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Transforming Disaster Education Through Immersive Technologies: A Comprehensive Bibliometric Review

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Systematic Review

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Transforming Disaster Education Through Immersive Technologies: A Comprehensive Bibliometric Review

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Abstract

Immersive technologies are increasingly being adopted in disaster education because they provide learners with opportunities to experience realistic scenarios within safe and controlled environments. However, the rapid growth of research in this field has not yet been accompanied by a comprehensive understanding of its intellectual structure, collaboration patterns, and thematic evolution. This study aims to map the development of research on immersive technologies in disaster education and to identify the dominant themes and emerging research directions. A bibliometric analysis was conducted on 289 Scopus-indexed documents published between 2003 and 2026. The findings indicate that research on immersive technologies has developed consistently, with an annual growth rate of 16.86%, reaching its highest publication output in 2025. The United States, Japan, China, New Zealand, Italy, and Indonesia emerge as major contributors, while New Zealand demonstrates particularly strong citation impact and international collaboration engagement. Keyword and influential-publication analyses reveal a thematic shift from virtual simulation and disaster exercises toward immersive learning, serious games, behavioral responses, risk awareness, and decision-making. The findings demonstrate that research on immersive technologies in disaster education has progressed beyond the use of technology merely as a simulation medium toward experiential, behavior-oriented, and decision-centered learning. Future research should prioritize the development of adaptive and context-aware immersive environments through the integration of artificial intelligence, spatial data, and real-time disaster information, while placing greater emphasis on long-term learning retention and the transfer of learned behaviors to real-world disaster situations.

Keywords: immersive technology; disaster education; serious games; natural hazards; bibliometric analysis

1. Introduction

Disaster education plays a critical role in enhancing knowledge, risk perception, and preparedness [1–4]. To date, disaster education has predominantly relied on conventional instructional methods, including lectures, textbooks, instructional videos, and basic simulation exercises [5]. Although these approaches can effectively convey conceptual knowledge, they often provide limited opportunities for students to engage with realistic and dynamic disaster scenarios. As a result, conventional approaches may not adequately provide the experiential learning required to develop practical competencies for responding to complex and uncertain disaster situations [6,7].

The emergence of immersive technologies encompasses technologies that create or augment a sense of presence and interactive experience, including augmented reality (AR), virtual reality (VR), mixed reality (MR), and extended reality (XR), has opened a new paradigm for disaster education [6–9]. These technologies enable users to interact with three-dimensional environments that provide a strong sense of presence, allowing learners to experience simulated disaster situations in a safe and controlled environment without exposure to real-world hazards [10,11]. Immersive technologies have increasingly been applied to a wide range of disaster education scenarios, including earthquakes, floods, tsunamis, fires, building evacuations, and emergency response [6,7,12–15]. Overall, previous studies have reported that immersive learning environments can enhance learner engagement, self-efficacy, decision-making skills, knowledge retention, and disaster preparedness [6,13,16–18].

In recent years, scientific publications addressing immersive technologies in disaster education have grown rapidly [19,20]. This expanding body of research has increasingly moved beyond technology-focused applications and begun to explore the integration of Artificial Intelligence (AI), game-based learning, serious games, the Internet of Things (IoT), haptic feedback, and adaptive learning. The increasing diversity of technological and pedagogical approaches indicates that immersive technology research in disaster education is evolving into a multidisciplinary field that intersects educational technology, human–computer interaction, artificial intelligence, simulation, and disaster risk reduction.

However, the rapid growth of publications has not yet been accompanied by a comprehensive knowledge mapping that captures the overall development and intellectual

structure of this emerging field. Previous literature reviews have largely focused on VR and serious games, with particular attention to pedagogical outcomes, behavioral responses, game-environment development, and user experiences [21]. Other reviews have primarily synthesized the benefits, opportunities, and challenges associated with the application of VR and AR in disaster management [22]. Although these reviews provide important foundations for understanding the potential of immersive technologies, their scope remains limited in systematically mapping the broader landscape of immersive technologies used in disaster education. In particular, the relationships among emerging technologies—including mixed reality, augmented reality, haptic technologies, AI-driven environments, adaptive learning, and other supporting technologies—remain insufficiently understood from a holistic perspective.

This gap is important because immersive disaster education is no longer characterized by the adoption of a single technological modality. Rather, the field is increasingly shaped by technological convergence, in which immersive environments interact with AI, intelligent agents, adaptive learning systems, haptic interfaces, and other digital technologies to create increasingly interactive and personalized learning experiences. Without a comprehensive mapping of this evolving research landscape, it remains difficult to determine how the field has developed over time, which actors and knowledge networks have shaped its growth, and how research priorities have shifted from technology-oriented simulation toward more sophisticated and learner-centered approaches.

Against this background, this study conducts a bibliometric analysis of immersive technologies in disaster education to systematically map the development of the field, its intellectual structure, collaboration networks, and thematic evolution. Specifically, the study addresses the following research questions:

- RQ1: How has research on immersive technology in disaster education evolved over time in terms of publication trends, sources, and geographical distribution?
- RQ2: Which authors, institutions, and countries contribute most to this field, and what collaboration networks characterize their knowledge production?
- RQ3: What are the main research themes, emerging topics, and influential works shaping immersive technology applications in disaster education?

The novelty of this study lies in its effort to move beyond a publication-oriented description of the field and provide a comprehensive account of the conceptual evolution of immersive

technologies in disaster education. By integrating temporal analysis, intellectual structure analysis, collaboration network analysis, and thematic evolution analysis, this study seeks to identify how research has evolved from technology-centered simulation toward learner-centered, intelligent, adaptive, and increasingly integrated immersive learning environments. This perspective provides a broader understanding of the transformation of immersive disaster education and identifies emerging research directions that can inform future technological development, pedagogical design, and research agendas in disaster education.

2. Methodology

2.1. Study Design

This study employed a bibliometric review to systematically examine the development, intellectual structure, collaboration patterns, and thematic evolution of research on immersive technologies in disaster education. Bibliometric review is a quantitative approach that systematically examines bibliographic metadata retrieved from a scientific publication database [23] . Relevant publications were retrieved from a selected database using a predefined search strategy and subsequently screened according to established inclusion and exclusion criteria. The final dataset was then analysed using two complementary techniques: performance analysis, which evaluates the contributions and productivity of various research constituents, and science mapping, which examines the relationships and intellectual connections among these constituents [24] .

2.2. Search Strategy

In this study, bibliographic data were retrieved from the Scopus database. Scopus was selected because of its broad multidisciplinary coverage and its provision of comprehensive bibliographic and citation metadata required for bibliometric performance analysis and science mapping [25]. The metadata obtained from Scopus are also readily compatible with a range of bibliometric analysis software, facilitating subsequent data processing and visualization [26]. Furthermore, Scopus provides access to high-quality research publications, as its content is selected for inclusion through a rigorous evaluation process.

The literature search was conducted on 12 July 2026 through the Scopus website. The search query was applied to article titles, abstracts, and keywords, incorporating three main concepts: immersive technologies, natural hazards and disaster-related phenomena, and education

and training (Table 1). The search terms within each concept were combined using the Boolean operator “OR”, while the three search concepts were combined using “AND” to ensure comprehensive retrieval of relevant literature. The retrieved bibliographic metadata were subsequently exported from Scopus as a comma-separated values (.csv) file for further bibliometric analysis.

Table 1. Search strategy for identifying literature

Search Concept	Search Fields	Search Terms
Immersive technologies	Titles, abstracts, and keywords	"Immersive technology*" OR "virtual reality" OR "augmented reality" OR "mixed reality" OR "extended reality" OR "VR simulation" OR "AR simulation" OR "MR simulation" OR "XR simulation" OR "VR technology*" OR "AR technology*" OR "MR technology*" OR "XR technology*"
Natural hazards and disaster-related phenomena	Titles, abstracts, and keywords	"Natural hazard*" OR "disaster*" OR "earthquake*" OR "tsunami*" OR "volcano*" OR "landslide*" OR "hurricane*" OR "typhoon*" OR "cyclone*" OR "tornado*" OR "drought*" OR "flood*" OR "wildfire*" OR "forest fire*"
Education and training for disaster risk management, learning, and knowledge development	Titles, abstracts, and keywords	educate* OR pedagogy* OR learn* OR train* OR drill* OR teach* OR knowledge* OR literacy* OR practice*

2.3. Data Screening and Selection

The retrieved dataset was screened through a sequential selection process to ensure its relevance to the research objectives. The screening and selection procedures were guided by the

Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework [27]. No restrictions were imposed on the publication year. However, the search was limited to publications written in English. Regarding document type, only articles, review articles, and conference papers were included, while other document types (such as editorials, book series, letters, short surveys, notes, conference reviews, and retracted publications) were excluded.

The screening and selection process is presented in Figure 1. The initial search in Scopus retrieved 1,545 records. Of these, 360 records were excluded based on the predefined eligibility criteria, including 57 records excluded based on language and 303 records excluded based on document type.

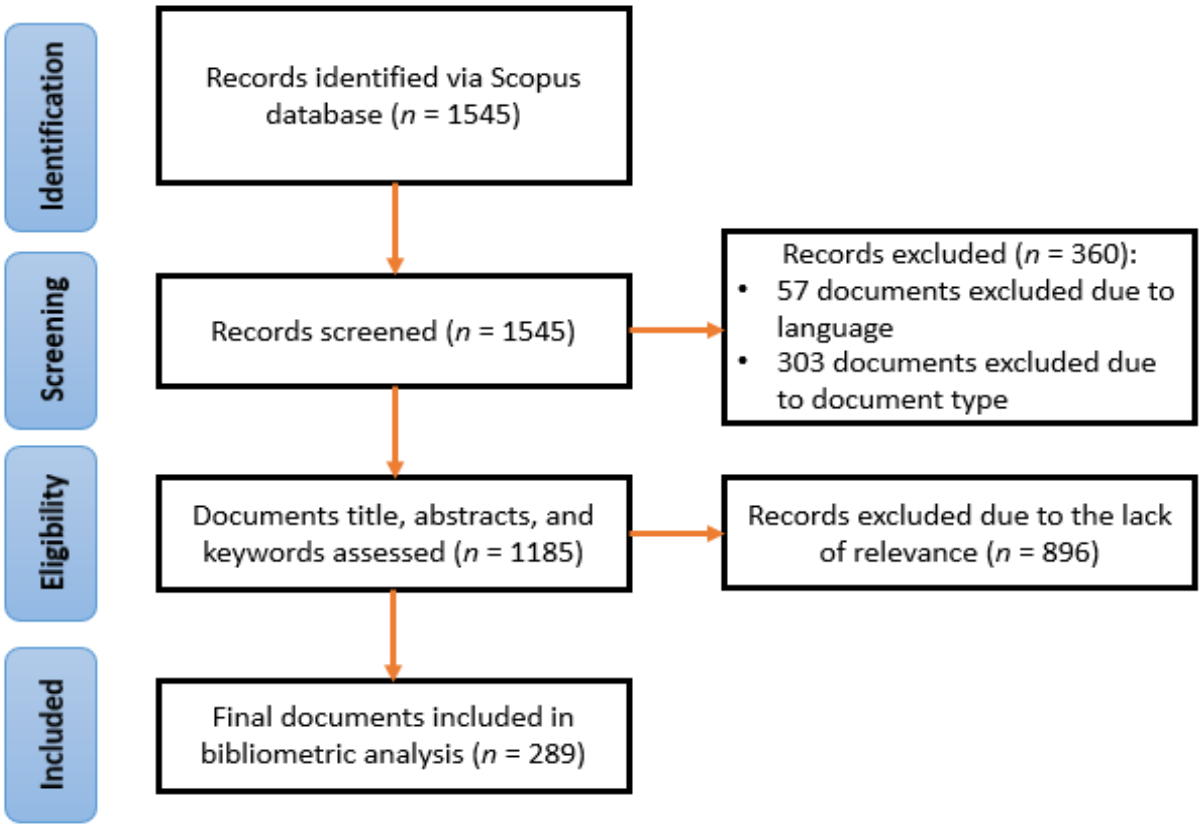


Figure 1. PRISMA protocol for document selection

The remaining 1,185 records were then screened based on their titles, abstracts, and keywords to assess their relevance to the research topic. Studies that focused solely on the technical design, development, or prototyping of immersive technology applications without a substantive educational component were excluded. Studies unrelated to natural hazards were also excluded, including those addressing chemical, biological, radiological, and nuclear (CBRN) incidents,

emergency medicine, terrorism, or construction-related incidents. In addition, records in which disaster-related or immersive-technology terms were mentioned only incidentally rather than constituting a central focus were excluded. Studies primarily addressing sectors other than education, such as communication, cultural heritage, healthcare, psychology, and tourism, were likewise removed. Ultimately, 289 documents were selected for the bibliometric analysis.

2.4. Data Analysis

The analysis was conducted using two complementary approaches: performance analysis and science mapping. Performance analysis was employed to examine the development and characteristics of the research field based on publication trends, publication sources, author productivity, and citation indicators. In addition, science mapping was performed to explore the intellectual and conceptual structures of the field through co-authorship analysis, co-word analysis, dan citation analysis. Data analysis and visualization were performed using Biblioshiny version 5.0, VOSviewer version 1.6.20, and Microsoft Excel [24,27]. The results were subsequently synthesized and interpreted to address the three research questions concerning the development of the field, the structure and networks of knowledge, and the evolution of research themes and directions.

3. Results

3.1. Overview

The characteristics of the documents included in the bibliometric analysis are presented in Table 2. A total of 289 documents were retrieved from the Scopus database. Approximately three-quarters of the total documents have received at least one citation. The total number of citations reached 4,322, resulting in an average of 14.96 citations per document. In total, 992 authors contributed to the dataset, with an average of 4.16 co-authors per document. The most prevalent document type was conference papers (n = 169; 58.48%), followed by journal articles (n = 105; 36.33%) and review papers (n = 15; 5.19%).

Table 2. Descriptive information

Category	Description	Value
	Timespan	2003:2026

Main Information Data	Documents	289
	Annual growth rate (%)	16.86
	Document average age	4.73
	Average citations per doc	14.96
Document Contents	Keywords plus	1724
	Author's keywords	794
Authors	Authors	992
	Authors of single-authored docs	10
Authors Collaboration	Single-authored docs	10
	Co-authors per doc	4.16
	International co-authorships (%)	20.76
Document Types	Article	105
	Conference paper	169
	Review	15

3.2. Research trends and global distribution

3.2.1. Publication trends over time

The data presented in Figure 2 illustrate insights into the progression of research within this field. The earliest identified publication dates to 2003, focusing on the development of a virtual reality–based distance learning program for earthquake education [28]. In general, between 2003 and 2016, the number of publications remained relatively low, consistently staying below the threshold of 10 documents per year. A noticeable increase in research interest began in 2017, followed by a steady upward trend, with the number of publications reaching its peak in 2025, totaling 45 documents. It is important to note that this bibliometric analysis was conducted in mid-2026; therefore, the number of publications recorded for 2026 does not fully represent the trend for the entire year.

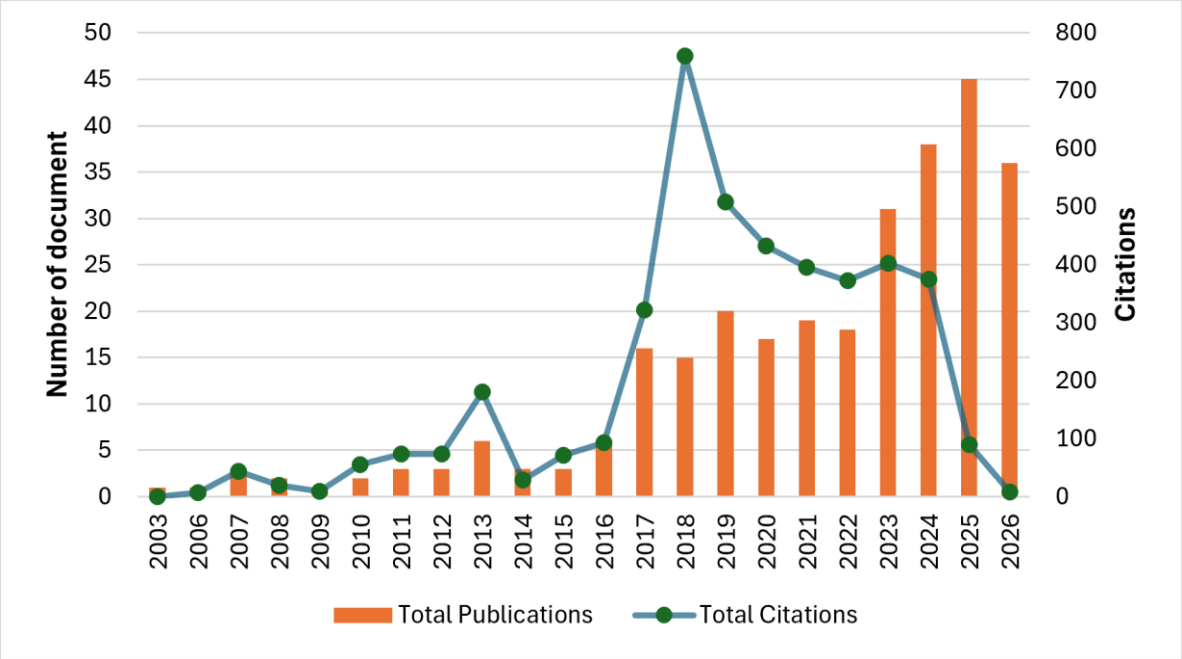


Figure 2. Annual trend of the number of documents and total citations

In terms of citations, a similar pattern to publication output can be observed, with a significant rise starting in 2017. The highest number of citations was recorded in 2018, with a total of 760 citations. Although the number of publications in that year was lower compared to subsequent years, this finding suggests the substantial impact of the scientific output published during that period.

3.2.2. Leading sources

Table 3 presents the most active sources publishing research on the application of immersive technologies in disaster education, with a minimum threshold of four documents. Research in this field was disseminated across a wide range of disciplines, with a strong presence in computer science, engineering, mathematics, and earth and planetary sciences. *International Journal of Disaster Risk Reduction* (TP = 8, TC = 150) emerged as the most prominent journal. This journal is widely recognized as a leading outlet for multidisciplinary disaster-related research. The second and third most productive sources were conference-oriented series, namely *Lecture Notes in Networks and Systems* (TP = 8, TC = 15) and *ACM International Conference Proceeding Series* (TP = 7, TC = 68), both of which were closely associated with the field of computer science.

Table 3. Most prominent sources (≥4 documents)

Source Title	Subject Area	Publisher	TP	TC	TC/TP	PY-Start
International Journal of Disaster Risk Reduction	Social science, earth and planetary sciences	Elsevier	8	150	18.75	2021
Lecture Notes in Networks and Systems	Computer science, engineering	Springer Nature	8	15	1.88	2022
Lecture Notes in Computer Science	Mathematics, computer science	Springer Nature	7	68	9.71	2009
Safety Science	Engineering, Medicine, Social sciences	Elsevier	6	370	61.67	2020
ACM International Conference Proceeding Series	Computer science	Association for Computing Machinery	5	35	7.00	2018
Advanced Engineering Informatics	Computer science	Elsevier	4	447	111.75	2018
Natural Hazards	Earth and planetary sciences, environmental science	Springer Nature	4	150	37.5	2012
International Multidisciplinary Scientific GeoConference Surveying Geology and	Earth and planetary sciences	International Multidisciplinary Scientific Geoconference	4	8	2.00	2018

Source Title	Subject Area	Publisher	TP	TC	TC/TP	PY-Start
Mining Ecology Management, SGEM						
Communications in Computer and Information Science	Mathematics, computer science	Springer Nature	4	4	1.00	2011

TP: Total Publications; TC: Total Citations; PY-Start: Publication Year Start

It is important to note that high productivity did not necessarily correspond to high research impact, as reflected in the ratio between the number of publications and citations. Journal-based sources tended to have a higher scholarly impact than conference-oriented publication outlets. Among the most productive sources, *Advanced Engineering Informatics* stood out with the highest average citation per paper (TC/TP = 111.75), followed by *Safety Science* (TC/TP = 61.67) and *Natural Hazards* (TC/TP = 37.5). In contrast, *Lecture Notes in Networks and Systems*, despite having one of the highest publication counts, exhibited a relatively lower citation impact.

The most dominant publisher contributing to this field was the Institute of Electrical and Electronics Engineers (IEEE), with a total of 64 publications (Figure 3). IEEE is widely recognized as a major global publisher that promotes scientific literature in engineering and technology. It is unsurprising that this publisher did not appear among the most productive individual sources, as its outputs were distributed across a wide range of outlets, particularly various conference proceedings. The next most prominent publishers were Springer Nature (TP = 36) and Elsevier (TP = 35). Notably, Elsevier demonstrated a substantially higher citation impact, accumulating 1,733 citations. This indicates that Elsevier's publications tended to achieve significantly greater visibility and influence within the academic community.

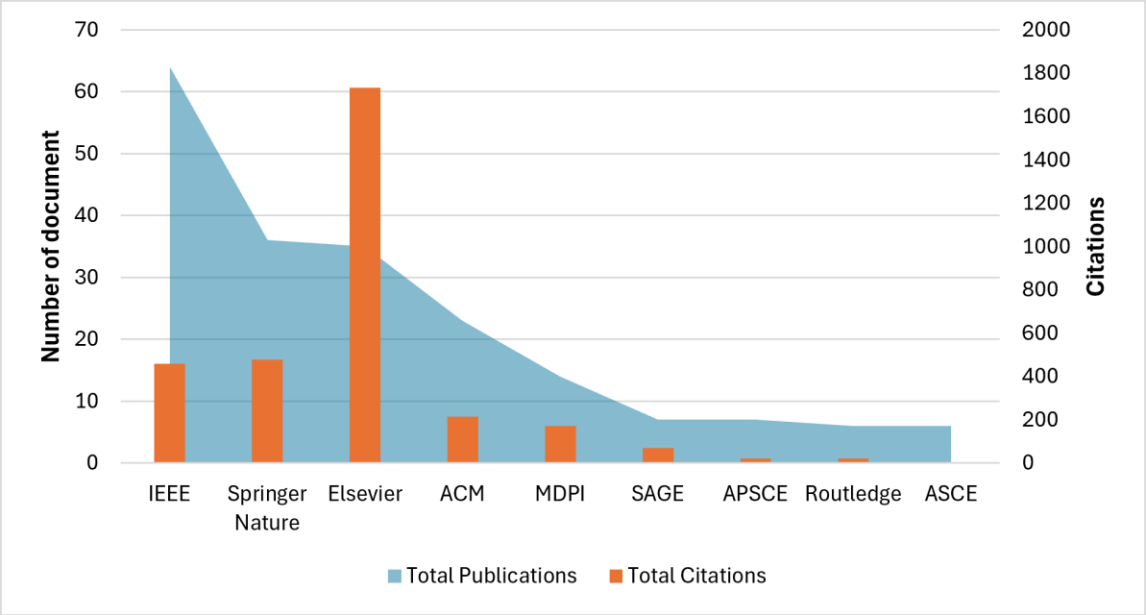


Figure 3. Most active publishers (≥5 documents)

3.2.3. Geographical distribution of research

Developed using Biblioshiny, Figure 4 visualizes the spatial distribution of research productivity in this field. The map is based on the number of author appearances by country affiliations. The darker blue color on the map is associated with a higher frequency of publications. The United States appeared as the most productive country, with a total of 118 documents. Other relatively dominant contributors included Japan (94 documents), China (80 documents), New Zealand (51 documents), Italy (42 documents), and Indonesia (40 documents). In contrast, regions such as Africa and parts of South America remained underrepresented, with limited scientific production in this area. This imbalance likely reflected disparities in access to technology, research funding, and institutional capacity.

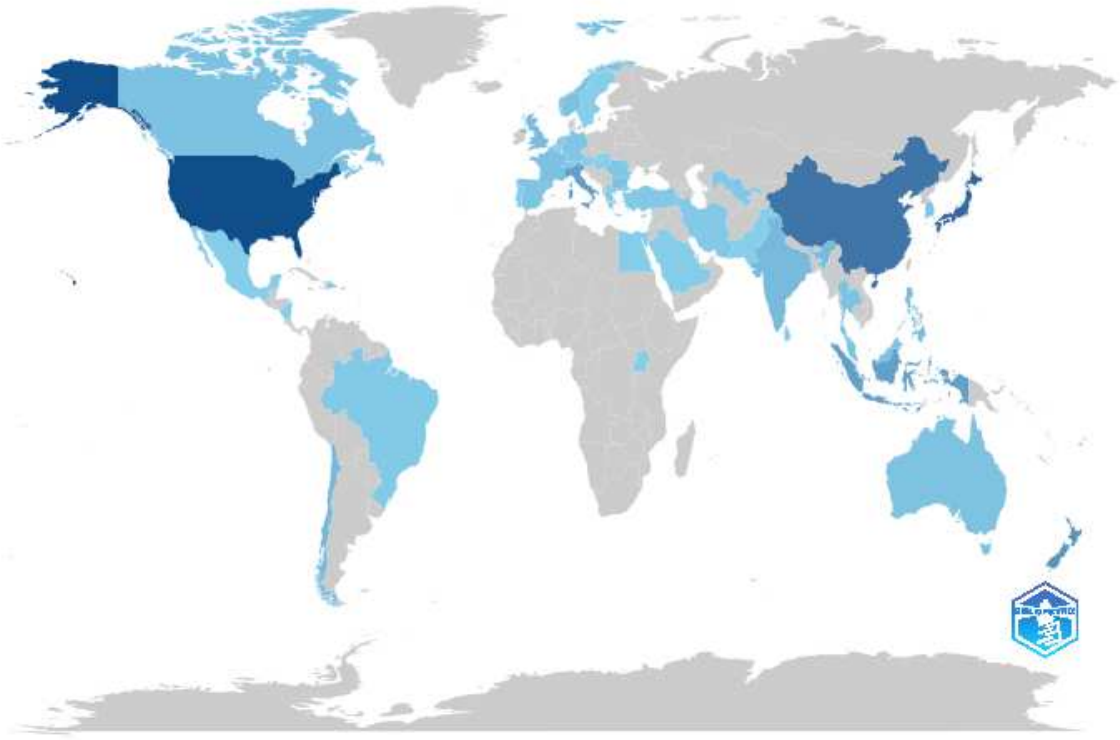


Figure 4. Country scientific production

This work further examined the publication trends of the six most productive countries mentioned above (Figure 5). Based on the Scopus database, China was the earliest country to contribute to this field. A notable competition was observed between the United States and Japan. From 2007 to 2016, the United States maintained a leading position; however, its dominance temporarily declined in the following years until 2021, after which it regained its status as the most productive country. Meanwhile, China consistently ranked as the third most active contributor. New Zealand and Indonesia could be considered emerging contributors, as they only began appearing within the last decade, yet their publication outputs increased rapidly. Publications affiliated with Italy had been present since 2011; however, growth remained relatively stagnant until a sharp increase was observed starting in 2021.

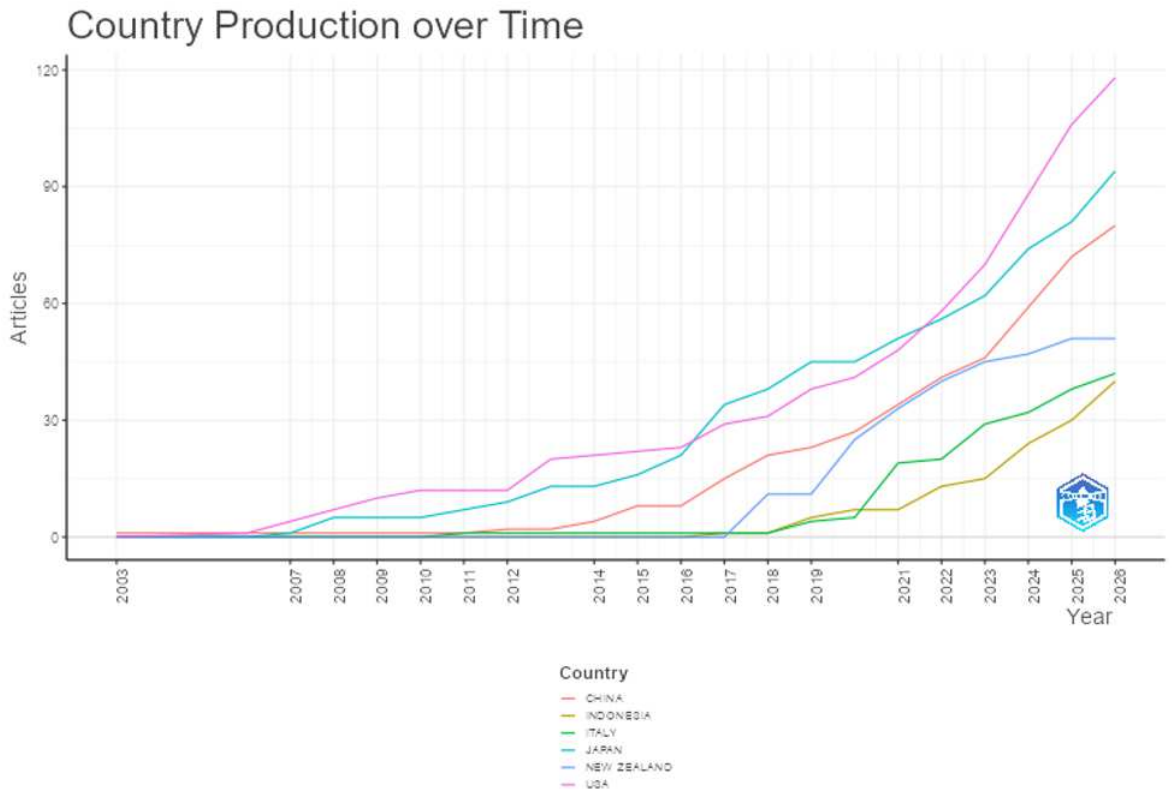


Figure 5. Country production over time

Based on citation counts, the six most productive countries were also consistently identified as the most influential, although their rankings varied considerably (Figure 6). New Zealand ranked first as the most cited country, with a total of 1,031 citations. It was followed by China (660 citations), the United States (309 citations), Italy (268 citations), Japan (143 citations), and Indonesia (111 citations).

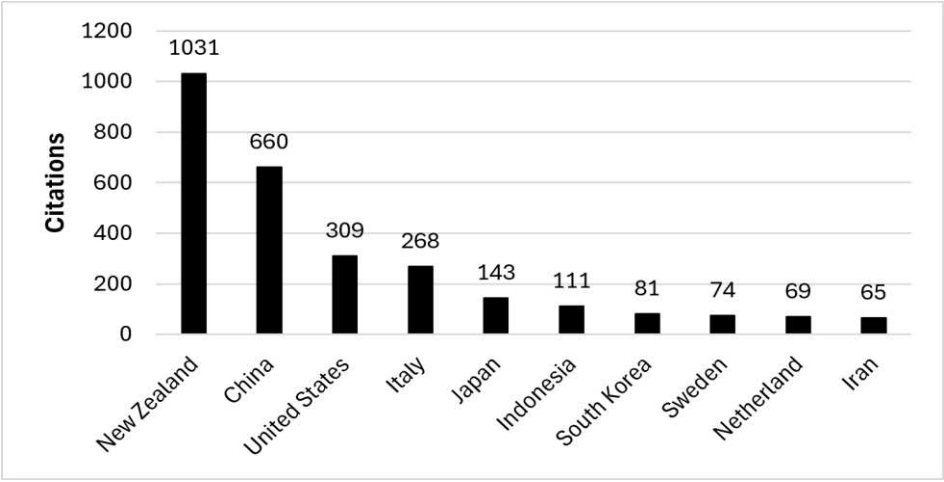


Figure 6. Most cited countries

3.2.4. Institutional contributions

Figure 7 displays the leading affiliations that have made significant contributions to the development of immersive technologies in disaster education. A minimum threshold of four documents was applied in constructing this figure. The finding indicates these top institutions originated from a diverse range of countries, including New Zealand, Japan, United States, Italy, Chile, and Romania. New Zealand demonstrated a strong presence, with institutions ranked in both first and third positions—namely, the University of Auckland with 21 documents and Massey University with 9 documents. Closely following the top position was Tokushima University (Japan), which contributed 17 documents. The University of California (United States) recorded the same number of publications as Massey University.

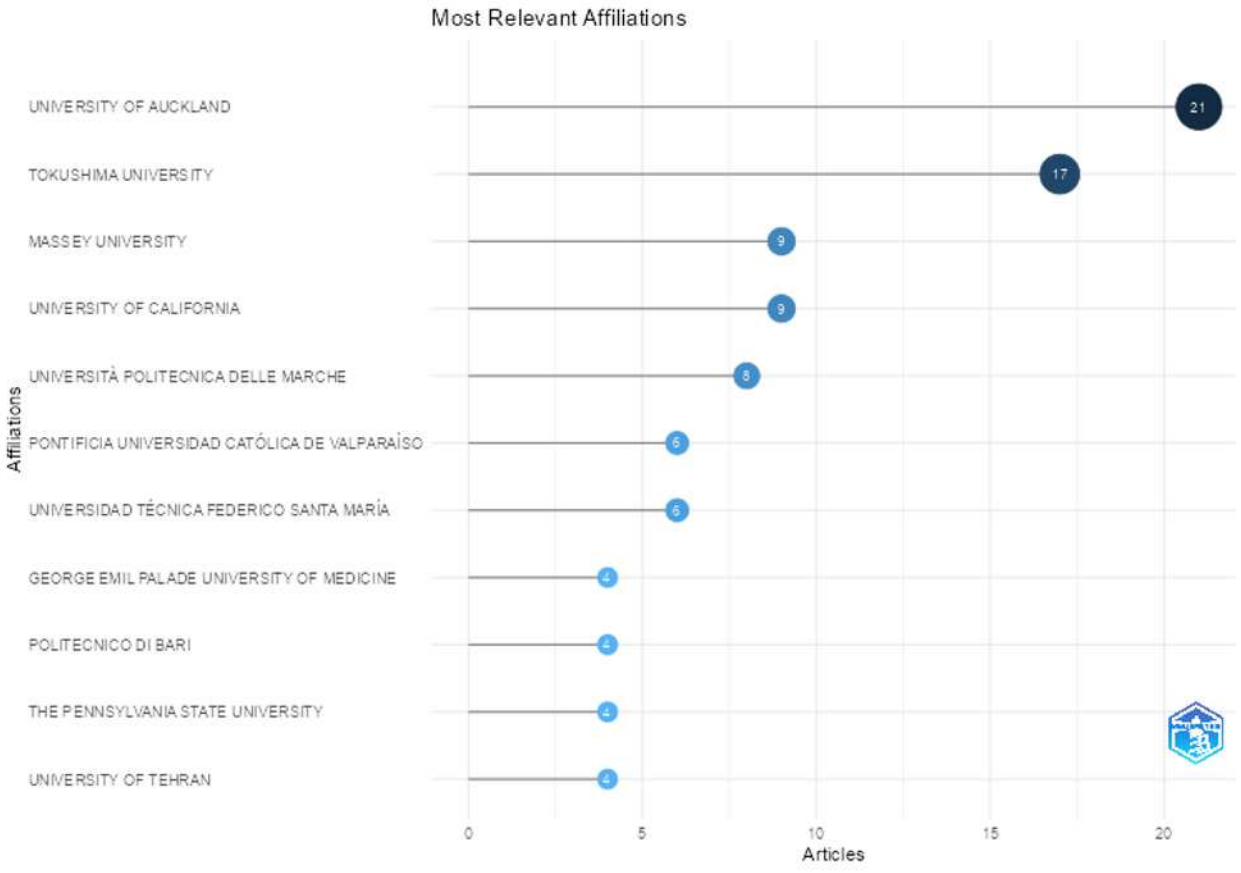


Figure 7. Most relevant affiliations

3.3. Scientific collaboration and knowledge production

3.3.1. Leading authors

Table 4 presents the top 10 most active authors, including information on their affiliations, H-index, total publications, total citations, citation-to-publication ratio, and year of publishing debut. Hiroyuki Mitsuhara was the most productive author (TP = 15), followed by Zhenan Feng and Vicente A. González, each with 10 publications. Most of these authors were affiliated with universities in developed countries, including Japan, New Zealand, Canada, and Italy. Moreover, most of the highly productive authors began contributing to this field from 2018 onward. This pattern suggested that the recent expansion of immersive technology research was accompanied by the emergence of several active research groups. In terms of scholarly impact, however, publication productivity did not necessarily correspond to citation performance. Zhenan Feng recorded the highest total citations among the most productive authors, accumulating 1,169 citations from 10 publications. When citation impact was assessed relative to publication output, Ruggerio Lovreglio ranked first, with an average of 142.57 citations per document.

Table 4. Most productive authors

Author Name	Affiliation*	H-Index*	TP	TC	TC/TP	PY-Start
Hiroyuki Mitsuhara	Tokushima University (Japan)	10	15	159	10.60	2013
Zhenan Feng	Massey University (New Zealand)	18	10	1169	116.90	2018
Vicente A. González	University of Alberta (Canada)	37	10	1030	103.00	2018
Masami Shishibori	Tokushima University (Japan)	11	10	137	13.70	2016
Enrico Quagliarini	Università Politecnica delle Marche (Italy)	39	9	181	20.11	2021
Ruggiero Lovreglio	Massey University (New Zealand)	41	7	998	142.57	2018
Robert Amor	University of Auckland (New Zealand)	25	7	930	132.86	2018

Author Name	Affiliation*	H-Index*	TP	TC	TC/TP	PY-Start
Gabriele Bernardini	Università Politecnica delle Marche (Italy)	30	7	165	23.58	2021
Guillermo Cabrera-Guerrero	Pontificia Universidad Católica de Valparaíso (Chile)	20	6	751	125.17	2018
Fabio Fatiguso	Politecnico di Bari (Italy)	22	5	68	13.60	2021

*Based on the Scopus database as of July 26, 2026; TP: Total Publications; TC: Total Citations; PY-Start: Publication Year Start

Local citations shown in Figure 8 measure the number of times an author within the dataset was cited by other authors included in the same collection. Zhenan Feng ranked first with 157 local citations, followed by Vicente A. González with 147, Robert Amor with 131, Ruggerio Lovreglio with 127, and Guillermo Cabrera-Guerrero with 104. In terms of local scholarly impact, eight authors were identified as having a local H-index of five or higher (Figure 9). Zhenan Feng and Vicente A. González, who also recorded the highest numbers of local citations, demonstrated the strongest performance according to this metric. At least nine of their publications had each received citations from a minimum of nine other documents authored by researchers within the analyzed dataset.

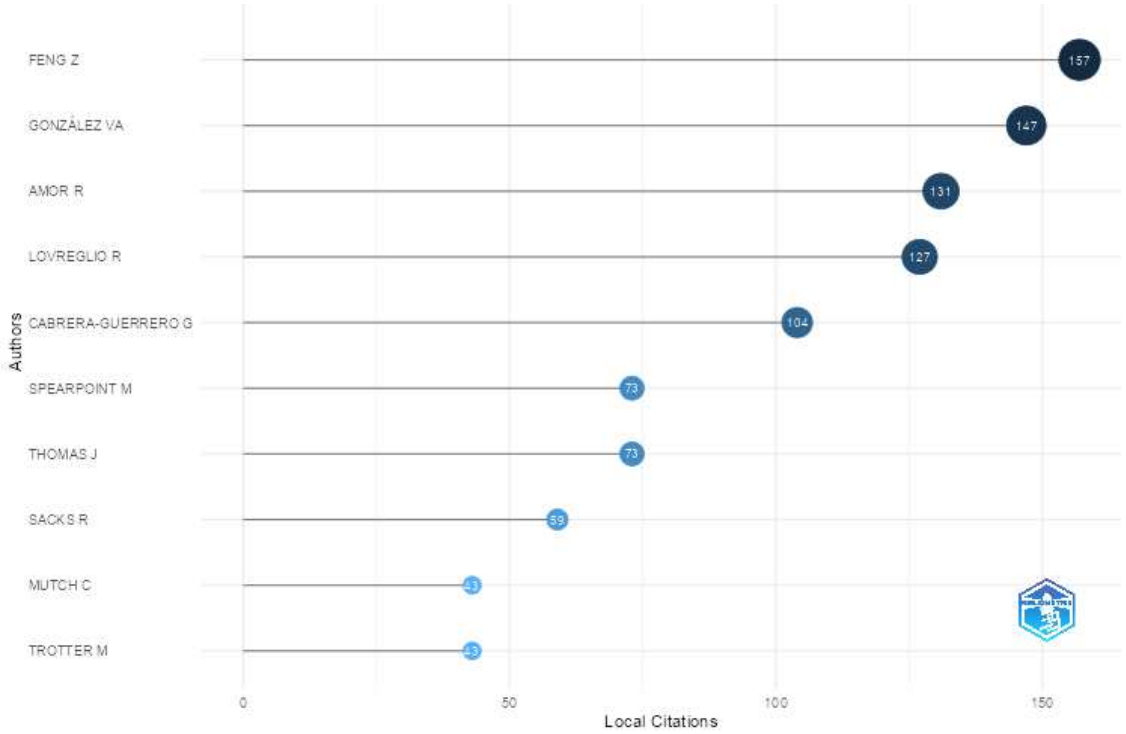


Figure 8. Most local cited authors

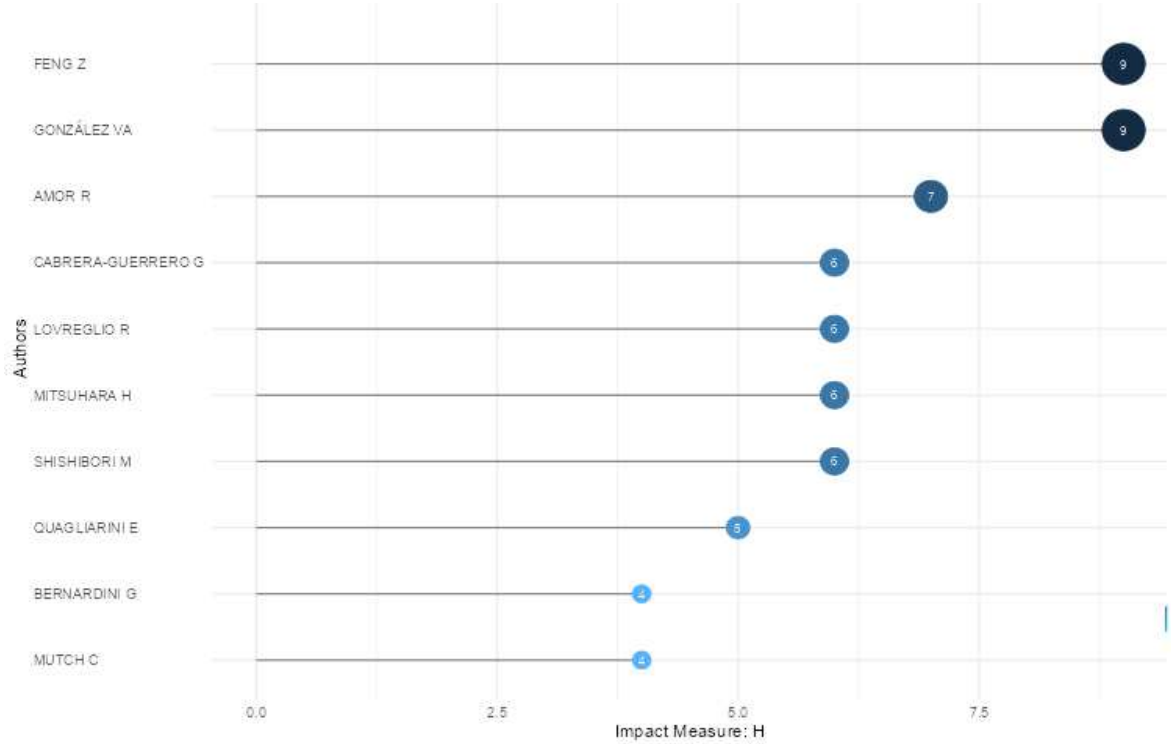


Figure 9. Authors' local impact by H-index

3.3.2. Author collaboration network

Figure 10 illustrates the author collaboration network generated using Biblioshiny. Node size reflected the number of publications, while links between nodes represented collaborative relationships among authors. Different research groups were distinguished by different colors. Overall, the collaboration network tended to form geographically based clusters, with researchers from the same country or institutions frequently collaborating with one another. The blue cluster constituted the largest and most interconnected group, centered on prominent authors such as Zhenan Feng, Vicente A. González, Robert Amor, Ruggerio Lovreglio, and Guillermo Cabrera-Guerrero, along with several closely connected co-authors. This research group predominantly comprised scholars from New Zealand, particularly those affiliated with Massey University and the University of Auckland. The red cluster represented another prominent collaboration group, centered on Hiroyuki Mitsuhara and involving several researchers from Tokushima University, Japan. Meanwhile, the green cluster, led by Enrico Quagliarini, comprised researchers primarily from Italy, particularly those affiliated with Università Politecnica delle Marche and Politecnico di Bari.

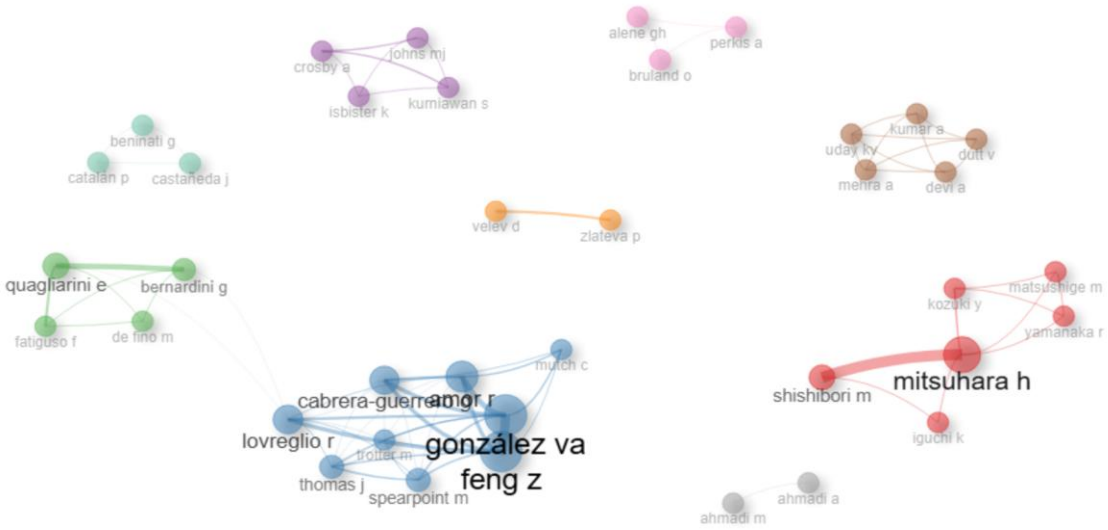


Figure 10. Author collaboration network

3.3.3. Country collaboration network

The international collaboration network among countries in research on immersive technologies for disaster education is presented in Figure 11. The intensity of collaboration is represented by the connecting lines, with thicker lines indicating stronger collaborative relationships. The results showed that international collaboration was concentrated among a relatively small number of highly productive countries.

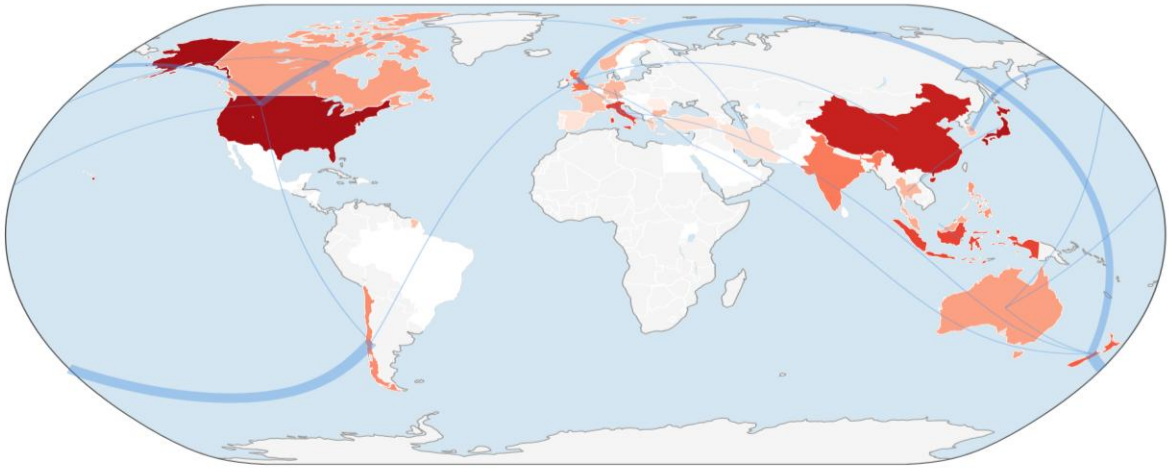


Figure 11. Country collaboration network

New Zealand emerged as a major hub in the international collaboration network, with key partnerships extending across continents. Particularly strong collaborative ties were observed between New Zealand and Chile, as well as between New Zealand and the United Kingdom. The United States showed a stronger collaborative connection with its neighboring country, Canada, while its linkage with South Korea was also relatively prominent. Overall, the network suggested that international collaboration was not evenly distributed worldwide but was instead concentrated around countries with relatively high research productivity.

Furthermore, the study examined the distribution of publications by country based on single country publications (SCP) and multiple country publications (MCP) (Figure 12). SCP represented publications produced entirely within a single country, whereas MCP referred to publications involving international collaboration. It should be noted that the document counts in this analysis were based on the country of the corresponding author. Japan recorded the highest number of publications in this category, with 32 documents; however, only 9.4% were MCP, indicating that its high publication productivity was largely supported by domestic research networks. China and the United States, which ranked second and third in terms of research output,

exhibited a similar pattern, with MCP shares of 14.3% and 12.0%, respectively. Indonesia, with 20 documents, demonstrated a comparatively higher level of international collaboration, with 25% classified as MCP. A different pattern was observed for New Zealand, which had a substantially larger proportion of MCP publications relative to its overall output (72,7%). Despite producing approximately 11 documents, a considerable share involved international collaboration, indicating a stronger orientation toward cross-country research than that observed among several of the more productive countries.

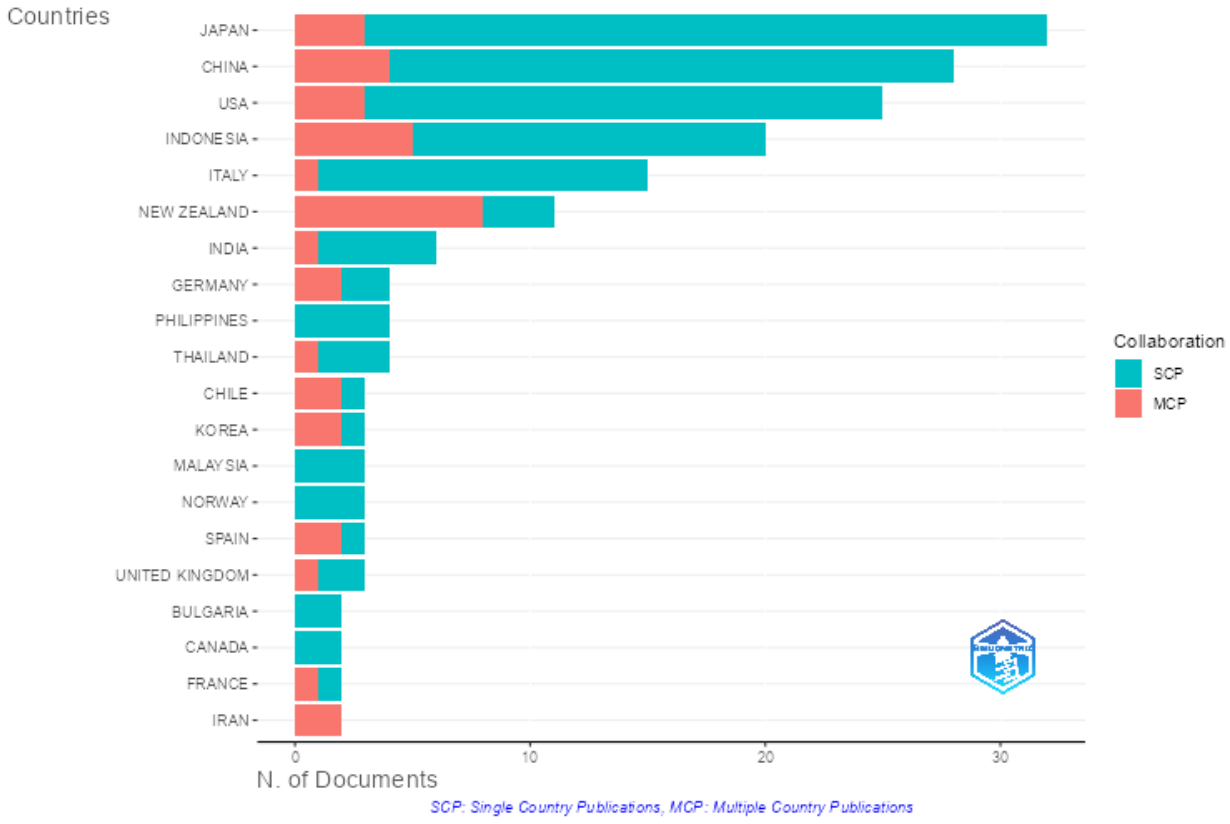


Figure 12. Corresponding authors' countries

3.4. Research themes and emerging topics

3.4.1. Keyword frequency analysis

Table 5 presents the ten most frequently occurring keywords based on their occurrence counts. The analysis was conducted using all keywords in VOSviewer. "Virtual reality" emerged as the most frequently occurring term, with 190 occurrences. Its frequency was substantially higher than that of other forms of immersive technology, such as "augmented reality," suggesting a strong preference among researchers for fully immersive simulation environments. This keyword also

recorded the highest Total Link Strength (TLS), at 1.125, indicating its strong co-occurrence relationships with other keywords across the analyzed document collection.

Table 5. Top 10 most frequent keywords

Keywords	Occurrences	Total Link Strength
Virtual reality	190	1125
Disasters	83	643
Disaster prevention	64	510
Augmented reality	62	336
Earthquakes	60	418
E-learning	47	354
Personnel training	35	283
Students	31	230
Serious games	30	162
Decision making	28	242

"Disasters" (83 occurrences; TLS = 643) and "disaster prevention" (64 occurrences; TLS = 510) were the next most prominent keywords after "virtual reality." Regarding specific hazard contexts, "earthquakes" (60 occurrences; TLS = 418) represented the most extensively investigated hazard in the literature. The pedagogical orientation of the field was also divided into two major target groups: educational institutions, represented by "students" (31 occurrences; TLS = 230), and specialized workforce preparedness, represented by "personnel training" (35 occurrences; TLS = 283). Other prominent terms, including "e-learning" (47 occurrences; TLS = 354), "serious games" (30 occurrences; TLS = 162), and "decision making" (28 occurrences; TLS = 242), further highlighted important technological and pedagogical developments within the field.

3.4.2. Keyword co-occurrence network

The study further explored the keyword co-occurrence network using VOSviewer. All keywords were considered, with a minimum occurrence threshold of five. Of the 1,236 identified keywords, 122 met this threshold and were included in the analysis. The resulting keyword network visualization is presented in Figure 13, where each node represents a keyword and its size

indicates the frequency of occurrence. The proximity between nodes reflects the strength of their associations, with closer nodes indicating stronger co-occurrence relationships. The colors of the nodes represent clusters of keywords grouped according to their core thematic areas.

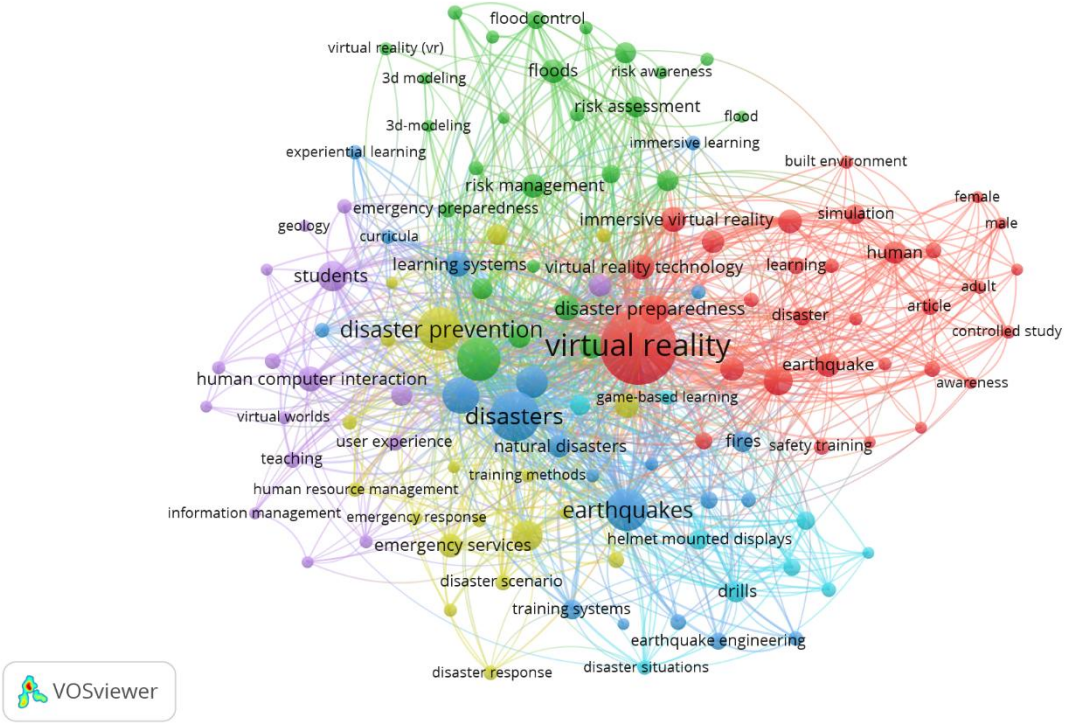


Figure 13. Network visualization of all keywords (weights: occurrences)

Six thematic clusters were identified. The red cluster consisted of 31 items and primarily focused on immersive virtual reality and its application in disaster preparedness. Notable keywords within this cluster included disaster preparedness, immersive virtual reality, training, virtual environments, virtual reality, and virtual reality technology. The green cluster comprised 26 items and highlighted the use of immersive and augmented reality technologies for disaster risk management. In terms of hazard context, this cluster contained a greater number of keywords related to floods. Prominent keywords in this cluster included augmented reality, floods, flood control, floodings, flood risk, immersive, and risk management. The dark blue cluster contained 21 items and represented the integration of e-learning, immersive technologies, and simulation-based systems for disaster education. In terms of hazard context, this cluster contained a greater number of keywords related to earthquakes. Notable keywords included disasters, e-learning,

earthquakes, earthquake learning, earthquake engineering, learning systems, natural disasters, personnel training, and training systems.

The yellow cluster consisted of 19 items and focused on the application of serious games to disaster education. Key terms within this cluster included disaster management, disaster prevention, disaster response, emergency response, emergency services, and serious games. The purple cluster comprised 16 items and emphasized the educational and human–computer interaction dimensions of immersive technologies, particularly their use in interactive learning environments. Representative keywords included education, human computer interaction, interactive computer graphics, and students. Finally, the light blue cluster consisted of 6 items and highlighted practical disaster education through immersive drills and evacuation training using head-mounted displays. Its notable keywords included disaster education, drills, evacuation drill, and head mounted displays.

3.4.3. Highly cited and influential works

The analysis of highly influential works reveals that research on immersive virtual reality in disaster education has been strongly shaped by studies focusing on evacuation training, earthquake preparedness, serious games, virtual drills, and safety training (Table 6). Feng et al. (2018) received the highest number of global citations (386), followed by Li et al. (2017) with 189 citations, Lovreglio et al. (2018) with 187 citations, and Shu et al. (2019) with 186 citations. These highly cited studies demonstrate the foundational role of immersive simulations and serious games in supporting evacuation training, earthquake preparedness, presence, and self-efficacy. More recent influential works, including Scorgie et al. (2024), further extend the application of VR toward safety training and broader evidence synthesis.

Table 6. Most cited documents

Title	Source	Reference	Citations
Immersive virtual reality serious games for evacuation training and research: A systematic literature review	*Computers and Education*	Feng et al. (2018) [29]	386

Title	Source	Reference	Citations
Earthquake safety training through virtual drills	*IEEE Transactions on Visualization and Computer Graphics*	Li et al. (2017) [30]	189
Prototyping virtual reality serious games for building earthquake preparedness: The Auckland City Hospital case study	*Advanced Engineering Informatics*	Lovreglio et al. (2018) [31]	187
Do virtual reality head-mounted displays make a difference? A comparison of presence and self-efficacy between head-mounted displays and desktop computer-facilitated virtual environments	*Virtual Reality*	Shu et al. (2019) [32]	186
Virtual reality for safety training: A systematic literature review and meta-analysis	*Safety Science*	Scorgie et al. (2024)[33]	160
An augmented representation method of debris flow scenes to improve public perception	*International Journal of Geographical Information Science*	Li et al. (2021) [34]	142
An immersive virtual reality serious game to enhance earthquake behavioral responses and post-earthquake evacuation preparedness in buildings	*Advanced Engineering Informatics*	Feng et al. (2020a) [35]	139
State of virtual reality-based disaster preparedness and response training	*PLoS Currents*	Hsu et al. (2013) [36]	131
Moving to 3-D flood hazard maps for enhancing risk communication	*Environmental Modelling and Software*	Macchione et al. (2019) [37]	98
Towards a customizable immersive virtual reality serious game for earthquake emergency training	*Advanced Engineering Informatics*	Feng et al. (2020b) [38]	98

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4. Discussion

4.1 Evolution of Immersive Technology in Disaster Education and Training

The evolution of research on immersive technologies indicates a shift from their use primarily as simulation tools toward learning environments increasingly oriented toward experience, behaviour, and decision-making**.** Early research positioned virtual environments mainly as a means of safely representing disaster scenarios, whereas subsequent developments have increasingly emphasized serious games, evacuation drills, behavioural responses, and decision-making. This trajectory suggests that the maturation of the field is reflected not merely in the growing adoption of immersive technologies, but more importantly in how immersive environments can enhance individuals' abilities to interpret situations, make decisions, and take appropriate actions under emergency conditions**.**

This shift is particularly important because the primary goal of disaster education extends beyond knowledge acquisition to preparing individuals to make appropriate decisions and take effective actions when confronted with emergency situations [39–41].

4.2. From Technological Development to Multidisciplinary Integration

The findings indicate that the development of immersive technologies for disaster education has evolved into a multidisciplinary field that brings together computer science, engineering, disaster science, and education. The distribution of publications across these disciplines suggests that the effectiveness of immersive technologies cannot be understood solely in terms of their technical capacity to generate realistic virtual environments. Rather, their educational value emerges when technical capabilities, hazard characteristics, and learning principles are meaningfully integrated into a coherent learning environment. In this context, the prominence of the *International Journal of Disaster Risk Reduction* and the high citation impact of *Advanced Engineering Informatics* among the publication sources may indicate that the field is developing at the intersection of disaster research, technological engineering, and learning system development**.**

From the perspective of Technology–Pedagogy–Content Knowledge (TPACK)**,** technology should not be regarded as an isolated component but rather as an element that needs to be integrated with pedagogical knowledge [42,43]. Applied to disaster education, this perspective suggests that VR development should integrate technology knowledge (e.g., 3D visualization, interaction,

simulation, and human–computer interaction), disaster content knowledge (e.g., hazard characteristics, risk, warning systems, and evacuation procedures), and pedagogical knowledge (e.g., learning objectives, activity design, feedback mechanisms, and learning outcome assessment). Thus, a technically sophisticated and highly realistic VR environment does not necessarily result in effective learning unless it is deliberately designed and aligned with specific disaster education objectives.

4.3. Geographical Concentration and the Uneven Development of International Collaboration

The concentration of research output in a limited number of countries indicates that the development of immersive technologies for disaster education is geographically uneven and shaped by research ecosystems emerging within specific institutional and regional contexts. The United States, Japan, China, New Zealand, Italy, and Indonesia are among the major contributors in terms of research productivity, whereas New Zealand demonstrates relatively greater scientific impact based on citation performance**.** This divergence between productivity and impact suggests that the development of a research field is determined not only by publication volume but also by the capacity of research communities to generate knowledge that is subsequently utilized and extended by the broader scientific community.

New Zealand's position is particularly noteworthy, given the strong contributions of its research groups to immersive serious games, evacuation simulation, and behavioral responses. This pattern suggests that scientific influence may emerge when technological development is directed toward specific educational and behavioral challenges rather than focusing exclusively on technical innovation. This observation is consistent with the broader development of VR research in education, where the pedagogical value of immersive technologies is increasingly associated with their capacity to facilitate experiential learning, problem-solving, and active learner engagement [44–46].

Differences between research productivity and scientific impact are also evident in international collaboration patterns. Although Japan and the United States demonstrate relatively high research output, their proportions of MCP are lower than that of New Zealand. In contrast, New Zealand exhibits a substantially higher proportion of MCPs. This pattern suggests that research productivity and international connectedness represent distinct dimensions of

scientific development. Countries with strong domestic research capacity may generate substantial publication output through national research networks, whereas countries with smaller publication volumes may achieve greater international visibility and scientific impact through cross-border collaboration.

In disaster education, international collaboration is particularly important because hazard characteristics, educational systems, cultural contexts, technological infrastructure, and community response behaviors vary considerably across regions**.** Consequently, the development and evaluation of immersive technologies for disaster education should not be based exclusively on a single geographical or institutional context. Cross-national research can provide opportunities to examine the transferability, contextual adaptation, and effectiveness of immersive learning interventions across different disaster and educational settings.

Furthermore, the limited representation of Africa and South America indicates a persistent geographical imbalance in knowledge production. This disparity may be associated with differences in access to advanced technologies, research funding, institutional capacity, and international collaboration networks. Future research should therefore expand its geographical coverage, particularly toward disaster-prone countries and regions that remain underrepresented in the literature. Such diversification would not only improve the geographical representativeness of the evidence base but also contribute to the development of immersive disaster education approaches that are more context-sensitive, inclusive, and globally applicable.

4.4. From Virtual Simulation to Experiential and Decision-Oriented Learning

The intellectual structure of research on immersive technologies reveals a gradual shift from a technology-oriented focus toward learning- and behavior-oriented applications. Rather than treating immersive environments primarily as tools for reproducing disaster scenarios, recent research increasingly examines how these environments can enhance experiential learning, preparedness, and decision-making. This trajectory reflects a broader transformation in the field, from virtual simulation toward experiential and decision-oriented learning.

This transition is particularly evident in the growing application of serious game-based virtual reality, which incorporates challenges, interaction, action–consequence mechanisms, and immediate feedback to enable learners to practice appropriate responses during disaster situations [38,47–51]. These characteristics are consistent with Experiential Learning Theory, which

conceptualizes learning as a cyclical process involving concrete experience, reflective observation, abstract conceptualization, and active experimentation. Within immersive virtual reality (IVR) environments, learners can experience simulated disaster scenarios, interact with virtual environments, make decisions, receive feedback, and repeat actions to refine their responses [52,53]. Thus, the educational value of IVR extends beyond visual representation by establishing a functional connection between knowledge, experience, decision, and action.

The increasing emphasis on decision-making also has important theoretical implications for disaster education. Disaster response decisions are typically made under conditions of time pressure, incomplete information, psychological stress, and rapidly changing environments. Consequently, preparedness depends not only on whether individuals possess knowledge about hazards but also on whether they can interpret evolving situations, evaluate alternatives, and select appropriate actions under uncertainty [49,54–56]. Immersive environments provide a mechanism for reproducing elements of these conditions in a relatively safe and controllable setting. This may explain the growing convergence between immersive technologies, behavioral research, and decision-oriented learning in the intellectual structure of the field.

Nevertheless, the intellectual landscape remained strongly concentrated on earthquake- and flood-related scenarios, indicating that immersive technology research in disaster education had predominantly addressed hazards with relatively well-established simulation and training applications. This concentration may reflect the maturity of earthquake simulation research and the practical relevance of flood scenarios for preparedness and risk communication. However, the keyword landscape also revealed a notable gap in the representation of several other natural hazards. Tsunamis, storms, volcanic eruptions, and landslides, for example, remained comparatively underrepresented, despite involving distinct hazard dynamics, warning lead times, spatial characteristics, and protective-action requirements. This uneven distribution suggests that the existing knowledge base has not yet fully explored the potential of immersive technologies across the broader spectrum of natural hazards. Future research should therefore expand beyond the dominant earthquake and flood contexts and develop hazard-specific immersive learning scenarios that account for the distinctive cognitive, experiential, and behavioral demands associated with different types of disasters.

Another important finding concerns the relationship between immersion, cognitive processing, and learning effectiveness. Greater visual richness, interactivity, and sense of presence do not

necessarily translate into better learning outcomes. Highly complex immersive environments can increase the amount of information that learners must simultaneously process, potentially imposing excessive cognitive demands. Recent evidence indicates that the use of *attentional guidance* in immersive environments can reduce cognitive load and improve academic performance, whereas increased presence does not necessarily produce superior learning when cognitive demands become excessive [57,58].

This finding suggests that the effectiveness of immersive disaster education depends on achieving an appropriate balance between immersion and cognitive manageability. In other words, technological sophistication should not be treated as an educational outcome. The design of immersive environments should selectively employ visual fidelity, interaction, environmental complexity, and sensory stimulation according to the learner's cognitive capacity and the intended learning objectives. From this perspective, the next stage of immersive disaster education should move toward instructionally optimized immersion, in which technological features are deliberately designed to support attention, comprehension, decision-making, and behavioral learning rather than maximizing realism alone.

Overall, the intellectual evolution identified in this study suggests that immersive disaster education is moving from simulation fidelity toward learning functionality. The emerging research frontier is therefore not simply how realistically a disaster can be reproduced, but how immersive environments can be designed to help learners perceive hazards, manage cognitive demands, make decisions under uncertainty, and translate knowledge into appropriate protective actions.

4.5. Beyond Immersion: Emerging Research Frontiers in Disaster Education

The bibliometric findings reveal several important knowledge gaps that may constrain its further development. The research agenda has progressively moved beyond the question of whether VR can simulate disaster scenarios toward understanding how immersive environments can produce meaningful improvements in learning, preparedness, and decision-making. However, the evidence base remains fragmented, particularly regarding the mechanisms through which immersive experiences can be transformed into adaptive, context-sensitive, and sustained learning outcomes.

First, the literature remains largely dominated by static or predetermined immersive scenarios, in which learners interact with relatively fixed environments and predefined sequences

of events. This approach provides valuable opportunities for experiential learning but may not fully reproduce the uncertainty and dynamic conditions of real disaster situations. In actual emergencies, hazard intensity, environmental conditions, available information, and evacuation options can change continuously in response to unfolding events and individual decisions. This creates a research gap concerning how immersive learning environments can move from pre-scripted simulation toward dynamic and adaptive simulation.

The integration of AI represents a promising direction for addressing this gap. AI could enable immersive environments to dynamically adjust the level of difficulty, disaster scenarios, feedback mechanisms, and learning activities according to learners' performance and decisions. For example, evacuation routes, hazard intensity, environmental conditions, or available information could change in response to users' actions. Such mechanisms could transform immersive environments from passive simulation spaces into adaptive learning systems that respond to learner behaviour [59]. However, further empirical research is needed to establish whether such adaptive features produce greater learning and preparedness benefits than conventional static immersive environments.

Second, the literature shows limited integration between immersive technologies and context-specific spatial and disaster information. Many existing applications emphasize technological immersion, while the geographical characteristics of the learning environment may receive less attention. Integrating digital twins, geographic information systems, and real-time disaster data could address this limitation by enabling virtual environments to represent the physical, environmental, and infrastructural characteristics of specific locations. Learners could consequently practice scenarios that correspond to the hazards, evacuation routes, buildings, and emergency systems in their own communities. This raises an important research question concerning whether contextual realism is more educationally valuable than technological realism alone.

Third, an important methodological gap concerns the predominance of short-term evaluations. Many studies assess learning immediately or shortly after exposure to an immersive intervention, providing limited evidence regarding whether learning is retained over time or transferred to real-world behaviour. Immediate improvements may partly reflect novelty, engagement, or the sense of presence generated by immersive technologies rather than durable changes in knowledge or preparedness. Longitudinal studies are therefore needed to

examine learning retention, situational awareness, decision-making, and behavioural transfer at multiple time points following the intervention.

This gap is particularly important because the ultimate objective of disaster education is not simply to improve performance within a virtual environment, but to support appropriate behaviour during real emergencies. Future studies should therefore move beyond measuring knowledge gains or user satisfaction toward evaluating whether learners can transfer skills acquired in immersive environments to unfamiliar or real-world disaster situations. Such research would provide stronger evidence regarding the practical effectiveness of immersive technologies in disaster risk reduction.

These gaps indicate that the next stage of research should move beyond immersion itself. The central challenge is increasingly how to design immersive learning environments that are adaptive, spatially contextualized, behaviourally responsive, and capable of producing sustained learning outcomes. Addressing this challenge will require greater integration of AI, digital twins, spatial and real-time data, learning analytics, and longitudinal evaluation. Such developments could shift the field from demonstrating the technological feasibility of immersive disaster education toward establishing its educational effectiveness, behavioural relevance, and real-world transferability.

5. Conclusion

This study demonstrates that the use of immersive technologies in disaster education has evolved from simulation-oriented applications toward learning environments increasingly focused on experience, behavior, and decision-making. This development reflects the growing integration of immersive technologies with serious games, pedagogy, evacuation training, and disaster preparedness.

The findings further indicate that research in this field is inherently multidisciplinary but remains geographically concentrated within a limited number of countries and research groups. The intellectual structure of the field shows increasing attention to decision-making and behavioral responses, although research remains predominantly focused on earthquake and flood scenarios. This concentration highlights the need to expand immersive applications to other hazards, including tsunamis, volcanic eruptions, storms, and landslides, while strengthening international research collaboration.

Future research should advance toward adaptive, context-aware, and decision-oriented immersive learning environments, particularly through the integration of artificial intelligence. Research priorities should extend beyond improving technological realism to determining whether immersive experiences can produce sustained improvements in learning capacity, disaster preparedness, and behavioral change that transfer to real-world disaster situations. This direction is particularly important because the ultimate purpose of disaster education is not simply to increase knowledge, but to translate knowledge into appropriate action when disasters occur.

Data Availability

Not Applicable

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Contributions

F.I.A. conceptualized the study, developed the methodology, and prepared the manuscript. I.A. contributed to the technical data processing, analysis, and visualization of the results. Both authors contributed to the interpretation of the findings, discussion of the results, and writing and revision of the manuscript, and approved the final version.

Ethics Declarations

Ethics Approval and Consent to Participate

Not applicable.

Consent for Publication

Not applicable.

Competing Interest

The author declares that there are no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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