DISASTER ADVANCES ISSN:0974-262X,E-ISSN:2278-4543

ISSN: 0974-262X E-ISSN: 2278-4543
Volume 18, Issue 05, October, 2025

Utilization Strategies of the Metaverse in Disaster Management: A Framework Based on Spatial Information and Digital Twin Integration

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ABSTRACT— The frequency and severity of disasters have been steadily increasing due to climate change, rapid urbanization, and socio-environmental complexity. While existing ICT-based disaster management systems have contributed to improving preparedness and response, they face limitations in real-time integration, citizen participation, and immersive training. This study explores the potential of metaverse technologies—such as Virtual Reality (VR), Augmented Reality (AR), Extended Reality (XR), and Digital Twin—in enhancing disaster management across the entire cycle of prevention, preparedness, response, and recovery. By analyzing domestic and international cases, including FEMA VR training (USA), earthquake VR simulations (Japan), Virtual Singapore (Singapore), and Korean initiatives (LX flood risk map and NDMI disaster-safety metaverse platform), this paper proposes a metaverse-based disaster management framework. The findings indicate that the metaverse can significantly strengthen disaster risk prediction, immersive training, real-time situational awareness, and participatory recovery planning. Finally, the paper discusses policy implications, challenges, and future research needs for the effective adoption of the metaverse in disaster management.

KEYWORDS: Metaverse, Disaster Management, Digital Twin, Spatial Information, Disaster Response

DOI:
05.5175/DA.30.10.2025.01

1. Introduction

The 21st century has witnessed a significant rise in the frequency and impact of disasters worldwide. According to the World Meteorological Organization (WMO), over 11,000 disasters occurred globally in the past 50 years, causing economic losses exceeding USD 3.6 trillion [1]. Moreover, disasters in the last two decades have increased nearly fivefold compared to earlier periods, affecting more than 100 million people annually [1]. In Korea, official statistics show that the average annual disaster-related losses exceed KRW 1 trillion, mainly due to typhoons, floods, and heatwaves [2]. These figures highlight the growing vulnerability of societies and the limitations of existing disaster management systems in addressing complex and large-scale hazards.

Disaster management encompasses four interconnected phases: prevention, preparedness, response, and recovery [3]. Traditional ICT technologies, including Geographic Information Systems (GIS), remote sensing, drones, and IoT sensors, have been utilized in each phase. While these technologies have enhanced risk mapping, early warning, and data collection, they still face challenges in real-time integration, citizen engagement, and immersive training [14], [15].

The metaverse, defined as a convergence of physical and digital spaces, integrates multiple technologies such as VR, AR, XR, Digital Twin, AI, IoT, and blockchain [4], [10]. Its immersive and interactive features offer new opportunities for disaster management. For example, disaster risk prediction through 3D digital twins, immersive VR evacuation drills, real-time virtual command centers, and participatory recovery planning represent innovative applications that go beyond the capabilities of conventional ICT systems.

Practical implementations already exist. FEMA in the United States has developed VR-based hurricane and fire training programs [5], Japan has implemented earthquake VR drills in schools [6], and Singapore's Virtual Singapore project provides a city-scale digital twin for flood prediction, urban safety, and crisis management [7]. In Korea, the LX Corporation has created a digital twin-based flood risk map [8], while the National Disaster Management Institute (NDMI) has piloted a metaverse disaster-safety education platform [9]. Despite these efforts, most applications remain limited to specific cases or training, lacking an integrated strategy across the entire disaster cycle.

This study aims to systematically examine the potential of metaverse applications in disaster management and propose a comprehensive framework that connects prevention, preparedness, response, and recovery. By analyzing domestic and international case studies, the paper highlights opportunities, challenges, and policy implications for the adoption of metaverse technologies in disaster management.

2. Theoretical Background

2.1 Concept and Core Technologies of the Metaverse

The metaverse is more than a virtual environment; it represents an integrated digital ecosystem where physical and virtual realities converge. It encompasses technologies such as Virtual Reality (VR), Augmented Reality (AR), Extended Reality (XR), and Digital Twins, all of which are supported by enabling infrastructures including artificial intelligence (AI), the Internet of Things (IoT), and blockchain [4], [10].

- **VR (Virtual Reality)** immerses users in fully simulated environments, allowing disaster responders or citizens to experience emergency situations in safe, controlled settings. It is particularly useful for practicing evacuation drills and emergency responses where real-world training would be costly or dangerous [5].
- **AR (Augmented Reality)** overlays digital information on the physical world, enabling real-time situational awareness. For example, AR can provide first responders with visual hazard indicators, evacuation routes, or sensor data during field operations [11].
- **XR (Extended Reality)** integrates VR and AR to create flexible mixed environments where responders can simultaneously access real-world views and immersive simulations.
- **Digital Twins** represent dynamic, data-driven replicas of physical systems, which can simulate disaster impacts, monitor ongoing events, and support predictive analysis [7], [8].

Furthermore, blockchain technology ensures data integrity and traceability in shared virtual platforms [12], while AI and IoT supply the real-time sensing and predictive analytics that make metaverse platforms intelligent and adaptive. Together, these technologies form the technical foundation for embedding the metaverse into disaster management systems.

2.2 Disaster Management Framework

Disaster management is conventionally organized into four phases: Prevention, Preparedness, Response, and Recovery (PPRR) [3], [13]. This cycle emphasizes that disasters are not isolated events but dynamic processes requiring continuous attention.

- The **Prevention** phase involves risk identification, hazard mapping, and mitigation measures aimed at reducing disaster likelihood and impact.
- The **Preparedness** phase focuses on training, drills, education, and resource management to ensure readiness for potential hazards.
- The **Response** phase begins once a disaster strikes, requiring rapid coordination of resources, real-time decision-making, and lifesaving actions.
- The **Recovery** phase encompasses both short-term restoration of critical services and long-term reconstruction and resilience-building.

While conceptually straightforward, integrating these phases in practice is challenging. Institutional silos, fragmented data systems, and inconsistent coordination often hinder seamless transitions across phases [14]. As a result, governments and agencies struggle to maintain continuity from prevention through to recovery, leaving gaps that can exacerbate disaster impacts. This underscores the need for innovative solutions, such as metaverse platforms, to provide cross-phase integration and collaboration.

2.3 ICT-based Disaster Management: Achievements and Limitations

Over the past two decades, ICT innovations have significantly advanced disaster management. GIS and remote sensing have enabled large-scale hazard mapping, drones have improved data collection in hard-to-access areas, IoT sensors provide continuous environmental monitoring, and big data analytics facilitate predictive modeling of disaster risks [15]. These tools have improved early warning systems, supported faster response times, and enhanced evidence-based decision-making.

However, critical limitations persist.

First, ICT systems often lack immersion and experiential learning, meaning that training remains abstract and less effective in preparing responders or citizens for the stress of real emergencies [16]. Second, there are data integration challenges due to heterogeneous data sources, varying formats, and the absence of common standards. This fragmentation prevents seamless real-time situational awareness and coordinated decision-making [14]. Third, ICT-based systems remain largely expert-centered, limiting the involvement of citizens. As a result, public awareness and participation in disaster management remain weak [17].

The metaverse provides an opportunity to address these limitations. By creating immersive and interactive environments, it enhances training and preparedness. By integrating IoT, GIS, and digital twins into shared virtual platforms, it improves real-time coordination and interoperability. Finally, by allowing communities to engage directly in disaster planning and recovery processes, it promotes participatory governance and resilience.

3. Potential Applications of the Metaverse in Disaster Management

3.1 Prevention

In the prevention phase, the metaverse can play a vital role in enhancing hazard identification and risk assessment. Through the use of digital twin technologies, entire urban environments can be replicated in three-dimensional virtual spaces, allowing for the simulation of potential disaster scenarios such as floods, earthquakes, and wildfires. For instance, the Virtual Singapore project demonstrates how a digital twin of a city can be used to model the impacts of natural disasters, enabling policymakers to test mitigation strategies before they are implemented in the real world [7]. Similarly, Korea's LX Corporation has developed flood hazard maps based on digital twin technology, supporting local governments in assessing vulnerable areas and prioritizing infrastructure reinforcement [8]. By providing intuitive visualizations, the metaverse can also improve public risk perception and awareness, allowing communities to better understand disaster threats and the importance of preventive measures [17].

3.2 Preparedness

Preparedness requires systematic training and education for both professionals and citizens. Traditional training methods often rely on documents, videos, or tabletop exercises, which may fail to replicate the stress and complexity of real disaster environments. The metaverse, with its immersive VR/AR/XR capabilities, enables highly realistic disaster simulations where participants can practice decision-making under conditions that closely resemble real emergencies [16].

A well-documented example is FEMA's virtual reality training programs in the United States, which simulate hurricanes and fires, offering emergency responders opportunities to practice procedures without physical risks [5]. In Japan, earthquake VR drills are widely used in schools, allowing students to virtually experience seismic events and practice safe evacuation routes [6]. In Korea, the NDMI has introduced a metaverse-based disaster-safety education platform that engages both public officials and citizens in immersive preparedness training [9]. These cases highlight that the metaverse not only enhances technical readiness but also fosters greater inclusiveness by enabling citizens to participate actively in preparedness activities. Furthermore, during the COVID-19 pandemic, non-contact VR training emerged as a critical tool for maintaining disaster preparedness while minimizing infection risks [18].

3.3 Response

The response phase is characterized by the urgent need for real-time situational awareness and effective coordination among multiple stakeholders. The metaverse can serve as a virtual command center, where decision-makers, field responders, and support agencies can collaborate in a shared digital environment. By integrating IoT sensors, drone feeds, and satellite imagery, the metaverse allows for comprehensive visualization of evolving disaster conditions [14]. Such visualization improves situational awareness and accelerates the coordination of resources and response activities.

For example, the European RESPOND-A project demonstrates how XR technologies can enhance emergency medical training and decision-making during disasters [19]. In Singapore, the Virtual Singapore platform is being expanded into a command center environment to support real-time crisis management [7]. Seoul has also employed VR-based simulations of subway fire incidents, which allow both responders and policymakers to test emergency procedures in a risk-free digital setting. These cases underscore the ability of the metaverse to bridge communication gaps, promote inter-agency collaboration, and facilitate rapid, evidence-based responses during emergencies.

3.4 Recovery

In the recovery phase, the metaverse can be leveraged to support reconstruction planning and community resilience. By creating digital twin replicas of disaster-affected areas, authorities can test and evaluate multiple recovery scenarios before committing resources to physical reconstruction [8]. This approach allows for more efficient allocation of funds, faster restoration of critical infrastructure, and more sustainable rebuilding strategies.

Equally important is the potential for participatory recovery planning through the metaverse. Citizens can be engaged in virtual environments to review proposed reconstruction plans, provide feedback, and collaborate with local governments [17]. Virtual Singapore serves as an example, enabling government agencies, private companies, and citizens to collaboratively explore recovery options [7]. In addition, VR technologies have been used for psychological rehabilitation of disaster survivors. Immersive VR environments can provide therapeutic interventions that help victims cope with trauma and build psychological resilience [20].

Collectively, these applications show that the metaverse is not limited to preparedness or training but can also extend into the long-term recovery phase, ensuring that rebuilding efforts are both technically sound and socially inclusive.

4. Case Analysis and Framework Proposal

4.1 Comparative Case Analysis

The review of domestic and international initiatives shows that metaverse technologies are being applied in disaster management, but mostly in fragmented or phase-specific ways. In the United States, FEMA's VR-based training programs have proven effective in improving the skills and readiness of emergency responders [5]. Japan's earthquake VR simulations focus primarily on public safety education, enabling students and communities to better understand evacuation protocols [6]. Singapore's Virtual Singapore project, however, illustrates a more holistic approach, as it incorporates prevention, response, and recovery functions within a city-wide digital twin model [7].

In Korea, projects have also been introduced that integrate spatial information and metaverse concepts. The LX Corporation developed a digital twin-based flood hazard map, which supports policymakers in identifying flood-prone areas and planning mitigation measures [8]. Meanwhile, the NDMI has piloted a disaster-safety education platform in the metaverse, which allows citizens and public officials to participate in virtual training environments [9]. While these initiatives demonstrate the feasibility of metaverse applications, they remain partial in scope—focused primarily on preparedness or single-hazard scenarios—rather than offering a fully integrated solution across all disaster management phases.

This comparative analysis highlights both the promise and the gaps of current practices: while immersive technologies can enhance training and awareness, there is still a pressing need for a comprehensive framework that systematically applies metaverse technologies throughout the disaster management cycle.

4.2 Synthesis of Case Findings

To synthesize the findings from these diverse cases, Table 1 organizes examples according to the prevention–preparedness–response–recovery (PPRR) framework. The table illustrates how different technologies and projects align with specific phases of disaster management. For example, prevention efforts are closely tied to digital twin-based risk simulations such as Virtual Singapore and LX flood hazard maps. Preparedness applications are dominated by immersive VR/AR/XR training platforms, including FEMA's VR programs, Japanese earthquake drills, and NDMI's education platform. Response-phase initiatives focus on virtual command centers and real-time visualization, with examples from EU RESPOND-A and Singapore's crisis management system. Finally, recovery initiatives emphasize digital twin reconstruction and participatory planning, as in Virtual Singapore and LX recovery models.

Table 1. Metaverse Applications in Disaster Management Phases

Phase	Metaverse Application	Case Examples
Prevention	Digital Twin hazard prediction, 3D risk mapping	Virtual Singapore, LX flood risk maps
Preparedness	VR/AR/XR immersive training, virtual evacuation drills	FEMA VR, Japan Earthquake VR, NDMI platform
Response	Virtual command center, IoT+drone XR visualization	EU RESPOND-A, SG Virtual Center, Seoul VR drills
Recovery	Digital Twin reconstruction, participatory metaverse platform	Virtual Singapore recovery planning, LX recovery, NDMI

By mapping case studies to disaster phases, it becomes clear that each project provides value in its respective phase, yet no single project currently integrates the entire PPRR cycle. This reinforces the need for a consolidated framework that bridges these fragmented applications.

4.3 Proposed Framework

Based on this synthesis, this study proposes a Metaverse-based Disaster Management Framework (Figure 1). The framework places the four disaster management phases in a cyclical structure and maps corresponding metaverse applications to each phase. Specifically:

- **Prevention:** Digital twin-based risk prediction and hazard visualization.
- **Preparedness:** Immersive VR/AR/XR simulations for public training and professional exercises.
- **Response:** Virtual command centers integrating multi-source data (IoT, drones, satellites) for real-time situational awareness and decision-making.
- **Recovery:** Digital twin-enabled reconstruction planning and participatory metaverse platforms for community engagement.

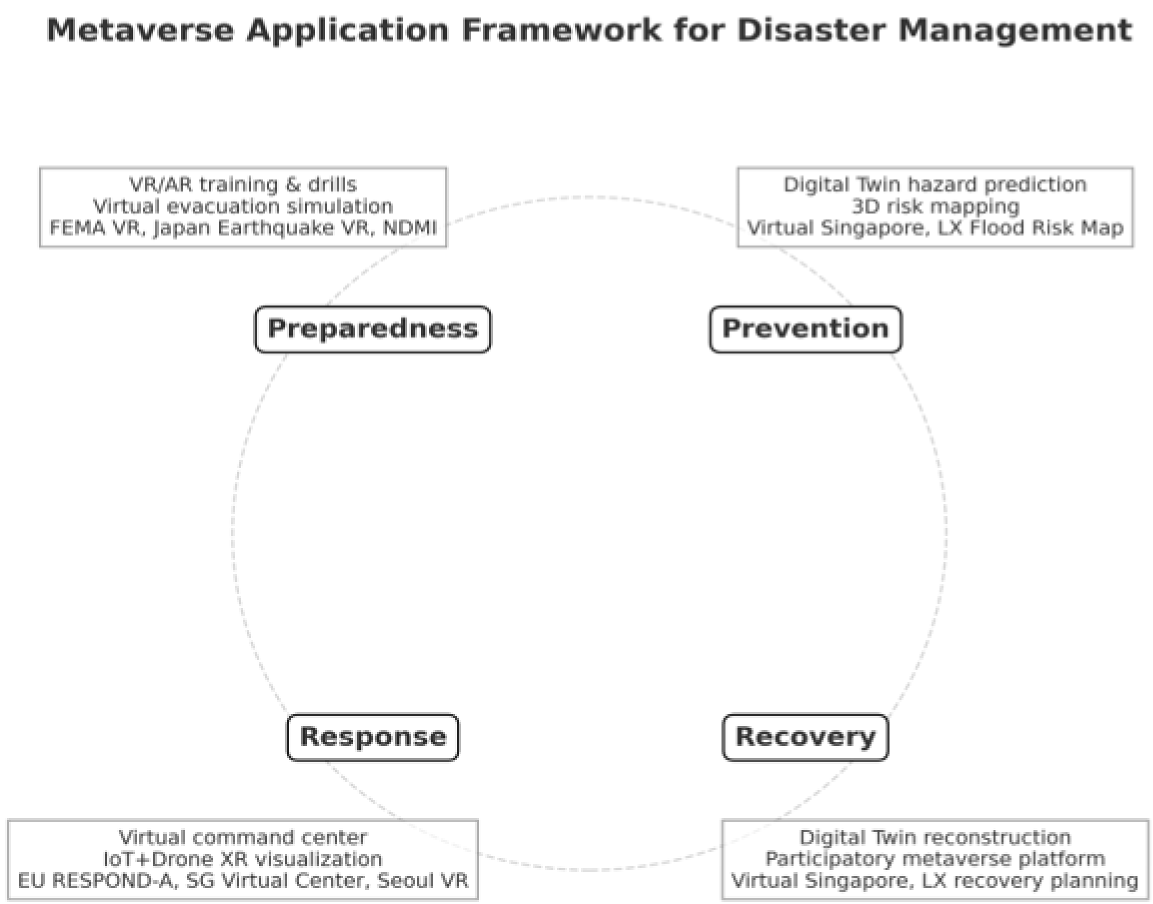

Figure 1. Proposed framework of metaverse applications across the disaster management cycle

This framework emphasizes continuity across the disaster cycle. Instead of treating each phase as isolated, the framework envisions a seamless system in which metaverse technologies allow information, training, and collaboration to flow continuously between prevention, preparedness, response, and recovery.

4.4 Implications of the Framework

The proposed framework offers several implications for research and practice. First, it provides a comprehensive perspective that addresses the current fragmentation of metaverse applications in disaster management. Second, it highlights the importance of citizen participation, demonstrating how metaverse platforms can empower communities to play an active role in disaster preparedness and recovery. Third, the framework promotes real-time, multi-agency collaboration during the response phase, thereby overcoming the limitations of siloed ICT systems [14]. Finally, it underscores the synergy of spatial information and emerging technologies, showing that metaverse-based disaster management is not just a technological innovation but also a governance innovation.

By proposing this framework, the study contributes to both academic discourse and practical policy-making. It demonstrates that the metaverse should not be confined to training or awareness but can be strategically embedded into all phases of disaster management, creating a more resilient and participatory system.

5. Discussion

5.1 Advantages of Applying the Metaverse

The analysis of international and domestic cases suggests several advantages of applying the metaverse to disaster management. First, immersive technologies such as VR and AR significantly improve the effectiveness of training and education. Unlike traditional document- or video-based exercises, immersive simulations place participants in lifelike environments where they can practice decision-making under stress. Studies show that such training improves not only technical competence but also knowledge retention and behavioral readiness [16]. This is particularly valuable for both first responders, who must react rapidly under extreme conditions, and for citizens, who benefit from intuitive experiential learning.

Second, the metaverse enhances situational awareness and decision-making during disaster response. By integrating IoT sensor data, drone imagery, and satellite feeds into a shared virtual environment, stakeholders can gain a comprehensive and dynamic view of evolving disaster conditions. This supports faster and more evidence-based decisions, while enabling multiple agencies to coordinate their responses more effectively [14], [19].

Third, the metaverse fosters greater citizen participation in disaster management. Traditionally, disaster management systems have been expert-centered, limiting the involvement of ordinary citizens. Metaverse platforms, however, allow residents to engage directly in preparedness activities, virtual evacuation drills, and even post-disaster recovery planning. This participatory approach not only strengthens local resilience but also increases public trust and acceptance of disaster policies [17].

Finally, the metaverse represents a technological convergence platform, where multiple emerging technologies—AI, IoT, blockchain, and digital twins—can be integrated. Such convergence creates synergies that extend beyond individual tools, enabling disaster management systems that are immersive, collaborative, and data-driven [10], [12].

5.2 Challenges and Limitations

Despite these advantages, several challenges remain. The first is technical limitations. The operation of metaverse platforms in disaster management requires high-performance computing resources and ultra-low-latency networks. During large-scale disasters, when many users and agencies attempt to connect simultaneously, network delays and system instability can critically undermine the effectiveness of virtual command centers [18].

The second challenge concerns financial costs. Building digital twin environments, developing VR-based training programs, and maintaining virtual platforms entail substantial investments. While national governments and large cities may afford such expenses, smaller municipalities and developing countries may struggle to adopt metaverse-based disaster management systems [15].

The third challenge involves privacy and security risks. Disaster management often requires the collection and processing of sensitive personal and location data. When integrated into metaverse platforms, these datasets are vulnerable to unauthorized access or misuse, raising ethical and legal concerns [12].

Finally, there are social acceptance and digital divide issues. While younger generations may adapt easily to virtual environments, elderly populations or communities with limited digital access may find it difficult to engage with metaverse platforms. Without strategies to address these disparities, metaverse applications risk exacerbating inequalities in disaster preparedness and recovery [17].

5.3 Policy and Governance Implications

To address these challenges, several policy and governance implications emerge. First, data standardization and interoperability must be prioritized. Disaster management involves multiple agencies and heterogeneous data sources, and without standardized formats, effective integration into metaverse platforms is impossible [14].

Second, legal and institutional frameworks must be established to safeguard privacy, ensure accountability, and define operational protocols for virtual disaster management systems. Issues such as data ownership, liability in virtual training, and cyber-security must be addressed proactively [12].

Third, public–private partnerships will play a critical role. Since metaverse platforms require both technological innovation and governance support, collaboration between governments, research institutions, and technology companies is essential. Such partnerships can also help share financial burdens and accelerate the development of practical applications [13].

Finally, social acceptance strategies are needed. Public education campaigns, community-based training programs, and inclusive design practices should be implemented to ensure that all demographics can benefit from metaverse applications. Building trust and ensuring accessibility will be key to embedding the metaverse into disaster management practices [17].

6. Conclusion

This study examined the potential of metaverse technologies in disaster management and proposed a comprehensive framework that integrates prevention, preparedness, response, and recovery. By analyzing both international and domestic cases—including FEMA's VR training in the United States, earthquake simulation programs in Japan, Singapore's Virtual Singapore project, and Korean initiatives such as LX's digital twin-based flood hazard maps and NDMI's disaster-safety education platform—this research has shown that the metaverse is not merely a conceptual innovation but a practical tool with transformative potential.

The findings of this study demonstrate that the metaverse can contribute to disaster management in several important ways. In the prevention phase, digital twin models provide an advanced mechanism for simulating hazard scenarios, identifying vulnerable areas, and improving both policy planning and public risk awareness. In the preparedness phase, immersive VR and AR technologies enable realistic, low-risk training environments that enhance learning outcomes and inclusiveness, extending disaster education beyond professionals to the general public. During the response phase, virtual command centers integrating real-time IoT, drone, and satellite data allow for rapid situational awareness and collaborative decision-making across multiple agencies. Finally, in the recovery phase, metaverse platforms facilitate not only efficient reconstruction planning through digital twin simulations but also participatory governance, where citizens can actively engage in reviewing and co-designing recovery strategies.

Nevertheless, the study also acknowledges significant challenges. Technical issues such as latency and scalability, financial constraints in building and maintaining virtual infrastructures, privacy and security risks in handling sensitive data, and social acceptance barriers represent obstacles that must be addressed. These challenges underscore the importance of establishing strong institutional frameworks, fostering public–private partnerships, ensuring data interoperability, and implementing inclusive design strategies to overcome the digital divide.

The contributions of this study are both academic and practical. Academically, it proposes a structured framework for understanding how metaverse technologies align with the established disaster management cycle. Practically, it highlights opportunities for policymakers and practitioners to incorporate immersive technologies into disaster management systems, thereby increasing resilience and societal preparedness.

Future research should pursue empirical validation by conducting pilot projects that apply metaverse solutions in real disaster scenarios. Quantitative evaluations of training effectiveness, community engagement, and loss reduction are also required to build a stronger evidence base. Moreover, the integration of next-generation technologies such as AI-driven predictive analytics, blockchain for secure data sharing, and 5G/6G ultra-low latency networks will be critical in advancing scalable and robust metaverse-based disaster management platforms.

In conclusion, the metaverse represents a paradigm shift in disaster management. By enabling immersive training, real-time collaboration, and participatory recovery planning, it offers a holistic approach that transcends the limitations of conventional ICT systems. If appropriately developed and governed, metaverse-based disaster management systems can significantly contribute to creating safer, more resilient, and more inclusive societies.

Acknowledgements

This work was supported by the National Research Foundation of Korea(NRF) grant funded by the Korea government(MIST)(NRF-2022R1A2C 1007942)

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