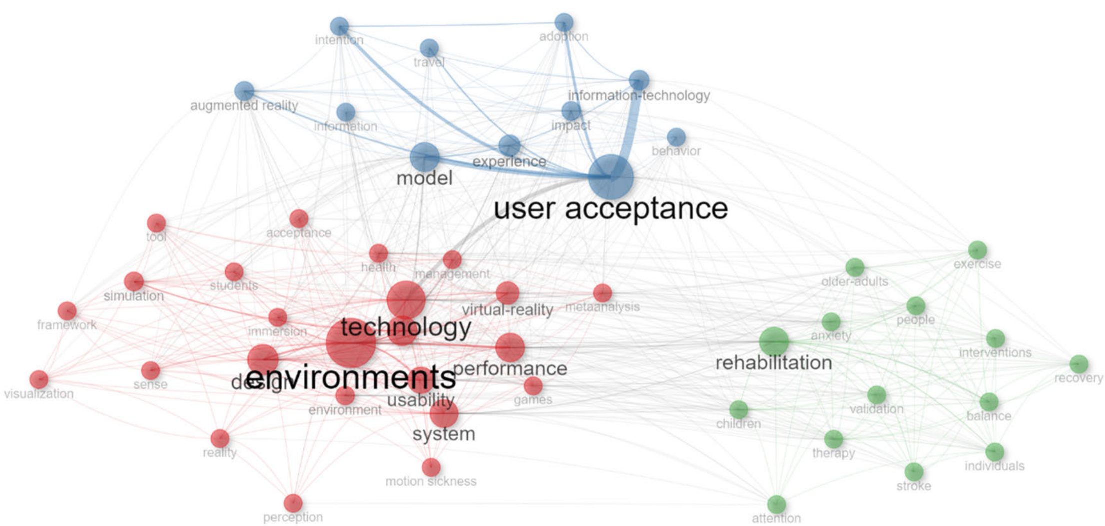

FIGURE 8. Author productivity over time.

also collaborate with Latin American countries where the same languages are spoken.

Another important analysis we provide is the impact of publications by country. The United States and China lead with significant output. The United States stands out not only for the number of articles produced but also for its total number of citations. This trend is consistent with other bibliometric studies in the field of VR, where the United

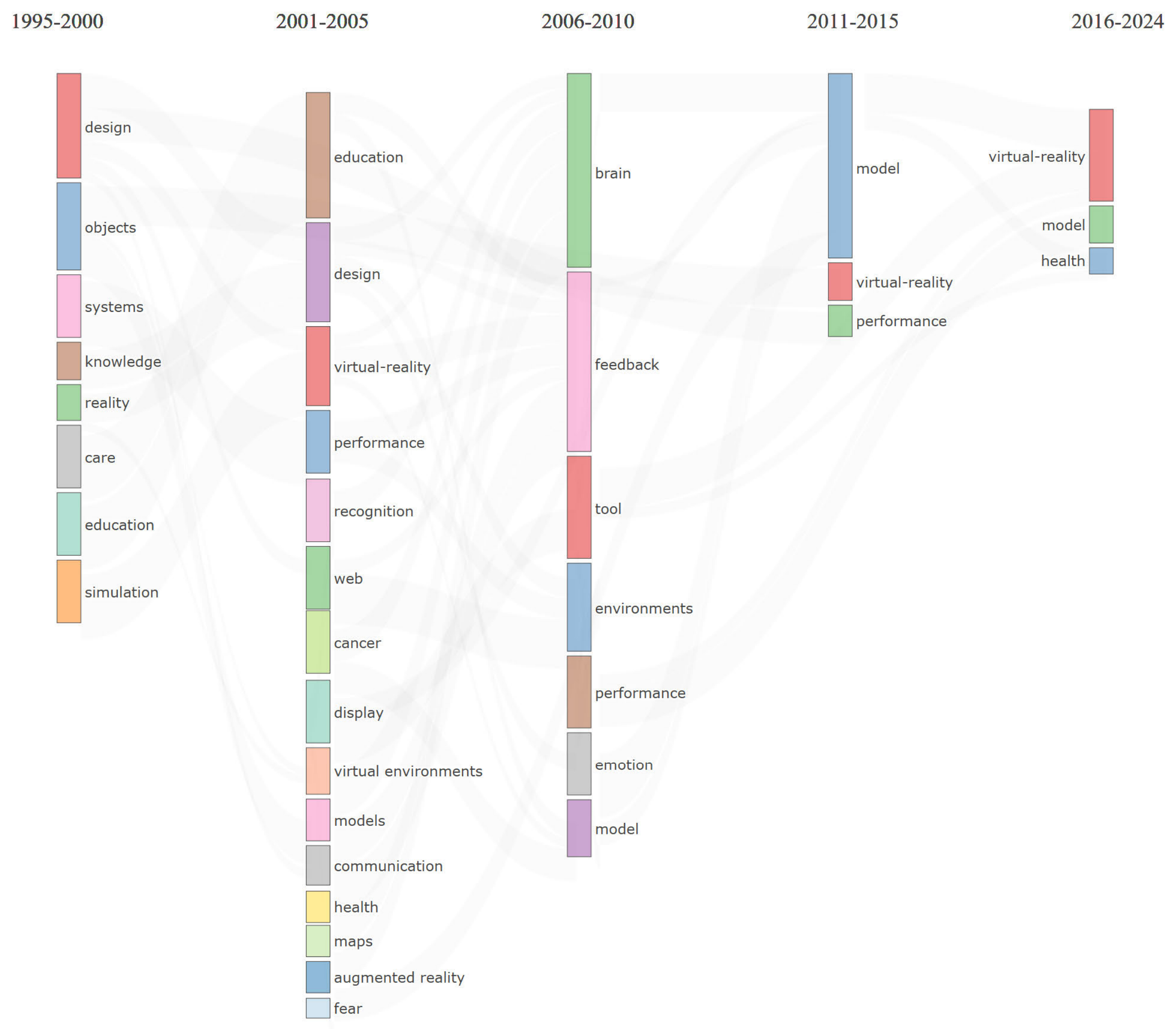

FIGURE 9. Thematic map.

States is positioned as a reference in scientific production [37], [38]. Such interest may be related to the search for innovative solutions to address public health challenges, as well as the projected increase in the elderly population in the coming decades, according to a United Nations report [39].

On the other hand, European countries like England and Spain show high impact in terms of citations per publication, indicating that, although their output is smaller in volume, their quality is comparable or even superior in some cases. Meanwhile, countries like Norway and Israel demonstrate a high relative impact despite a lower volume of publications, a trend linked to its strategic focus on high-impact research areas such as extended reality and simulation. Their collaborative networks with leading institutions in the UK, the US and Germany amplify the visibility of their work, while their selective publication strategy ensures that its studies receive substantial citations.

Despite the increase in research output, there has been a decline in the average number of citations per article in recent years. This may indicate saturation in the field, where the abundance of new publications competes for attention and recognition in an overcrowded space. Hanson [40] mentions that in 2022, scientific production in the major databases increased by 47% compared to 2016. This growth not only affects the visibility of new findings and innovative research but could also slow the advancement of knowledge in this and other fields. Therefore, researchers and academic journals must implement stricter criteria to ensure the publication of relevant documents. Although studies have used user experience data to improve product and service design, a systematic review is needed to comprehensively analyze these data [41]. Additionally, the lack of standardized methodologies to evaluate and compare factors such as immersion, presence, or cognitive load limits the design of interfaces and virtual environments.

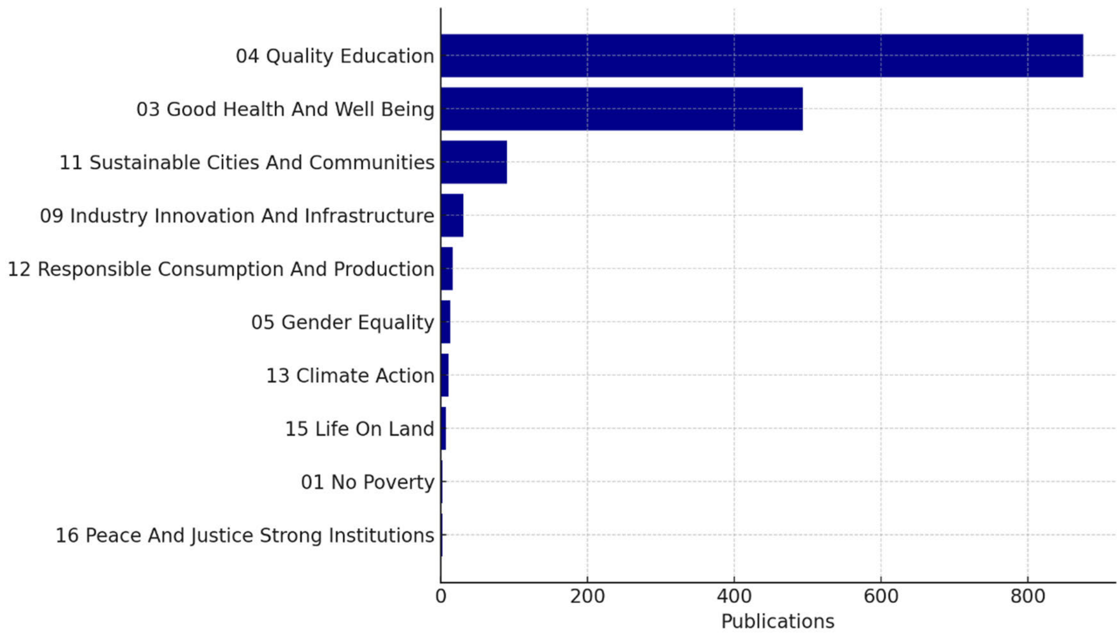

FIGURE 10. Distribution of publications aligned with the sustainable development goals.

The analysis of funding agencies also reveals a concentration of resources in a few countries. Developed nations such as China, the United States, and South Korea lead the list. The National Natural Science Foundation of China (NSFC) stands out for funding the largest number of publications, while the European Union (EU) is consolidated as an institution that supports high-impact research projects, as reflected in the high number of citations generated by these publications [42].

Furthermore, the results show a growing alignment with the 2030 Agenda. Two goals cover more than 70% of the publications reported in this review. SDG 04 ''quality education'' was the most representative category, as immersive technologies have transformed learning environments by improving knowledge retention, participation and accessibility. [43]. This is in line with recent bibliometric and systematic reviews [44], [45], which highlight that VR-based training has a significant impact on STEM education, vocational programs, and distance learning by allowing students to practice real-world scenarios in a safe and controlled virtual space. [46]. VR has been shown to be effective in developing skills for high-risk environments, such as fire safety training, where immersion enhances procedural learning but has limited effects on conceptual knowledge acquisition [47]. Additionally, serious VR games designed for vocational education have shown potential in hazard perception training, helping students understand workplace safety regulations in an engaging and interactive way [48].

In addition, VR contributed significantly to SDG 03 ''health and well-being'', as 26.46% of the analyzed publications address health-related applications [49]. In rehabilitation, Mekbib et al. [50] demonstrated how VR-based interventions demonstrated greater motor recovery in patients who have suffered a stroke by stimulating mirror neurons and improving bilateral upper limb training. In mental health, customizable VR environments enhance relaxation, engagement, and stress management, reinforcing their potential for personalized therapeutic applications [51].

B. CURRENT TRENDS AND OPPORTUNITIES

The increasing adoption of VR can be attributed to several factors, most notably advances in hardware and software, which have significantly improved the performance, accessibility, and affordability of these systems [52]. Devices such as HMDs, motion controllers, and haptic interfaces have evolved beyond their initial functions, incorporating higher refresh rates, lower latency, and improved ergonomics, which together enhance spatial immersion and user comfort [53]. Among the most researched current topics are perception and interaction, reflecting the growing need for true interaction with the virtual system [54], [55].

Current research trends reflect the increasing focus on developing models and simulations that create more immersive and realistic experiences. Mäkinen et al. [41] highlighted that while haptic simulators are valuable tools in training due to their tactile realism, HMDs provide a more complete sensory immersion, promoting greater spatial awareness, knowledge retention and active participation. However, the interaction between different VR technologies and their long-term impact on usability and learning effectiveness remain open questions that require further empirical validation.

Usability, accessibility and cognitive load influence users' willingness to adopt VR technologies. Li et al. [56] found that factors such as interactivity, immersion and presence improve the perception of ease of use, enjoyment and usefulness, which impacts the intention to use. Similarly, Sumunar et al. [57] remarked that the acceptance of VR in educational environments is linked to the usability of the system, the depth of the content and the optimization of the hardware, aspects that determine its effectiveness as a learning tool. Models such as the Technology Acceptance Model (TAM) [58] and the Unified Theory of Acceptance and Use of Technology (UTAUT) [59] were used to analyze how design and functionality influence the integration of VR.

Currently, applications that employ voice commands, electromyographic signals, and eye tracking are being developed, or even combinations of these to offer greater accessibility and adaptability to different users [60], [61], [62]. Voice commands have proven to be useful in environments where the use of hands is restricted, such as in medical or industrial applications. Hombeck et al. [63] pointed out that this technology improves efficiency and reliability, as it allows quick adjustments using natural language, thus reducing the cognitive load on the user. On the other hand, eye tracking has established itself as one of the most advanced techniques for VR interaction, offering a higher level of customization and immersion. By allowing more intuitive interaction without the need for physical controllers, this technology facilitates navigation and improves accessibility in hands-free scenarios [64]. Its potential to adapt the interface according to the direction of the gaze and the user's intention allows optimizing the immersive experience in advanced virtual environments [65].

In parallel, the integration of affective computing in VR is redefining interventions in mental health, behavioral therapy, and stress management, through real-time physiological monitoring, adaptive environments, and analysis of emotional states [66], [67]. This convergence between VR and affective HCI allows systems to dynamically adjust their behavior according to the user's emotional responses, optimizing immersion and interactive experience. Current trends include the use of VR to innovate cognitive rehabilitation processes, perceptual training, and human-computer interaction, with both experimental and practical applications [68], [69].

There is a strong focus on the technical aspects of VR, while other topics, such as its integration into real-world contexts and its impact on users' daily activities, seem to receive less attention. This focus could ensure that virtual environments are accessible, functional, and comfortable for all users, leveraging their ongoing contributions in the health sector. VR-based interventions are effective in improving physical rehabilitation, as they allow patients to perform exercises in an immersive and controlled manner [70], [71]. The inclusion of more diverse input devices could better accommodate users' physical needs and contribute to their training or rehabilitation processes. Additionally, VR has applications in mental health, allowing the treatment of disorders such as post-traumatic stress and phobias. Gradual exposure to various stimuli in a controlled environment is becoming a promising trend and an innovative alternative to traditional therapies [72].

C. CHALLENGES AND LIMITATIONS

Despite the availability of various VR devices, it is still unknown which one is the most effective at optimizing UX and immersion based on the context of use [73], [74]. Choosing the appropriate interaction paradigm remains a challenge, as it involves considering variables such as latency, proprioceptive feedback, and cognitive load. Furthermore, system performance plays an important role in user perception; high latency or frame rate drops can affect the sense of presence and increase the risk of adverse symptoms [75]. Therefore, optimizing graphical performance and processing efficiency are important elements to ensure a smooth and immersive experience.

Implementation of applications that employ voice commands still faces challenges. Korkiakoski et al. [76] pointed out that interference in noisy environments and the need to memorize phrases affect their effectiveness, so combining them with gestures or other methods could optimize their use. While the application with eye tracking presents challenges related to high implementation costs and the need for robust machine learning models to interpret gaze data accurately [77].

In terms of the senses, another current area of interest, there remains a high dependence on visual stimuli, while olfactory and auditory stimuli, though fewer in number, are beginning to gain relevance [78], [79]. Auditory stimuli, while effective in increasing presence, often compete with visual stimuli, which may reduce their impact due to the visual dominance in VR experiences [78]. Lee et al. [80] showed that auditory cues can significantly improve reorientation in virtual environments, suggesting a positive impact on spatial awareness.

Similarly, olfactory systems face technical limitations, including bulky size, slow response times, and variability in user perception, making standardization difficult [81]. However, studies such as the one conducted by Liu et al. [79] demonstrated that advances in miniaturized and wireless olfactory interfaces are improving odor concentration control, energy efficiency, and long-term stability, expanding their potential applications in entertainment, education, and medical treatment. Magalhães et al.'s review [82] suggests that multisensory approaches that include at least two senses could significantly improve immersion and emotions in the virtual experience.

Furthermore, the adoption of VR poses several ethical and social challenges that have not yet been fully addressed [83]. Cybersickness remains one of the common problems due to the variability of neurophysiological responses between individuals. Lawson and Stanney [84] and Caserman [85] suggested that genetic predisposition, vestibular sensitivity and cognitive adaptability may influence susceptibility to motion sickness and sensory disorientation. This variability challenges the effectiveness of general solutions, requiring customized VR settings based on real-time physiological monitoring and adaptive algorithms [86].

Beyond physiological challenges, immersion-driven behavioral changes are gaining attention. Highly immersive environments not only alter social perception and interactions, but may also influence decision-making processes and emotional regulation in ways that are not yet fully understood [87]. It is also important to consider whether highly immersive virtual environments could affect social interactions, perception of reality, or even lead to addiction [88]. This has implications for VR applications in mental health, training simulations, and virtual social spaces, where unintended psychological effects could arise. Addressing these concerns requires interdisciplinary collaboration between cognitive scientists, ethicists, and VR engineers to develop frameworks for responsible design and use guidelines.

Data privacy concerns have also evolved beyond mere collection risks. With advances in AI-driven behavioral analytics, VR is increasingly capable of predicting users' emotions, preferences, and cognitive states with high accuracy, raising questions about data sovereignty, unconscious behavioral tracking, and the potential for manipulative design practices [89]. Future research should not only focus on stronger data protection policies, but also on transparent AI models and decentralized data ownership structures to ensure ethical governance in immersive environments.

D. FUTURE RESEARCH DIRECTIONS

Future research should focus on understanding VR from a multidisciplinary perspective. Martingano et al. [90] suggested that while VR can foster emotional empathy, its impact on cognitive empathy remains limited. From a psychological perspective, one could analyze how cognitive and emotional responses influence user immersion and engagement, allowing for the design of experiences that are not only realistic but also emotionally meaningful. In this regard, Li et al. [91] highlighted that exposure to simulated natural environments in VR can reduce stress and improve emotional state, highlighting the importance of integrating psychological principles into the development of these environments.

VR design should focus on developing intuitive and accessible interfaces that reduce cognitive load and enable more natural interaction through multimodal systems that integrate visual, auditory, and haptic feedback [92]. Ergonomics plays a key role in optimizing comfort and interaction, considering factors such as eye strain, user posture, and adaptation to different levels of immersion to maximize the virtual experience. Furthermore, UX analysis has begun to be applied in the continuous optimization of VR products and services, ensuring more adaptive and user-centered developments [22].

Wu et al. [93] mentioned that the integration of industrial design and interaction design could improve usability and UX, which directly impacts the commercial viability of VR. Current research has started to use UX data to optimize ergonomics, interface, and functionality, which not only improves the adoption of the technology but also maximizes its market impact. Furthermore, the customization and adaptability of virtual environments, driven by design economics, are facilitating more efficient production processes, allowing VR to evolve into a more sustainable and accessible model.

Future research should focus on refining the integration of other emerging technologies to improve the functionality and adaptability of VR applications [94]. Recent studies indicate that AI-powered VR systems can personalize experiences and align with assistive technologies and digital health applications. Raza et al. [95] demonstrated that detecting user immersion levels through advanced machine learning models can optimize application design, achieving a 98% accuracy rate using explainable AI techniques. Similarly, Saranya et al. [96] explored deep learning and genetic algorithms for human-computer interaction, developing adaptive and intelligent virtual environments that enhance user experience and personalization in real-time.

To further refine these applications, future studies should develop advanced methods for collecting and analyzing large volumes of UX data, using machine learning and predictive analytics to identify usage patterns and report best practices in application design and interaction frameworks [97]. Furthermore, ergonomic risks need to be addressed, as prolonged use of VR can lead to muscle fatigue, wrist pain, and postural discomfort. Research should focus on designing ergonomically optimized interfaces that reduce physical strain while maintaining high levels of immersion and usability [98].

Furthermore, the increasing computational power of modern systems has improved real-time rendering and adaptive user interfaces, expanding accessibility and accelerating the adoption of VR across several research domains [99]. By integrating multi-sensory feedback, biometric recognition, and AI-driven interaction models, future VR applications can deliver more immersive, adaptive, and inclusive experiences, broadening their impact in education, healthcare, and industrial training.

In the field of health and well-being, studies are needed to evaluate the effectiveness of these applications and develop protocols for their safe and effective implementation [100]. It is important to assess how these devices affect the user experience in the long term, considering factors such as visual fatigue or physical discomfort after prolonged use and cybersickness [101]. Research should focus on identifying factors that contribute to cybersickness and developing mitigation strategies, such as latency optimization, adaptive motion algorithms, and desensitization techniques [102].

Pöhlmann et al. [103] indicated that prior exposure to virtual environments, particularly through video games, can improve visuospatial skills and increase resistance to motion sickness, thereby reducing discomfort in VR applications. Future research should explore non-VR training methods to improve user adaptation, along with real-time physiological monitoring and adaptive visualization techniques to improve accessibility.

As Geslin and Saldivar [104] pointed out, further research is required on optimized UX design, adaptive motion algorithms, and better latency management. Tracking Simulator Sickness Questionnaire (SSQ) scores [105] and presence metrics can further refine interaction models, minimize cognitive load, and integrate multisensory feedback, creating more inclusive and user-centric virtual experiences [106], [107].

Finally, research should address how to protect user privacy and ensure that data collected in virtual environments is managed securely and ethically [108]. The integration of VR with cybersecurity should also be considered for better data protection [109]. Current privacy mechanisms include encryption protocols, anonymization techniques, and secure data storage systems, which help safeguard sensitive user information [110]. However, significant challenges remain, such as improving transparency in data collection practices, developing more robust consent mechanisms, and addressing the risks associated with the misuse of biometric data, including eye tracking and physiological responses.

Furthermore, privacy concerns in VR extend beyond data security, as immersive environments enable new forms of user tracking that can compromise anonymity. For example, biometric and behavioral data could be used for user profiling and targeted advertising, raising ethical concerns [110]. Future research should focus on integrating privacy-preserving techniques, such as differential privacy models and secure multi-party computation, to limit unauthorized access to user data while maintaining usability. This combination of VR and cybersecurity should explore real-time threat detection and prevention mechanisms to protect against emerging risks.

V. CONCLUSION

As VR becomes more accessible and affordable, its application has experienced significant expansion, particularly in areas such as education, healthcare, and entertainment. However, this increase in research output presents new challenges for the visibility and recognition of innovative findings. In this regard, institutional and geographical collaboration emerges as a strategy that could improve the distribution and advancement of knowledge in VR research. One limitation of the bibliometric analysis deals with the fact that it did not compare exponential smoothing with other models, which could have provided a broader perspective on the growth of scientific production.

Strong collaboration networks, such as those observed in several European countries, demonstrate the importance of connectivity in fostering innovation and scientific production. Moreover, disciplinary diversity and international collaboration will allow for addressing the ergonomic, social, and ethical challenges faced by this technology. Despite these advances, important limitations remain, such as the occurrence of cybersickness, variability in user perception and the absence of standardized methodologies for evaluating UX in virtual environments. These barriers can be mitigated by developing more intuitive and adaptive interfaces, refining AI-based interaction models, and implementing strategies that reduce the negative effects of prolonged use of VR systems. By overcoming these obstacles, VR will be able to reach its full potential in various sectors.

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