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A Systematic Review of Challenges in Applying Immersive Technologies for Critical Infrastructure Emergency Response

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Abstract

Given the rapid advancements and growing importance of immersive technologies in the critical infrastructure sector, it is essential to understand the challenges to their effective implementation. Thus, this article aimed to identify and investigate the challenges hindering the application of these technologies for emergency response, irrespective of the specific technology or sector involved. This was achieved through a qualitative approach, utilizing a systematic review via bibliometric analysis using VOSviewer software. Additionally, R Studio and the biblioshiny package were used to create interactive visualizations for the project. Scopus was chosen for this search due to its comprehensive coverage of current scientific literature and its efficiency in handling large datasets. The research yielded a comprehensive list of 114 challenges, which were then reviewed and reduced to 33 challenges after rounds of refinement. These were subsequently grouped into five key categories based on thematic similarities. By categorizing these challenges into key thematic areas, this study contributes to a deeper understanding of the obstacles that need to be addressed to leverage the full potential of immersive technologies in enhancing emergency response and critical infrastructure resilience. The originality of this study lies in its rigorous approach to identifying and categorizing the myriad challenges faced by the critical infrastructure sector, offering both researchers and practitioners a structured approach to guide future efforts in overcoming these issues. This contribution not only highlights the specific areas requiring attention but also paves the way for targeted innovations and policy developments that can facilitate the broader implementation of immersive technologies in emergency management.

Keywords: Critical infrastructure, Disaster preparedness, Emergency management, Emergency response, Environmental impact, Immersive technologies, Risk management.

1. Introduction

The Department of Homeland Security's Cybersecurity and Infrastructure Security Agency (CISA) describes critical infrastructure as "the physical and cyber systems and assets that are so vital to the United States that their incapacity or destruction would have a debilitating impact on our physical or economic security or public health or safety" (CISA,2022). This broad definition encompasses a range of sectors, including energy, transportation, communications and financial systems, which are essential to the functioning of American society. Critical infrastructure not only supports daily operations but also underpins national security and economic stability (Bronk and Conklin, 2022). The importance of safeguarding critical infrastructure has grown in response to increasing threats from both physical and cyber attacks. As technology advances, the integration of physical systems with digital networks has created new vulnerabilities. For instance, a cyber attack on the power grid could disrupt electricity supply across vast regions, affecting everything from residential homes to critical emergency services (Bekaroo and Dawarka, 2023). Similarly, failures in financial infrastructure could destabilize markets and erode public confidence in economic systems.

As one of the major contributors to the economic well-being and social development of both global and local economies, the critical infrastructure sector plays a crucial role. According to Al-Mhdawi *et al.,* (2024), the critical infrastructure industry contributes around 7% to the global gross domestic product (GDP) on average, with this number expected to rise further. Zahid (2024) projects this percentage to reach 9% by 2030. This projected growth holds significant importance due to the positive implications such as increased job creation, enhanced economic activity and improved efficiency and productivity (Sathurshan *et al.,* 2022). However, despite its significant contributions, the critical infrastructure sector faces numerous longstanding challenges, including aging infrastructure, cybersecurity threats, climate change, funding shortfalls, workforce shortages, sustainability concerns, integration of new technologies, and so on (Kumar *et al.,* 2021; Sathurshan *et al.,* 2022; Bernhardt, 2023; Damaševičius *et al.,* 2023). Consequently, researchers are exploring potential solutions with Wisniewski *et al.,* (2022) and Sathurshan *et al.,* (2022) positing that immersive technologies hold promise in addressing these challenges. Kumar *et al.,* (2021) outlined some of the benefits of adopting immersive technologies as a means of enhancing disaster preparedness, improving emergency response coordination, facilitating risk assessment, optimizing maintenance procedures for proactive infrastructure protection, streamlining design and construction processes for increased resilience and even enhancing worker training for a wider range of scenarios.

Several industries have begun reaping the benefits of adopting immersive technologies such as manufacturing, healthcare, retail and marketing, logistics and supply chain, travel and tourism and so on (Aliu *et al.,* 2024). These benefits include a competitive advantage and increased efficiency and innovation. However, the critical infrastructure sector has yet to fully capitalize on these advancements at a way and scale through which other sectors are already reaping the benefits (Rathnayaka *et al.,* 2022; Okafor *et al.,* 2023). Therefore, the goal of this study is to identify and investigate the challenges hindering the application of immersive technologies for critical infrastructure emergency response. This goal was achieved through the following objectives:

1) Scoping existing studies to comprehensively identify the challenges that currently limit the use of immersive technologies in critical infrastructure emergency response scenarios.
2) Categorizing and explaining the clusters of challenges and some of the underlying causes and reasons behind them.
3) Conducting a bibliometric analysis to gain a quantitative and visual understanding of current global research efforts surrounding the use of immersive technologies.

While several studies (Rathnayaka *et al.,* 2022; Sathurshan *et al.,* 2022; Okafor *et al.,* 2023) have explored the potential of immersive technologies for critical infrastructure, a crucial gap remains. Many focus on benefits, with a limited investigation into the underlying challenges. This necessitates a shift beyond mere listings or rankings of challenges, often based on single-country case studies. This is because effective solutions require a deep dive into the challenges themselves and their sector-wide impact. This study stands out by addressing this critical gap. It uses R Studio and the biblioshiny package to conduct a network analysis visualization of connections and relationships, which offers deeper insights in comparison to traditional literature reviews. The findings of this study are not only beneficial to researchers and academics seeking a more comprehensive understanding of the challenges but also to industry professionals and policymakers who can leverage this knowledge to develop targeted solutions for wider adoption of immersive technologies in critical infrastructure emergency response. This research also has the potential to contribute to a significant increase in preparedness, efficiency and ultimately, the safety and well-being of communities around the United States and beyond.

2. Literature Review

The proliferation of immersive technologies has led to significant advancements, increased efficiency and innovation in numerous sectors globally, and the critical infrastructure industry is not exempt from this. Technologies such as Virtual Reality (VR) and Augmented Reality (AR) have been used in various ways to address challenges within critical infrastructure. For instance, VR has been employed extensively for training purposes (Stone *et al.,* 2021). Emergency response teams can engage in highly realistic simulations of disaster scenarios, allowing them to practice and refine their responses to events such as earthquakes, floods, or terrorist attacks. These VR training modules can replicate complex environments and conditions that would be difficult, dangerous, or impossible to create in real life, thereby enhancing preparedness and response efficiency (Feng *et al.,* 2020). Moreover, AR is being utilized to provide real-time information and enhance situational awareness for emergency responders (Wisniewski *et al.,* 2022). During an emergency, AR glasses or headsets can overlay critical data, such as building layouts, hazard locations and escape routes, directly onto the user's field of view. This immediate access to information can drastically improve decision-making and response times (Damaševičius *et al.,* 2023).

Additionally, AR is being employed in post-disaster assessment and damage evaluation as emergency responders equipped with AR devices can capture real-time imagery and videos of disaster-affected areas, which are then overlaid with data overlays showing structural damage, infrastructure status and potential hazards (Candela *et al.,* 2022). This enables responders to quickly assess the extent of damage, prioritize response efforts and allocate resources more effectively (Rathnayaka *et al.,* 2022). AR visualization tools can also allow for the creation of interactive 3D models of disaster sites, facilitating better coordination among response teams and aiding in the planning of recovery operations (Bernhardt, 2023).

3D visualization is another critical technology that enhances situational awareness and decision-making in emergency management (Zhu *et al.,* 2024). According to their study, high-fidelity 3D models of infrastructure, including buildings, bridges and other critical assets, can be used for real-time monitoring and analysis. These models enable emergency managers to assess damage, plan repairs and allocate resources more efficiently (Zhu *et al.,* 2024). For example, after an earthquake, 3D visualization tools can quickly generate detailed maps of affected areas, highlighting damaged structures and identifying safe routes for emergency responders. Spatial computing also plays a significant role as this technology leverages data from sensors, GPS and other sources to create dynamic, real-time maps and models of physical spaces (Tzavella *et al.,* 2024). According to Damaševičius *et al.,* (2023), spatial computing can enhance disaster response by providing a comprehensive view of the affected area and integrating data from various sources to inform decision-making. Immersive technologies are also increasingly being used for the maintenance and inspection of critical infrastructure. According to Aghimien *et al.,* (2023), drones equipped with 3D scanning capabilities can conduct aerial surveys of infrastructure such as bridges and power lines, capturing detailed images and data that are processed into 3D models. These models help identify structural issues and guide maintenance efforts without requiring personnel to be in potentially hazardous locations (Zhu *et al.,* 2024).

The adoption of immersive technologies in the critical infrastructure industry has been found to lead to enhanced training and simulation (Stone *et al.,* 2021), improved situational awareness (Tzavella *et al.,* 2024), efficient maintenance and inspection (Aghimien *et al.,* 2023), advanced disaster planning and resilience (Feng *et al.,* 2020), real-time monitoring and analysis (Wisniewski *et al.,* 2022), remote collaboration capabilities (Rathnayaka *et al.,* 2022) and so on. Existing studies have also revealed various approaches taken to investigate application challenges. Some studies focused specifically on challenges affecting certain technologies like AR/VR (Bhattacharya *et al.,* 2021; Tzavella *et al.,* 2024) and 3D visualization (Zhu *et al.,* 2024), among several others. Other existing studies have employed a generic stance with a focus on terminologies such as smart infrastructure or digital transformation (Rupeika-Apoga, 2022; Singh and Maheswaran, 2024).

3. Research Methodology

This study seeks to identify and investigate the challenges hindering the application of immersive technologies for critical infrastructure emergency response. This objective was achieved via a qualitative approach and systematic review of existing literature. According to Olonilua (2019), qualitative research is an iterative process that involves collecting and analyzing non-numerical data to understand concepts, opinions, or experiences. It often employs techniques such as interviews, observations and thematic analysis to uncover underlying meanings and patterns within the data. The systematic literature review is defined as a methodical and structured approach to synthesizing existing research findings on a specific topic or research question (Sathurshan *et al.,* 2022). It also involves systematically searching, selecting, appraising and synthesizing relevant studies from academic databases, journals, conference proceedings and other sources of scholarly literature. Going by these descriptions, a systematic literature review must be comprehensive in its approach and must adhere to predefined criteria and protocols to ensure transparency and reproducibility throughout the review process.

Due to these characteristics, the systematic literature review method was adopted for this study for several reasons. Firstly, it ensures comprehensive coverage by systematically searching multiple databases and sources, minimizing the risk of overlooking relevant studies (Rathnayaka *et al.,* 2022). Additionally, the predefined criteria and transparent methodology help reduce bias in study selection, data extraction and synthesis, enhancing the credibility and reliability of the findings (Sathurshan *et al.,* 2022). Moreover, systematic reviews enable the synthesis of evidence from multiple studies, providing a thorough understanding of the topic and revealing insights that may not be apparent from individual studies alone (Olonilua, 2019). The transparent and reproducible nature of systematic reviews ensures that the research process is transparent and reproducible, allowing other researchers to replicate the study and verify its findings (Rathnayaka *et al.,* 2022).

While systematic reviews offer a comprehensive and structured way to synthesize existing literature, incorporating quantitative research alongside them can further strengthen the analysis. According to Nas *et al.,* (2023), quantitative research involves the systematic empirical investigation of observable phenomena through statistical, mathematical, or computational techniques, aiming to quantify relationships, patterns and trends. Building upon the insights from the systematic review, the quantitative component of this research employs a bibliometric analysis method. This analysis aims to provide a deeper understanding by quantitatively examining the characteristics, trends and impact of immersive technologies in critical infrastructure emergency response, along with the challenges hindering their adoption.

3.1. Retrieval of Bibliometric Data

To gain a deeper understanding of how research on immersive technologies for critical infrastructure emergency response interacts, a bibliometric analysis was undertaken. According to Sajovic and Boh Podgornik (2022), bibliometric visualization is considered a powerful tool for revealing the knowledge structure and emerging trends within a particular research field. Through the bibliometric analysis, several analyses can be performed, including identifying frequently explored themes, collaborations between research groups, potential knowledge gaps, authorship trends and the geographic distribution of research. For this study, the bibliometric analysis was performed using VOSviewer software, a popular tool specifically designed for visualizing and analyzing bibliographic data. Additionally, R Studio and the biblioshiny package were used to create interactive visualizations for the project. Scopus was chosen for this search given its comprehensive coverage of current scientific literature and its efficiency in handling large datasets (Zhao *et al.,* 2018).

The search string used for the search was (TITLE-ABS-KEY), focusing on the title, abstract and keywords of articles to ensure the most relevant results were captured. The final search string used was (TITLE-ABS-KEY) ("immersive technology" OR "virtual reality" OR "augmented reality" OR "mixed reality" OR "extended reality" OR "3D visualization" OR "spatial computing") AND (("critical infrastructure" OR "infrastructure" OR "built environment") AND ("emergency response" OR "disaster management" OR "crisis management" OR "disaster preparedness") AND ("challenge" OR "obstacle" OR "barrier") AND PUBYEAR > 2014 AND PUBYEAR < 2024 AND (LIMIT-TO [SUBJAREA, "ENGI", "SSCI", "LSCI", "PSCI"]) AND (LIMIT-TO [DOCTYPE, "j"] OR LIMIT-TO [DOCTYPE, "cp"]) AND (LIMIT-TO [LANGUAGE, "English"]). Note: "ENGI" ≈ Engineering, "SSCI" ≈ Social Sciences and Humanities, "LSCI" ≈ Life Sciences, and "PSCI" ≈ Physical Sciences, j ≈ journals and cp ≈ conference proceedings. To ensure the recency of the study, a timeline from 2000 to 2024 was considered and the search was conducted on the 28th of May 2024. The bibliometric data was downloaded in comma-separated values (CSV) format. Figure 1 presents the framework underpinning this study.

Figure 1: Research framework underpinning this study

3.2. Systematic Review of Research on Application Challenges

This study adopted a four-step process for conducting a systematic research review as proposed by Dehkordi *et al.,* (2021). This is illustrated in Figure 1. The research began with the planning process, where the core objective was established which is to identify and explore the challenges hindering the application of immersive technologies in critical infrastructure emergency response. Selection, the second step, focused on establishing inclusion criteria and searching relevant literature. This entailed searching peer-reviewed journals and conference proceedings for articles discussing challenges that are both technological and critical to the critical infrastructure industry. This search yielded 1,656 relevant studies based on the search string conducted in Section 3.1. The third step, extraction, involved collecting relevant data from the selected studies. Here, the researchers focused on studies that explored emergencies related to critical infrastructure (power grids, transportation, etc) and the use of immersive technologies in those situations. Studies on non-critical infrastructure emergencies or those that did not probe deeply into the technical challenges faced were excluded. This rigorous selection process yielded a preliminary list of 114 challenges. The fourth and final step involved analyzing and synthesizing the 114 challenges. The authors examined each challenge and assigned a keyword for easier organization. The authors then filtered the list, excluding inapplicable or overly specific challenges identified, resulting in a set of 76. Finally, by analyzing the assigned keywords, the authors identified related concepts and grouped the remaining 33 challenges based on their core characteristics into five distinct categories based on their similarities. These five categories were presented and discussed next.

4. Results and Discussion

4.1. Bibliometric Analysis of Existing Research on Application Challenges

Figure 2 charts the annual trends of extracted bibliographic records from 2000 to the present day. The graph depicts a steady rise in scholarly interest, highlighting the growing focus on studies associated with immersive technologies in critical infrastructure emergency response. While attention remained relatively low from 2000 to 2018, 2019 saw the number of articles surpass the 100 mark. Notably, 2023 witnessed the highest number of published articles (462), compared to a mere 4 articles in 2004.

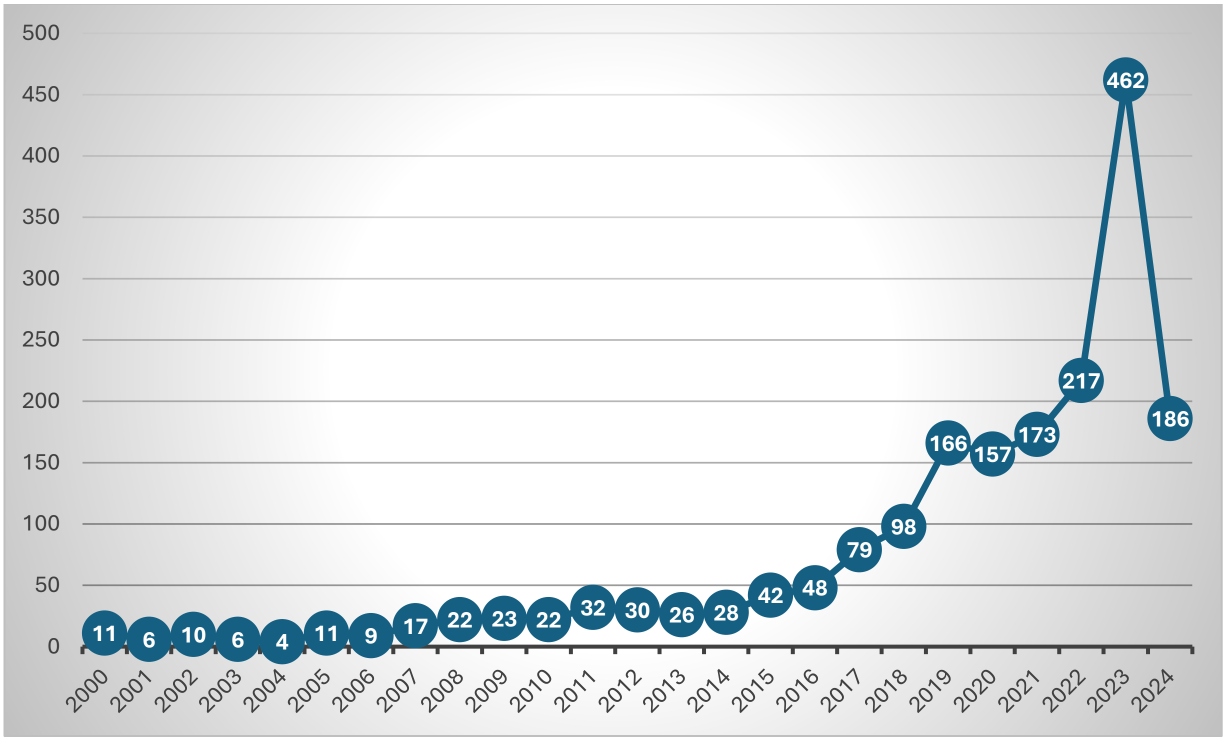

Figure 2: Publication per year on studies around existing challenges

(Source: Author's creation)

In terms of the country of publication, Figure 3 presents countries with at least 70 publications and 1,000 citations. The United States leads the way with a staggering 507 publications and 8,818 citations. Studies on immersive technologies in critical infrastructure emergency response have also gained prominence in countries such as China (207 documents, 2,717 citations), Germany (184 documents, 2,853 citations), the United Kingdom (164 documents, 3,447 citations) and Australia (100 documents, 1,683 citations), rounding out the top five. This aligns with the findings of Okafor *et al.,* (2023), who identified the US, China, Germany, the United Kingdom and Australia (often categorized as developed countries) as major contributors. One striking observation emerges from the map: while Europe, North America and Asia all have a presence in this research area, there seems to be a notable lack of studies from South America and Africa. This highlights a potential need for increased research efforts and resource allocation in these regions.

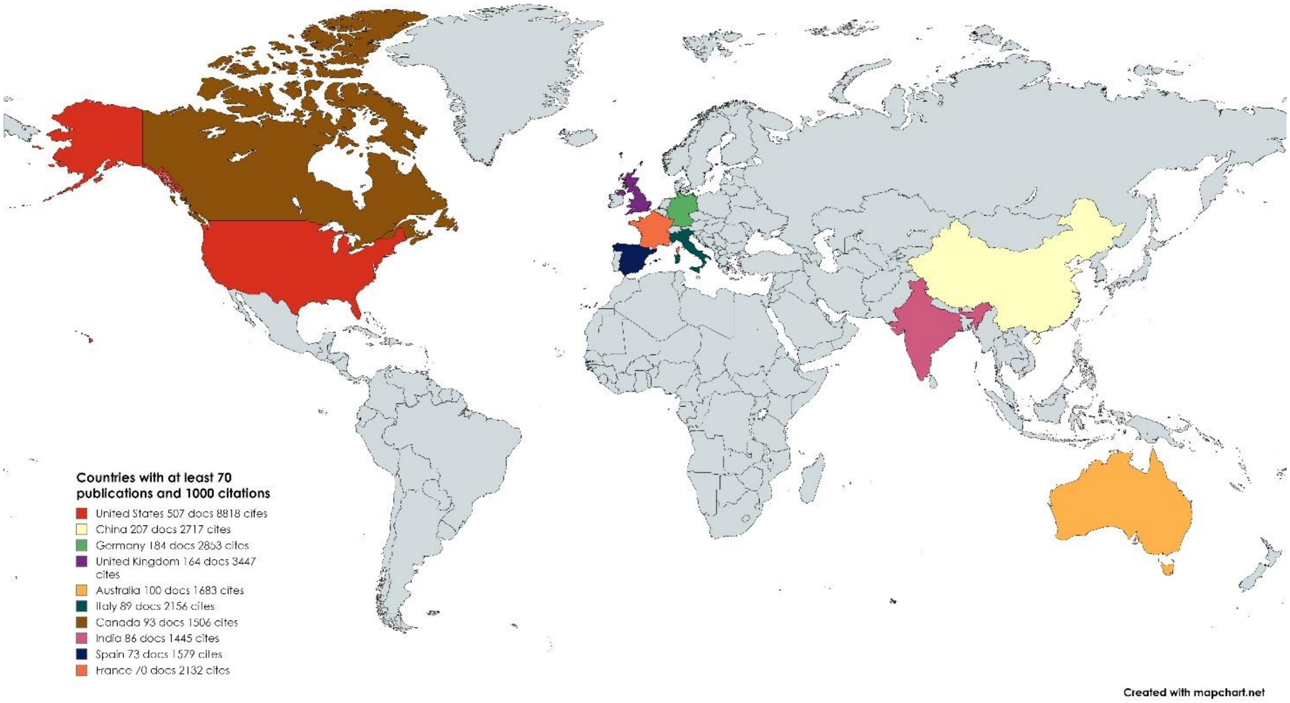

Figure 3: Publication per country on studies around existing challenges

(Source: Author's creation)

VOSviewer also helped assess countries' collaboration through a "co-authorship" analysis, treating countries as the unit of analysis. In this case, a minimum publication threshold of 20 was set for countries. Figure 3 reveals that 54 countries are clustered into nine distinct groups. Each country is represented by a node on the map, with larger nodes signifying a greater influence within the research area (Aliu and Aigbavboa, 2023). Figure 4 shows that the USA, China, Germany and the UK hold the most significant influence in collaborative research efforts. Figure 5 sheds light on the top publishing outlets for research on immersive technologies in critical infrastructure emergency response. Notably, the extracted articles originated from a diverse range of 907 sources. Leading the way is "Lecture Notes in Computer Science" with 80 publications. This is followed by the "ACM International Conference Proceeding Series" with 71 publications. These two entities stand at the forefront of disseminating research in this field.

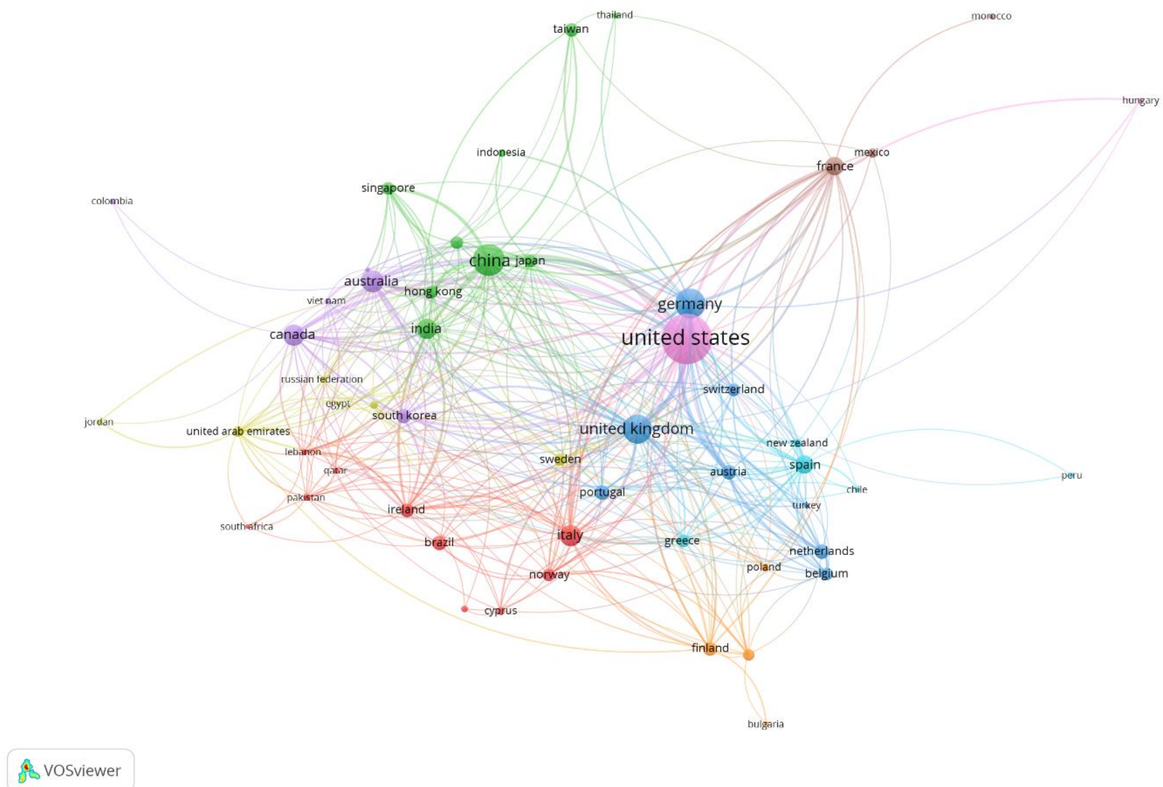

Figure 4: Collaborative efforts on studies around challenges

(Source: Author's creation)

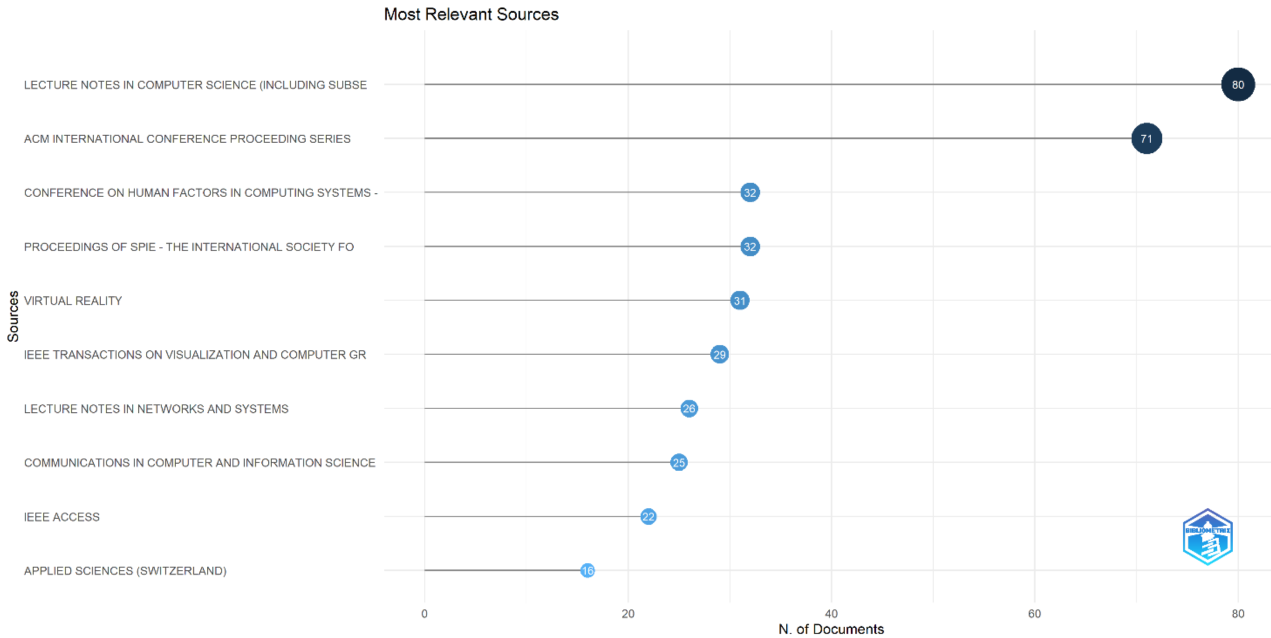

Figure 5: Leading sources of studies around challenges

(Source: Author's creation)

4.2. Cluster Analysis of Existing Research on Application Challenges

Table 1 presents a summary of the 33 challenges which were clustered into five categories with their corresponding references.

4.2.1. Technological-related Challenges

One significant issue under this cluster is hardware limitations, which include the high cost and limited availability of advanced devices needed for effective deployment (Bekaroo and Dawarka, 2023). For example, virtual reality (VR) headsets and augmented reality (AR) glasses require substantial investment and maintenance, which can be a barrier to widespread adoption (Stone *et al.,* 2021). Data security and privacy issues are another major concern, as the sensitive nature of critical infrastructure data necessitates robust security measures to prevent unauthorized access and breaches (Kumar *et al.,* 2021). For instance, during a cyber-attack on a power grid, the use of AR glasses by technicians could inadvertently expose critical infrastructure details if the data is intercepted. Moreover, immersive technologies often struggle to accurately replicate real-world environments, which can diminish their effectiveness in emergency response scenarios. According to Khanal *et al.,* (2022), this can lead to errors and reduced trust in the technology. For example, a VR training module for firefighters might not accurately simulate the heat, smoke and visibility conditions of a real fire, leading to less effective training. Additionally, immersive technologies often require significant power, which can be problematic in emergency situations where power sources may be limited (Buljat, 2021). Studies suggest the need for more energy-efficient hardware to address this challenge (Stone *et al.,* 2021). In some cases, data integration and analysis could be complex due to the need to process large volumes of data quickly and accurately during extreme situations (Mohsen and Alangari, 2024). For instance, during an earthquake, combining data from drones, ground sensors and AR devices to provide comprehensive situational awareness in real time can be technically demanding (Khanal *et al.,* 2022).

4.2.2. Human-related Challenges

This set of challenges deals with human-related aspects that hinder the deployment of immersive technologies. One significant challenge is cognitive overload, which occurs when users are overwhelmed by the amount of information presented through immersive technologies (Han *et al.,* 2021). Also, the extended use of VR or AR can lead to discomfort, including headaches, nausea and dizziness. For instance, emergency personnel using VR for training might experience sensory fatigue after prolonged sessions, diminishing the effectiveness of the training (Han *et al.,* 2021). Moreover, constant exposure to high-stress simulations can lead to increased anxiety and stress among users, which can impact their mental health on the long run (Fadeev *et al.,* 2020). In certain high-stakes situations, such as natural disasters or terrorist attacks, users might be skeptical about the accuracy and reliability of immersive technologies. For example, during a hurricane, emergency responders might distrust an AR system's real-time data about structural damage and potential hazards, preferring to rely on their own experience and traditional methods instead (Bernhardt, 2023). Accessibility considerations have also been regarded as a paramount concern (Feng *et al.,* 2018). In emergencies, ensuring that immersive technologies are accessible to all individuals, including those with disabilities, becomes even more critical. For instance, VR environments often rely heavily on visual and spatial interactions, which may pose challenges for individuals with visual impairments or other disabilities (Feng *et al.,* 2018). Similarly, individuals with hearing impairments may face barriers if important auditory cues or instructions are not adequately conveyed through visual or text-based prompts. Therefore, addressing these accessibility challenges requires designing VR interfaces that accommodate a diverse range of users.

4.2.3. Organizational -related Challenges

These challenges stem from internal factors within organizations and can impact various aspects of implementation and adoption. Often, the lack of awareness and, in some cases, buy-in within emergency management organizations can hinder the adoption of immersive technologies as stakeholders may not fully understand the potential benefits that these tools offer (Zhu and Li, 2021). The lack of clear understanding can also lead to hesitancy among decision-makers due to concerns about their compatibility with traditional emergency management approaches (Buljat, 2021). Likewise, inconsistencies in procedures and protocols for using immersive technologies can lead to confusion and inefficiencies among teams and departments within an organization (Kumar *et al.,* 2021). Another persistent issue in this cluster is the misalignment of immersive technologies with existing organizational goals and objectives. According to Stone *et al.,* (2021), emergency management organizations often face challenges when introducing new technologies that do not align with their overarching strategic priorities or operational needs. This could occur for several reasons, such as a lack of clarity or communication, which may prompt decision-makers to struggle to justify investment and garner support from stakeholders (Zhu and Li, 2021). Misalignment can also arise when immersive technology initiatives are driven by technology trends or external pressures rather than strategic planning and needs assessment (Babalola *et al.,* 2023). For example, organizations may feel compelled to adopt immersive technologies simply because they are seen as innovative or cutting-edge, without considering whether they address specific operational challenges or support key organizational objectives. Overall, the consequences of misalignment with existing goals can lead to wasted resources, ineffective implementation and limited adoption of immersive technologies (Bernhardt, 2023).

4.2.4. Financial and resource-related Challenges

This cluster of challenges stem from the high costs associated with acquiring, maintaining and utilizing immersive technology solutions, as well as the competition for limited funding and resources within organizations. One major challenge is the high upfront costs associated with acquiring immersive technology hardware, software and infrastructure (Khanal *et al.,* 2022). According to Khanal *et al.,* (2022), the initial investment required to purchase and deploy immersive technology solutions can be substantial, especially for organizations operating with limited budgets or facing competing priorities for funding allocation. Similarly, regular updates, upgrades and repairs may be necessary to ensure the continued functionality and effectiveness of immersive technology systems, adding to the overall cost of ownership over time (Mohsen and Alangari, 2024). Moreover, training personnel on how to effectively use immersive technology tools and integrate them into existing workflows requires time, resources and expertise. Likewise, ongoing training may be necessary to keep personnel updated on new features, functionalities and best practices. Limited grant opportunities also exacerbate financial hurdles, as several emergency response agencies often rely on grants for technology initiatives. However, specific grants for immersive technologies might be scarce or fiercely competitive (Li *et al.,* 2022). As a result, organizations may struggle to secure the necessary funding to implement immersive technology projects, hindering their ability to leverage these tools for crisis management and critical infrastructure protection. Return on Investment (ROI) uncertainty further adds another layer of complexity to financial decision-making as organizations may face uncertainty about the potential ROI of immersive technology initiatives (Han *et al.,* 2021). This can make it difficult to justify the initial investment and assess the long-term impact on operational effectiveness, cost savings, or stakeholder satisfaction.

4.2.5. Legal and Ethical Challenges

According to Damaševičius *et al.,* (2023), these challenges arise from the complex legal and ethical implications associated with data ownership, potential misuse, liability, privacy concerns and transparency in AI-powered immersive systems. As mentioned earlier, immersive technologies generate vast amounts of data, including real-time sensor data, user interactions and environmental information. As such, determining ownership rights and access privileges for this data can be challenging, especially in collaborative or multi-agency environments where multiple stakeholders may have vested interests (Han *et al.,* 2021). While immersive technologies offer valuable capabilities for enhancing situational awareness and decision-making, they also have the potential to be used for malicious purposes, such as surveillance, manipulation, or deception (Fadeev *et al.,* 2020). Thus, emergency response agencies must establish clear policies and safeguards to prevent misuse and ensure the responsible use of immersive technology tools. Liability is a significant legal consideration in the deployment of immersive technologies. In the event of accidents, errors, or incidents involving immersive technology systems, questions of liability may arise regarding who is responsible for any resulting damages or harm (Feng *et al.,* 2020). Therefore, organizations must carefully assess and mitigate potential liability risks through appropriate risk management strategies, contractual agreements and insurance coverage. Privacy concerns are also critical considerations as immersive technology systems often capture audio, video, and other sensory data from surrounding environments, raising concerns about the privacy rights of individuals who may be inadvertently recorded or monitored (Bernhardt, 2023). Therefore, organizations must implement robust privacy safeguards, such as anonymization, encryption and consent mechanisms, to protect the privacy rights of bystanders and comply with relevant privacy regulations.

Table 1: Categorization of challenges for immersive technologies in critical infrastructure response

Category	**Challenges**	**Literature sources**
Technological	Hardware limitations, Data security and privacy issues, Limited environmental fidelity, Scalability constraints, Power and energy requirements, Remote management and control, Data integration and analysis, Limited bandwidth for implementation.	Kumar *et al.,* (2021); Stone *et al.,* (2021); Khanal *et al.,* (2022); Bekaroo and Dawarka (2023); Mohsen and Alangari (2024).
Human Factors	Cognitive overload, Sensory fatigue and cyber sickness, Psychological impact, Lack of user trust, Accessibility considerations, Difficulty in developing realistic training scenarios, Cultural and language considerations.	Feng *et al.,* (2018); Fadeev *et al.,* (2020); Han *et al.,* (2021); Bernhardt (2023).
Organizational	Lack of awareness and buy-in, standardization hurdles, Resistance to change, Budget constraints and resource allocation, Misalignment with existing goals, Governance and regulatory compliance, Integration with existing workflows and systems	Kumar *et al.,* 2021; Zhu and Li (2021); Stone *et al.,* (2021); Bernhardt (2023).
Financial and Resource-related	High upfront costs, Ongoing maintenance costs, Training and development costs, Competition for funding, Limited grant opportunities, Return on Investment (ROI) uncertainty	Han *et al.,* (2021); Khanal *et al.,* (2022); (Li *et al.,* 2022); (Mohsen and Alangari, 2024).
Legal and Ethical	Data ownership and access, Potential for misuse, Liability, Privacy of bystanders, Transparency challenges and bias in AI-powered immersive systems	Han *et al.,* (2021); Bernhardt (2023); Damaševičius *et al.,* (2023).

(Source: Author's creation)

5. Practical Applicability of the Findings

This study has systematically identified some of the most prevalent challenges associated with deploying immersive technologies for critical infrastructure emergency response based on studies conducted since the turn of the 21st century. Through bibliometric analysis, 114 challenges were further analyzed into five different clusters. These findings hold significant practical implications for emergency management practitioners, policymakers and technology developers in Texas and beyond.

In addressing hardware limitations, which have been regarded as one of the most critical issues plaguing the development of VR/AR technologies (Bekaroo and Dawarka, 2023), several organizations in the United States, such as the National Institute of Standards and Technology (NIST), have over the years initiated research and development programs focused on creating more affordable and accessible VR/AR hardware. Additionally, cybersecurity firms and federal agencies, including the Department of Homeland Security (DHS), are constantly working on advanced encryption technologies to secure sensitive data used in immersive technologies. Increased funding for research, as proposed by this study, could accelerate the development of affordable, high-performance VR/AR hardware solutions specifically suited to Texas' diverse environments. Public-private partnerships between Texas universities and tech companies could further expedite this process. Investments in energy-efficient technology and alternative power sources such as portable generators and solar panels could also help mitigate power consumption issues in remote areas where traditional power infrastructure is lacking.

Human-related challenges are also being tackled. Institutions across the United States are actively researching the cognitive load and physical effects of VR/AR use, while also developing guidelines to minimize user discomfort (Souchet *et al.,* 2023). Also, the Federal Emergency Management Agency (FEMA) offers training programs integrating VR/AR to reduce cognitive overload and physical strain for first responders. These programs cover critical areas like Incident Command System (ICS) training, active shooter response, mass casualty incident (MCI) management and several others. This study recommends expanding these programs in Texas, with a focus on user acclimation through clear interfaces and ergonomic equipment design. Additionally, mental health support programs tailored to VR/AR training simulations should be established. Public demonstrations showcasing the technology's capabilities in Texas-specific scenarios (e.g., oil rig accidents, hurricane response) can foster user acceptance.

Organizational challenges can be addressed by raising awareness through workshops and seminars hosted by the Texas Division of Emergency Management (TDEM). Strategic alignment of immersive technology initiatives with organizational goals in Texas emergency response agencies is also crucial. The confusion of emergency response teams due to unfamiliarity with immersive technologies (Woodcock and Au, 2013), can be addressed by developing standardized procedures and protocols created collaboratively by TDEM and local agencies. Financial and resource limitations can be overcome through existing federal grants and funding opportunities, such as those from DHS and FEMA. This study highlights the potential of Large Language Models (LLMs) to enhance immersive technologies in emergency response (Javaid *et al.,* 2024). Increased collaboration between Texas A&M University and other research institutions with TDEM could secure funding to explore LLM applications specific to Texas emergencies. For instance, LLMs could be used for real-time translation during disasters impacting Texas' diverse population, improving communication and response times. This would not only ensure critical information reaches all residents in their native language but could also be applied to other areas, such as automating damage assessments or generating personalized evacuation plans. Finally, clear data ownership and privacy policies, advocated for by organizations like the Electronic Frontier Foundation, should be a priority not only in Texas but across the United States. Stringent safeguards such as responsible use protocols and regular audits are essential to ensure the ethical implementation of immersive technologies. Also, promoting transparency through regular reporting and stakeholder engagement will build trust and accountability in the use of these technologies. By taking these steps, emergency management organizations can better leverage immersive technologies to enhance emergency response and critical infrastructure protection while safeguarding individual privacy and rights.

6. Conclusion and Areas of Future Studies

The critical infrastructure industry has been slower to adopt immersive technologies compared to other sectors. These technologies which comprise virtual reality (VR), augmented reality (AR), mixed reality (MR), extended reality, 3D visualization and spatial computing offer potential for enhancing emergency response capabilities. However, realizing this potential requires overcoming challenges hindering their widespread adoption. This study aimed to identify and investigate these challenges. Employing a systematic review approach using bibliometric studies, the research yielded a comprehensive list of 114 challenges. These were then reviewed and categorized into 33 distinct challenges, further grouped into five key categories based on thematic similarities. Overall, the analysis shows a growing research interest in immersive technologies for critical infrastructure emergency response, particularly in the US, China, Germany, UK and Australia. This surge aligns with the recent intensification of climate change, leading to more extreme weather events and natural disasters that threaten critical infrastructure.

Practically, the insights provided can guide policymakers, technology developers and emergency response organizations in addressing the specific challenges identified. For instance, investments in affordable and energy-efficient VR/AR hardware, robust data security measures and comprehensive training programs can mitigate technological and human-related challenges. Furthermore, aligning immersive technology initiatives with organizational goals and developing standardized protocols can address organizational challenges. Researchers can probe deeper into specific challenge categories by conducting case studies of critical infrastructure organizations that are either struggling with or successfully implementing immersive technologies.

Another key contribution of this study is the categorization of the challenges into a clear taxonomy. This approach allows for a more targeted approach to developing solutions across different contexts. Emergency management practitioners can readily identify the challenges most relevant to their organization and tailor their implementation strategies accordingly. Researchers can also benefit by having a structured approach to guide their empirical investigations into the effectiveness of different approaches to addressing these challenges. Furthermore, the taxonomy can serve as a valuable tool for future research efforts. It can be used to rank the importance of challenges across regions, technologies and organization sizes, informing targeted resource allocation and development efforts. With the current storms and floods plaguing Texas, this study's findings are particularly relevant. By prioritizing solutions that address these challenges, such as budgetary constraints or training gaps, emergency response teams in Texas and other vulnerable regions can be better equipped to leverage the potential of immersive technologies for faster, more effective responses during future disasters. Overall, this research has the potential to contribute to a significant increase in preparedness and resilience for critical infrastructure systems, leading to a safer future for communities worldwide.

A few limitations in this study are acknowledged. While this study provides valuable insights, the absence of empirical data collection limits the ability to confirm or quantify the identified challenges. Future research could address this gap by employing a mixed-methods approach. This approach could combine surveys with critical infrastructure professionals to gauge their specific experiences and perspectives on the identified challenges, alongside in-depth case studies of organizations that have implemented immersive technologies during emergency response efforts. Such an approach would provide a deeper understanding of the challenges and their real-world impact. Though this study offers a global view, future research could probe into regional or sub-sector challenges. For example, the challenges faced by a power grid operator in a densely populated urban area might differ significantly from those faced by a water treatment facility in a remote rural location. Tailoring research to these specific contexts can lead to more targeted solutions that address the most pressing needs of different stakeholders.

Declaration of Competing Interest

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

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