

Review

AI-Driven Sensing Technologies and Digital Twins for Firefighter Safety: Technologies, Challenges, and Future Directions

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Highlights

What are the main findings?

- The review identified four major technological domains shaping firefighter digital twin systems: AI-enabled fire-risk modeling, sensing infrastructures, IoT communication systems, and predictive analytics.
- Current firefighter digital twin systems increasingly integrate environmental sensing, physiological monitoring, and artificial intelligence to support real-time safety monitoring and operational decision-making.
- Key challenges remain in multimodal sensor integration, predictive simulation, explainable AI, interoperability, and intelligent decision-support systems.

What are the implications of the main findings?

- AI-driven digital twin ecosystems have strong potential to improve firefighter safety, situational awareness, and emergency-response coordination.
- Future research should focus on sensor fusion, explainable AI, predictive simulations, edge-enabled analytics, and human-centered decision-support technologies.

Abstract

Firefighters operate in high-risk, rapidly evolving environments where exposure to extreme heat, toxic gases, and physiological stress significantly increases the likelihood of injury and fatality. This study systematically maps the emerging research landscape of real-time artificial intelligence (AI)-driven digital twins for environmental and physiological risk prediction in firefighting contexts. A combined bibliometric and qualitative content analysis was conducted using peer-reviewed literature retrieved from the Web of Science database (2010–2025). Bibliometric techniques were used to identify publication trends and thematic clusters, while content analysis examined the integration of sensing technologies, AI models, and digital twin architectures. The results reveal four dominant technological domains shaping the field: AI-enabled fire risk modeling, sensor data acquisition systems, IoT-based digital infrastructures, and predictive analytics for disaster

Academic Editor: Pierluigi Siano

Received: 02 June 2026

Revised: 07 July 2026

Accepted: 08 July 2026

Published: 12 July 2026

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simulation. Sensing technologies such as temperature, gas, particulate matter, thermal imaging, heart rate, and blood oxygen monitoring form the foundational data layer, while machine learning and deep learning models enable real-time hazard prediction and situational awareness. Digital twin architectures serve as the integration layer, fusing multi-source data and supporting simulation-based decision-making. Despite rapid advancements, key gaps persist, including limited integration of environmental and physiological data, insufficient predictive capabilities, a lack of standardized architectures, and minimal development of human-centered decision-support systems. This study provides a structured synthesis of current technologies and identifies future research directions toward integrated, explainable, and real-time digital twin systems to enhance firefighter safety and operational resilience.

Keywords: artificial intelligence; digital twin; emergency response systems; firefighter safety; risk prediction; sensing technologies

1. Introduction

Firefighters operate in some of the most hazardous occupational environments, characterized by rapidly evolving fire dynamics, extreme temperatures, toxic gases, and structural instability. These conditions threaten both operational effectiveness and personal safety, requiring firefighters to make rapid decisions under intense physical and cognitive stress. Studies have shown that firefighters' exposure to extreme heat, smoke, carbon monoxide, and particulate matter can result in physiological strain, heat stress, respiratory complications, and long-term health risks [1,2]. Additionally, complex structural environments increase the risks of collapse, disorientation, and entrapment [3]. Despite advancements in training and protective equipment, firefighter injuries and fatalities remain a persistent concern. For instance, the United States National Fire Protection Association (US NFPA) estimates that 53,575 municipal firefighters were injured in the line of duty, while 62 on-duty deaths were reported in 2024 [4]. This data emphasizes the need for technologies that support real-time risk assessment and decision-making [5,6].

Recent advances in sensing technologies and digital systems have created new opportunities to improve safety monitoring in high-risk environments [7,8]. Wearable sensors and environmental monitoring devices are increasingly used to collect real-time physiological and environmental data during firefighting operations [9–11]. These sensors measure heart rate, body temperature, respiratory rate, blood oxygen saturation, and movement patterns, providing insights into firefighter health and performance [10,12]. Environmental sensors can monitor temperature, humidity, toxic gases, and particulate levels, enabling early detection of hazardous conditions [11,13]. These sensing technologies support continuous monitoring of firefighter health and environmental exposure.

The availability of real-time sensing data has also driven the use of artificial intelligence (AI) and machine learning to transform raw data into actionable insights. AI models can analyze complex datasets to detect anomalies, predict physiological stress, and identify emerging hazards [14]. For instance, predictive models have been used to estimate heat stress and workload in firefighters, while environmental analytics can forecast fire behavior and smoke propagation [15,16]. These capabilities enhance proactive safety management by enabling early warnings and improved risk prediction.

In parallel, digital twin (DT) technology has emerged as a powerful approach for integrating sensing and analytical systems. A digital twin is a dynamic virtual representation of a physical entity that continuously updates using real-time sensor data [17]. By combining data, simulation, and analytics, digital twins enable real-time monitoring,

predictive analysis, and decision support [18–20]. Widely applied in manufacturing and infrastructure, digital twins allow operators to simulate scenarios and optimize system performance [21].

In firefighting contexts, digital twins can model firefighters, equipment, and environmental conditions in real time. By integrating physiological and environmental data, AI-driven digital twins can predict risks such as heat exhaustion, oxygen depletion, and hazardous exposure [15,16]. These systems could provide incident commanders with actionable insights to improve safety and operational decisions. However, existing research remains fragmented across sensing, AI, and digital twin domains. Many studies focus on individual technologies rather than integrated systems, limiting the ability to assess combined physiological and environmental risks [10,22]. Furthermore, digital twin applications have largely focused on industrial systems rather than human-centered safety applications [23].

As a result, the growing intersection of sensing technologies, artificial intelligence, cyber–physical systems, and digital twin platforms presents both significant opportunities and emerging challenges for firefighter safety and emergency response operations. Although substantial progress has been made in wearable sensing, environmental monitoring, predictive analytics, and digital twin modeling, existing research remains fragmented across multiple technological and disciplinary domains. A comprehensive synthesis of these developments is needed to better understand how AI-driven digital twin ecosystems can support real-time environmental monitoring, physiological risk prediction, operational decision-making, and emergency-response resilience in high-hazard firefighting environments.

This review examines the evolving technological landscape of AI-driven sensing and digital twin technologies for firefighter safety, with an emphasis on sensing infrastructure, artificial intelligence models, cyber–physical integration, predictive analytics, and human-centered decision-support systems. In addition, the review explores emerging technological trends, major implementation challenges, and future research opportunities related to multimodal sensor fusion, explainable AI, predictive simulation environments, immersive visualization systems, and next-generation digital twin architectures for emergency response applications.

By synthesizing advances across sensing systems, AI-enabled monitoring platforms, and digital twin technologies, this review contributes to the development of intelligent firefighter safety systems that enhance situational awareness, operational resilience, and data-driven decision-making in emergency response. This study is intended for researchers and practitioners in the fields of fire safety engineering, artificial intelligence, smart cities, and digital twin technologies. It also provides relevant insights for emergency response professionals and policymakers seeking to leverage data-driven systems to improve firefighter safety and operational decision-making.

The remainder of this paper is organized as follows. Section 2 presents the research methodology, including the bibliometric and content analysis approach, data sources, and study selection process. Section 3 discusses the results of the analysis, including publication trends, thematic research clusters, sensing technologies, artificial intelligence methods, and digital twin architectures for firefighter safety. Section 4 highlights key technological gaps and emerging research opportunities for advancing AI-driven digital twin systems. Finally, Section 5 concludes the study by summarizing the main findings and outlining directions for future research.

2. Research Approach and Knowledge Mapping Method

2.1. Research Design and Analytical Approach

This review adopts a combined bibliometric and thematic analysis approach to examine the evolving technological landscape of AI-driven digital twins for predicting firefighters' environmental and physiological risks (see Figure 1). The analytical framework integrates bibliometric visualization techniques with qualitative synthesis to identify dominant technological themes, emerging research directions, and conceptual relationships across sensing technologies, artificial intelligence models, cyber-physical systems, and digital twin architectures relevant to firefighter safety applications. The analytical framework adopted in this study was developed through an iterative and systematic process informed by both prior literature and the study's research objectives. Initial framework categories were derived from established bibliometric and technology-mapping approaches and refined through repeated examination of the selected studies to ensure alignment with the technological characteristics of sensing systems, artificial intelligence models, and digital twin architectures [24,25].

To minimize potential bias from the use of a predefined framework, several measures were implemented. First, the study followed a PRISMA-based systematic review process to ensure transparent and reproducible study selection [26,27]. Second, the coding framework was iteratively refined during the analysis to reflect emerging themes rather than imposing rigid predefined categories [20,28,29]. Third, to ensure consistency and reduce subjective bias, the coding process involved iterative cross-checking of article classifications across multiple rounds of review. This process was used to verify that each study was appropriately categorized based on its primary technological contributions. Finally, the integration of quantitative bibliometric analysis with qualitative content analysis provided methodological triangulation, enhancing the robustness and objectivity of the findings.

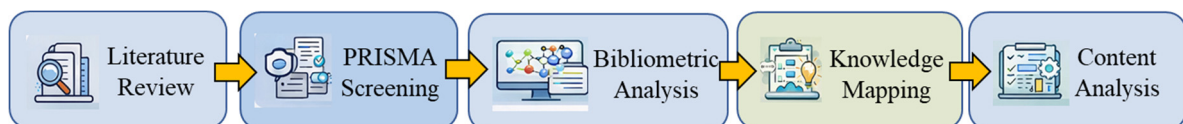


Figure 1. Overview of the Review and Knowledge Mapping Approach.

To guide the review, an initial conceptual framework describing the technological ecosystem of AI-enabled firefighter digital twin systems was developed (see Figure 2). This framework provides a structured representation of the relationships among sensing infrastructures, predictive analytics, communication systems, and decision-support environments within next-generation firefighter monitoring systems.

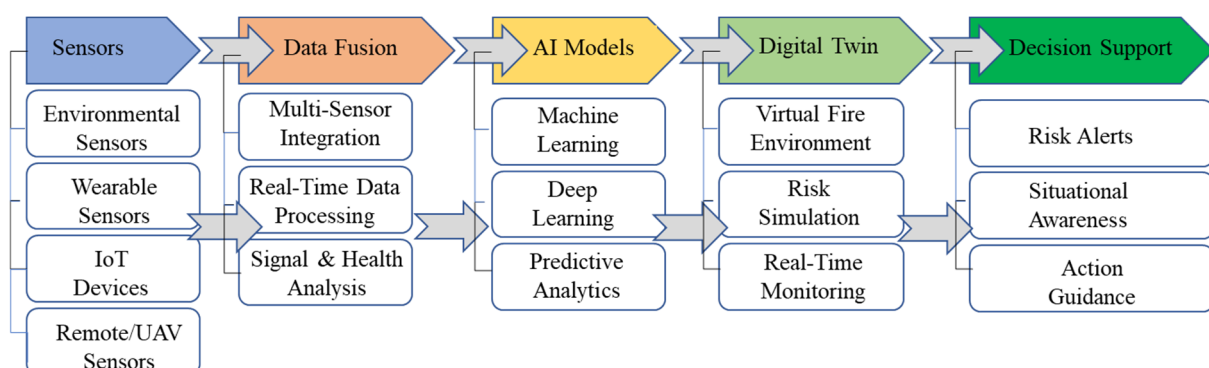


Figure 2. Conceptual Framework of the Technology Landscape for an AI-driven Digital Twin for Firefighter Risk Prediction (Authors' Design).

Bibliometric and scientometric methods are widely used to examine the intellectual structure, publication trends, and thematic evolution of emerging research domains through quantitative analysis of large bodies of scholarly literature [24,25]. These approaches enable researchers to identify dominant research clusters, collaboration networks, and technological trajectories within interdisciplinary fields where traditional narrative reviews may be insufficient for capturing the complexity of research developments [30]. Previous studies have successfully applied bibliometric and content analysis techniques to investigate emerging topics such as digital twins, artificial intelligence applications, and smart city technologies [24,25,31]. In the context of safety-critical domains, these methods have also been used to map research trends in disaster management, digital twins for infrastructure resilience, and AI-enabled monitoring systems, providing valuable insights into technological gaps and future research opportunities [20,28,29]. The combination of bibliometric mapping and qualitative content analysis enables both quantitative exploration of research trends and in-depth examination of technological characteristics across the literature. This integrated methodological approach provides a comprehensive understanding of how sensing technologies, artificial intelligence models, and digital twin systems are evolving to support firefighter safety and decision-making.

2.2. Data Source and Database Selection

Relevant literature on digital twins, artificial intelligence, sensing technologies, cyber-physical systems, and firefighter safety applications was primarily identified in the Web of Science Core Collection database [32]. The database was selected because of its broad coverage of engineering, smart systems, artificial intelligence, and safety-related research, as well as its compatibility with bibliometric visualization tools such as VOSviewer v. 1.6.20. The review focused on peer-reviewed studies discussing sensing infrastructures, predictive analytics, digital twin systems, emergency-response technologies, and firefighter monitoring applications [20,25,31].

2.3. Search Strategy

The literature examined in this review was identified through a structured keyword-based search strategy targeting digital twins, artificial intelligence, sensing technologies, wearable systems, firefighter safety, emergency response, predictive analytics, and real-time monitoring systems (see Figure 3). Emphasis was placed on studies discussing the integration of sensing infrastructures, AI-enabled monitoring systems, and digital twin architectures for safety-critical applications. The search query was applied in the Web of Science advanced search interface. The search was limited to publications between 2010 and 2025, reflecting the period during which digital twin technologies and AI-driven sensing systems have experienced significant development.

Search Query:

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("digital twin*" OR "AI-enabled digital twin*" OR "AI-driven digital twin*" OR "cyber-
physical system*" OR "virtual twin*" OR "intelligent digital twin*")
AND
("artificial intelligence" OR "machine learning" OR "deep learning" OR "data-driven
model*" OR "predictive model*" OR "AI")
AND
("sensor*" OR "wearable*" OR "physiological monitor*" OR "biometric*" OR
"environmental sensor*" OR "thermal sensor*" OR "gas sensor*" OR "biosensor*" OR "IoT
sensor*")
AND
("firefighter*" OR "firefighting" OR "emergency responder*" OR "first responder*" OR "fire
service")
AND
("real-time" OR "risk prediction" OR "risk assessment" OR "decision support" OR
"situational awareness" OR "safety monitoring" OR "hazard detection")

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Figure 3. Search query applied in the Web of Science.

Note: The asterisk (*) represents an operator used in the search query to capture multiple word variations (e.g., “digital twin*” includes “digital twin” and “digital twins”).

2.4. Inclusion and Exclusion Criteria

The inclusion criteria for this review focused on peer-reviewed journal articles and conference proceedings that explicitly addressed digital twins, artificial intelligence, sensing technologies, cyber-physical systems, and firefighter safety or emergency response applications. Studies were included if they demonstrated the integration of sensing systems with AI-driven analytics or digital twin frameworks for real-time monitoring, prediction, or decision support in safety-critical environments. Exclusion criteria were applied to remove studies that (1) focused solely on theoretical modeling without practical implementation or validation, (2) addressed unrelated domains without relevance to safety monitoring or emergency response, (3) lacked integration of sensing, AI, or digital twin components, or (4) were non-peer-reviewed sources such as reports, editorials, or abstracts without full-text availability.

2.5. Study Selection and PRISMA Procedure

The study selection process followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework to ensure transparency and reproducibility [26]. The literature search initially identified 40 records from the Web of Science Core Collection database. After removing duplicates (5 unique records), titles and abstracts were screened to exclude irrelevant studies, resulting in 35 articles for full-text review. Following a detailed eligibility assessment against predefined inclusion and exclusion criteria, a final set of 23 relevant studies was selected for bibliometric and content analyses. A PRISMA flow diagram illustrating the identification, screening, eligibility, and inclusion stages is shown in Figure 4.

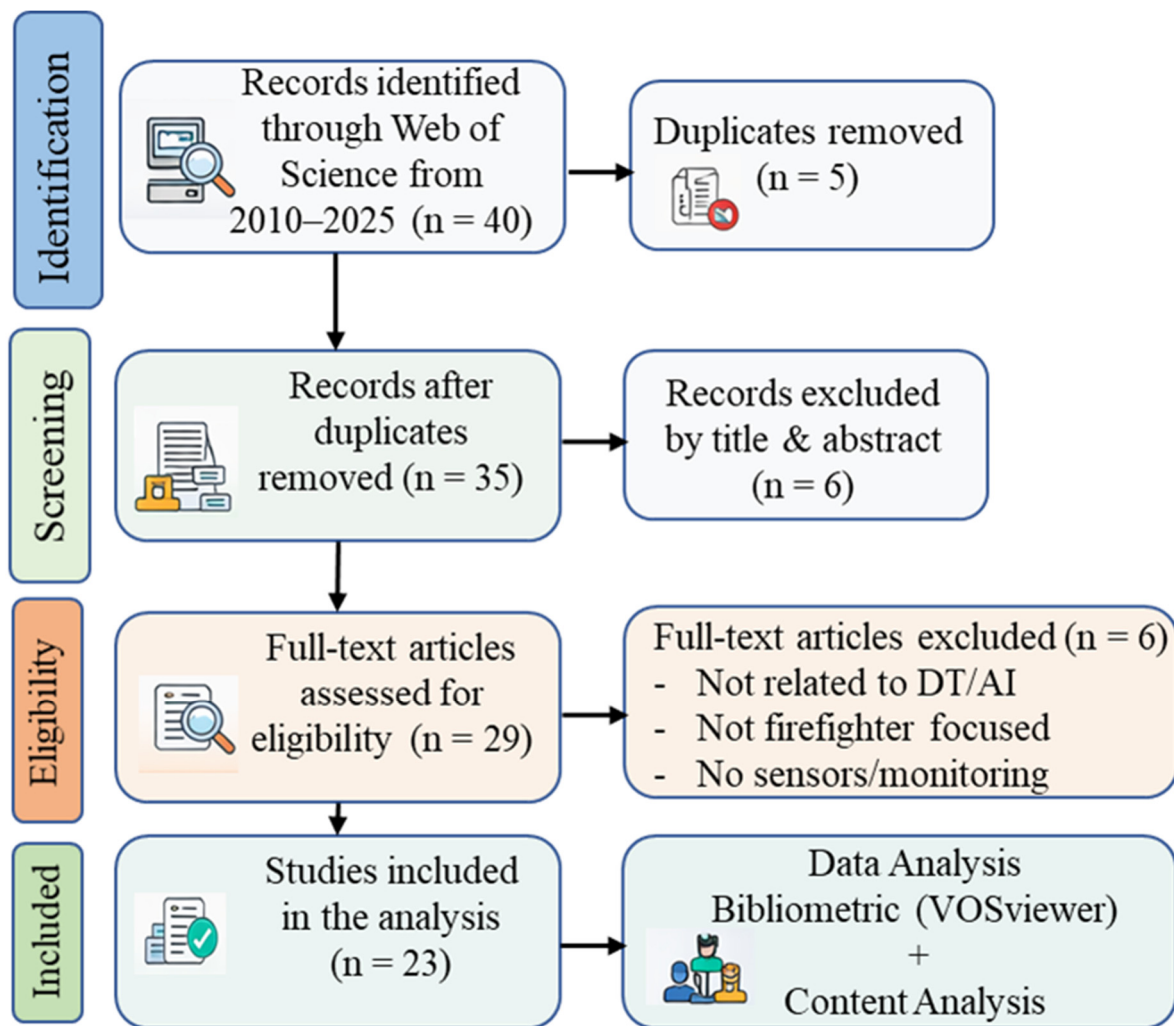


Figure 4. PRISMA Workflow used in research.

2.6. Bibliometric Analysis and Visualization

Bibliometric visualization techniques were used to examine research trends, thematic relationships, and emerging technological domains related to AI-driven digital twins for firefighter safety. Citation metadata and keyword information from the reviewed literature were analyzed using VOSviewer to generate keyword co-occurrence networks and thematic visualization maps [31,33]. These analyses supported the identification of dominant technological themes in firefighter monitoring environments, including sensing systems, predictive analytics, cyber–physical infrastructures, and digital twin architectures.

2.7. Thematic Technology Analysis

In addition to bibliometric visualization, a thematic analysis was conducted to examine the technological characteristics of AI-driven firefighter digital twin systems discussed across the literature [24,34]. Particular attention was given to integrating environmental monitoring systems, wearable physiological sensing platforms, predictive AI models, and cyber–physical infrastructures into firefighter safety applications.

3. Technological Landscape of AI-Driven Firefighter Digital Twin Systems

This results section examines the evolving technological landscape of AI-driven digital twin systems for predicting firefighter environmental and physiological risks. The discussion synthesizes emerging research on sensing technologies, artificial intelligence models, cyber-physical infrastructures, predictive analytics, and digital twin architectures that support firefighter safety and emergency-response operations. In addition, the section highlights dominant technological themes, interdisciplinary research directions, and emerging opportunities for developing next-generation intelligent firefighter monitoring and decision-support systems.

3.1. Evolution of Research Activity and Interdisciplinary Contributions

The literature on AI-driven digital twins for predicting firefighters' environmental and physiological risks has grown significantly in recent years, reflecting increasing academic and technological interest in intelligent safety-monitoring systems for high-risk operational environments (see Figure 5). The quantitative analysis of the selected literature reveals clear trends in the evolution of research on AI-driven digital twins for firefighter safety. A total of 40 records were initially identified, with 23 studies meeting the final inclusion criteria after screening. Figure 5 illustrates the progressive growth of publications and citation impact in the literature on AI-driven digital twins for environmental and physiological risk prediction between 2020 and 2025. Even though the Web of Science search covered 2010 to 2025, it returned only publications from 2020 to 2025. The results show a gradual increase in scholarly output over the observed period, indicating growing academic interest in integrating sensing technologies, artificial intelligence, and digital twin platforms for safety-critical environments such as firefighting. The number of publications was relatively low in the early stage, with only one publication (68 citations) recorded in 2020 and none in 2021, reflecting the nascent stage of research in this domain. A notable increase occurred in 2022, when the number of publications rose to 6, accompanied by a sharp increase in citations (414), suggesting that foundational studies published during this period significantly influenced subsequent research. Although publication and citation counts (5 publications, 390 citations) declined temporarily in 2023, they rebounded strongly in 2024, indicating renewed research momentum and expanding interdisciplinary attention to digital twin-enabled safety monitoring systems.

The highest research activity is observed in 2025, with approximately ten publications and the highest citation count (569 citations), demonstrating both increased research productivity and growing recognition of the field's importance. The steady rise in citations over time indicates that earlier publications are gaining influence and serving as key references for emerging studies. The trend suggests that AI-enabled digital twins, combined with sensor technologies and predictive analytics, are becoming an increasingly important research area, particularly for applications requiring real-time situational awareness, risk prediction, and decision support in hazardous operational environments. This upward trajectory highlights the expanding role of digital twin ecosystems in enhancing safety, resilience, and operational decision-making for emergency response systems.

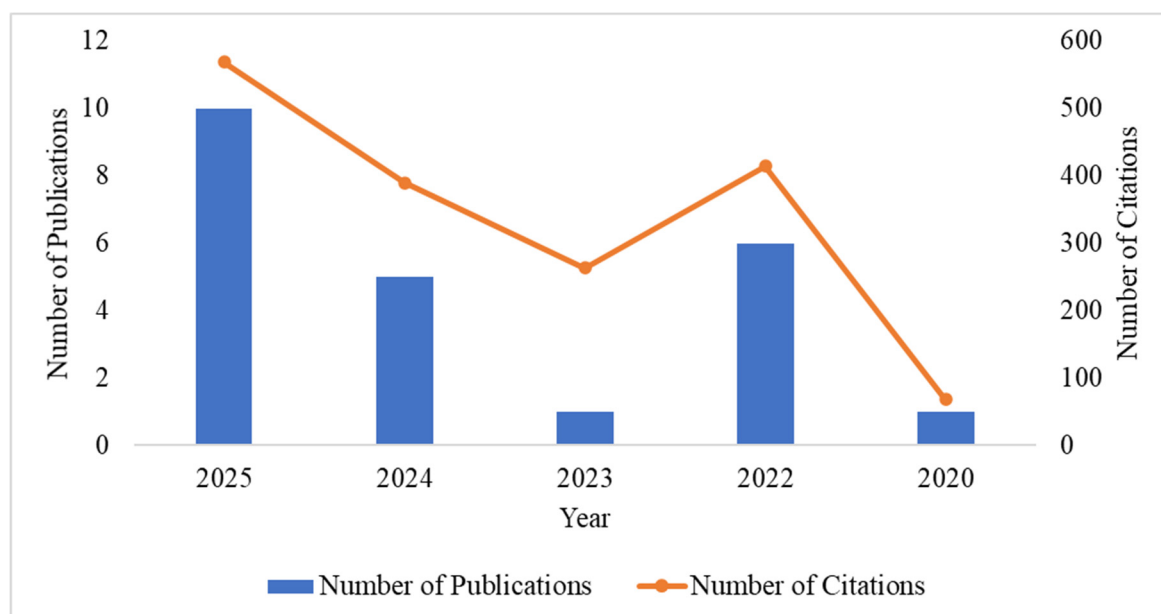


Figure 5. Evolution of Research Activity in AI-Driven Firefighter Digital Twin Systems.

The reviewed studies are distributed across a broad range of interdisciplinary journals spanning sensing technologies, artificial intelligence, cyber–physical systems, smart infrastructure, disaster resilience, and built-environment applications (see Figure 6). The journal *Sensors* emerged as one of the leading outlets in the field, highlighting the foundational role of sensing technologies in enabling real-time monitoring and data acquisition in digital twin environments. Similarly, journals focusing on disaster resilience and emergency management demonstrate the growing integration of digital twin technologies into safety-critical operational systems and disaster-response research.

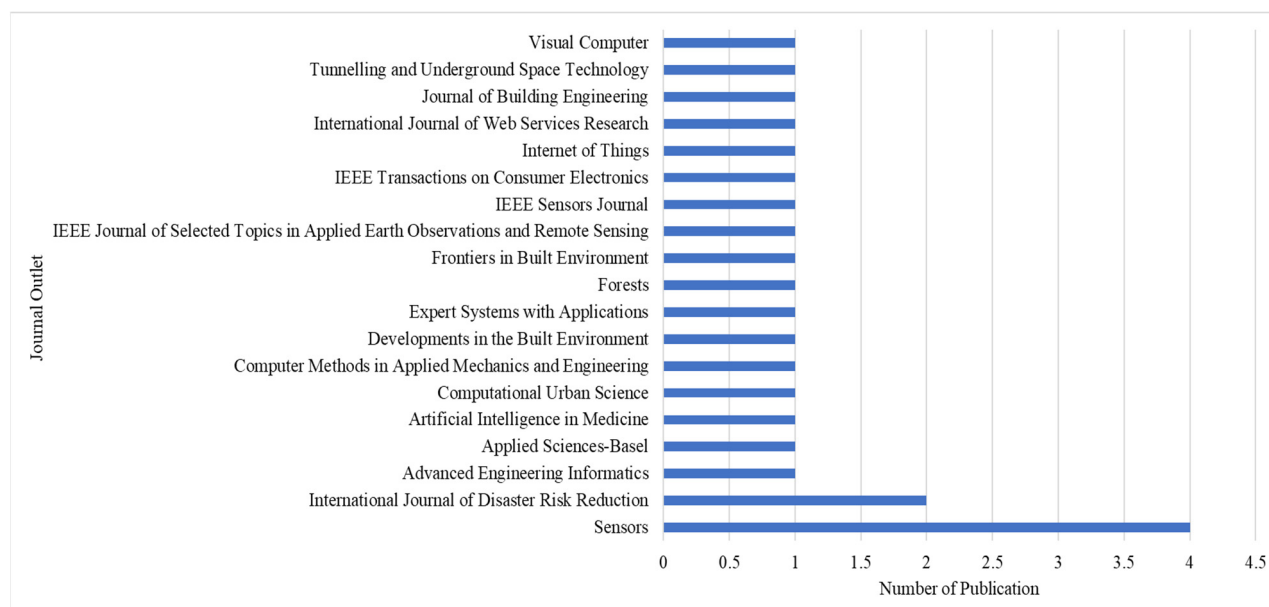


Figure 6. Interdisciplinary Distribution of Research Publications.

The diversity of publication outlets further demonstrates the interdisciplinary nature of AI-driven firefighter digital twin research. Contributions from journals specializing in artificial intelligence, Internet of Things systems, cyber–physical infrastructures, engineering informatics, healthcare analytics, and smart environments illustrate how the field increasingly combines sensing networks, predictive analytics, digital simulations, and

intelligent monitoring systems to support environmental and physiological risk prediction in hazardous operational contexts. This interdisciplinary convergence reflects the transition from isolated monitoring technologies to integrated, intelligent digital twin ecosystems designed to support real-time firefighter safety and emergency response decision-making.

The comparative analysis presented in Table 1 highlights key differences and similarities among representative studies in sensing technologies, artificial intelligence methods, and digital twin implementations. Most studies demonstrate strong capabilities in environmental monitoring using temperature, gas, and thermal imaging sensors; however, fewer systems integrate physiological monitoring for comprehensive firefighter safety assessment. In terms of artificial intelligence, deep learning models such as CNNs and LSTMs are widely used for spatial and temporal prediction tasks, while hybrid models are emerging to improve predictive performance. Additionally, while many digital twin systems support real-time monitoring and simulation, only a limited number provide fully integrated decision-support capabilities. This comparison underscores the need for unified, multimodal digital twin systems that combine sensing, predictive analytics, and operational decision support.

Table 1. Comparative analysis of AI-driven digital twin systems for firefighter safety.

Work	Domain	Digital Twin Type	Sensor Type	AI Modeling Method	Nature of Real-Time	Key Contribution
[35]	Industrial Cyber-Physical Systems (CPS)	Hybrid/Conceptual Digital Twin	Wireless Sensor Networks (WSNs); IoT devices	Machine Learning & Hybrid AI	Near real-time/quasi real-time	Three-layer framework (Data Acquisition, Fusion, Analytics)
[36]	Smart Monitoring Systems	Embedded Digital Twin	Multimodal IoT Sensors	Deep Learning	Full Real-time data acquisition	Intelligent monitoring architecture
[37]	Smart Healthcare CPS	Conceptual/System-level Digital Twin	Biomedical & IoT Sensors	Machine Learning & AI	Real-time and near real-time monitoring	Multi-layer MCPS architecture
[38]	Smart Infrastructure	Infrastructure Digital Twin	Environmental sensors	Machine Learning (multi-model)	Real-time and near real-time monitoring	GUIDE2FR platform: Integrated digital twin platform
[39]	Disaster Monitoring	Hybrid environmental & regional digital twin	Environmental IoT sensors	Deep Learning (multi-model)	Real-time hazard monitoring	Smart disaster monitoring system
[40]	Disaster Management, Wildfire Simulation, Smart Disaster Response	Hybrid disaster digital twin	IoT-based environmental sensing	Hybrid AI	Real-time monitoring; adaptive prediction	Proposed similarity-based hybrid digital twin architecture
[41]	Disaster Management, Wildfire Simulation, Large-Scale Environmental Systems	Distributed disaster digital twin	IoT environmental sensing	CNN-based machine learning	Near real-time/accelerated prediction	Proposed semantic data-driven distributed DT framework
[42]	Smart Buildings, Fire Safety Engineering, Urban Resilience, Disaster Management	AIoT-enabled building fire digital twin	IoT wireless sensor network	Hybrid deep learning	Real-time & predictive forecast	Proposed AIoT-integrated digital twin system
[43]	Tunnel Engineering, Fire Safety, Smart Infrastructure, Intelligent Transportation Systems	AIoT-enabled tunnel digital twin	Wireless Sensor Networks (WSN), thermocouples, CCTV cameras, environmental sensors (temperature, smoke, gas), IoT communication	Transformer-based deep learning model	Real-time monitoring; prediction; visualization	Proposed AIoT-integrated digital twin framework
[44]	Fire Safety	Fire Risk Digital Twin	Multi-sensor system: smoke sensors, temperature sensors, CCTV cameras	Transformer & CNN hybrid deep learning model	Real-time risk prediction	Proposed AIoT-enabled digital twin framework

[45]	Smart Fire Systems	Building a fire digital twin (AIoT-enabled cyber-physical system)	IoT fire sensors	ConvLSTM (Convolutional Long Short-Term Memory)	Real-time monitoring	Intelligent fire monitoring network
[46]	Disaster Management	Conceptual building-level digital twin (event-driven, AI-integrated)	Multi-modal IoT sensors: temperature, heat flux, gas sensors, CCTV/video, fire alarm systems	Data-driven AI/ML	Real-time forecasting	Proposed Critical Event Library & AI-driven Digital Twin Framework
[47]	Smart Healthcare, Digital Health, Smart Environments, IoMT	Human-centric digital twin	Wearable & ambient sensors	AI/ML-driven health analytics	Continuous real-time monitoring & adaptive feedback	Proposed Sensor-driven Digital Twin Framework & Intelligent Connectivity Framework
[48]	Smart Cities, Urban Resilience, Fire & Smoke Management, Disaster Management	City-scale urban digital twin	Multi-source sensing: air quality sensors (PM2.5), meteorological data, fire incident reports, satellite data, GIS/3D building data, UAV	Hybrid AI	Near real-time & predictive	Proposed FireCom platform—a real-time fire tracking dashboard
[49]	Fire Science, Wildfire Modeling, Emergency Response	Adaptive digital twin (environment-level fire propagation)	Multi-source (conceptual integration): Cameras, UAVs, Sensors	Machine learning	Near real-time adaptive simulation	Proposed adaptive digital twin framework
[50]	Multi-sector Safety Management	Hybrid digital twin (system-level, cross-sector, scenario-based simulation)	Multi-modal sensors: IoT sensors (environmental, equipment), Wearables (physiological monitoring), CCTV/computer vision, GPS, RFID, BLE, Smart meters	AI-driven analytics ecosystem	Real-time & predictive (proactive safety management) enabled by IoT and AI integration.	Proposed Safety 4.0 framework
[51]	Smart Forestry/Environmental Monitoring/Climate & Fire Management	Conceptual & Emerging Forest Digital Twin	Environmental sensors (temperature, humidity, gas, CO ₂), remote sensing (satellites, drones), microclimate sensors, LiDAR	Machine Learning, hybrid AI-IoT models, predictive analytics, time-series models	Near real-time monitoring and prediction	Integrated IoT-AI-Digital Twin ecosystem for forest monitoring
[52]	Smart Safety Systems	Cognitive Digital Twin (CDT) built on BIM-GIS integration	GIS	AI & ML (future integration)	Near real-time to future real-time CDT	Proposed BIM-GIS AMS platform (GeoBIM-based)
[53]	Smart Cities/Emergency Response/First Responders	Human-Centric Digital Twin	Physiological sensors, Environmental sensors, IoT & smart city infrastructure sensors	Hybrid AI (Ensemble Learning & Reasoning)	Near real-time	NGFR SmartHub (AI-enabled platform)
[54]	Smart Cities/Urban Flood Management/Disaster Resilience	City-Scale Digital Twin	Multi-sensor networks: Hydrological, Meteorological sensors, Remote sensing	Machine learning (RF, SVM, XGBoost), Deep learning (CNN, LSTM)	Real-time monitoring	AI-Assisted Digital Twin Framework via Intranet
[55]	Fire Safety/Tunnel Infrastructure/Emergency Response	Infrastructure-Level Digital Twin (Tunnel Fire Twin)	Temperature sensors (fiber optic heat detection), Smoke sensors, Flame detection, Sensor networks	Deep learning: LSTM	Real-time monitoring	Smart Firefighting Digital Twin System (SFDT)
[56]	Wildfire Monitoring/Forest Surveillance/Emergency Response	Environmental Monitoring Digital Twin (Pre-Digital Twin/Sensing-Driven System)	UAV-mounted RGB cameras, Thermal/Infrared sensors, and multispectral imagery	Deep Learning (Computer Vision)	Real-time UAV data capture, processing, and visualization	UAV-Based Intelligent Monitoring System
[57]	Wildfire Emergency Response/Disaster Management/Swarm Robotics	Integrated System-Level Digital Twin	RGB, thermal, infrared cameras, LiDAR sensors, Atmospheric sensors, IMU, and navigation sensors	Machine Learning/Deep Learning, Swarm Intelligence	Real-time prediction	Human-Centered UAV Swarm System

3.2. Technological Domains and Conceptual Architecture of AI-Driven Firefighter Digital Twin Systems

Current research on AI-driven digital twins for predicting firefighters' environmental and physiological risks has evolved into several interconnected technological domains that collectively support intelligent emergency-response ecosystems (see Figure 7). The literature demonstrates increasing integration among sensing technologies, artificial intelligence, cyber-physical systems, predictive analytics, and digital twin architectures to support real-time situational awareness, hazard forecasting, and operational decision-making in high-risk firefighting environments. These technological domains reveal the transition from isolated monitoring systems to integrated digital twin ecosystems that support proactive firefighter safety management and emergency-response resilience.

Figure 7 illustrates the conceptual relationships among the field's dominant technological themes. The reviewed literature highlights four major interconnected domains: AI-enabled fire risk modeling, sensor data acquisition systems, IoT-enabled digital infrastructures, and predictive analytics with disaster simulation capabilities. Together, these domains form a layered technological ecosystem in which sensing systems provide real-time environmental and physiological data, communication infrastructure enables data transmission and integration, artificial intelligence models generate predictive insights, and digital twin simulations support operational planning and emergency response decision-making.

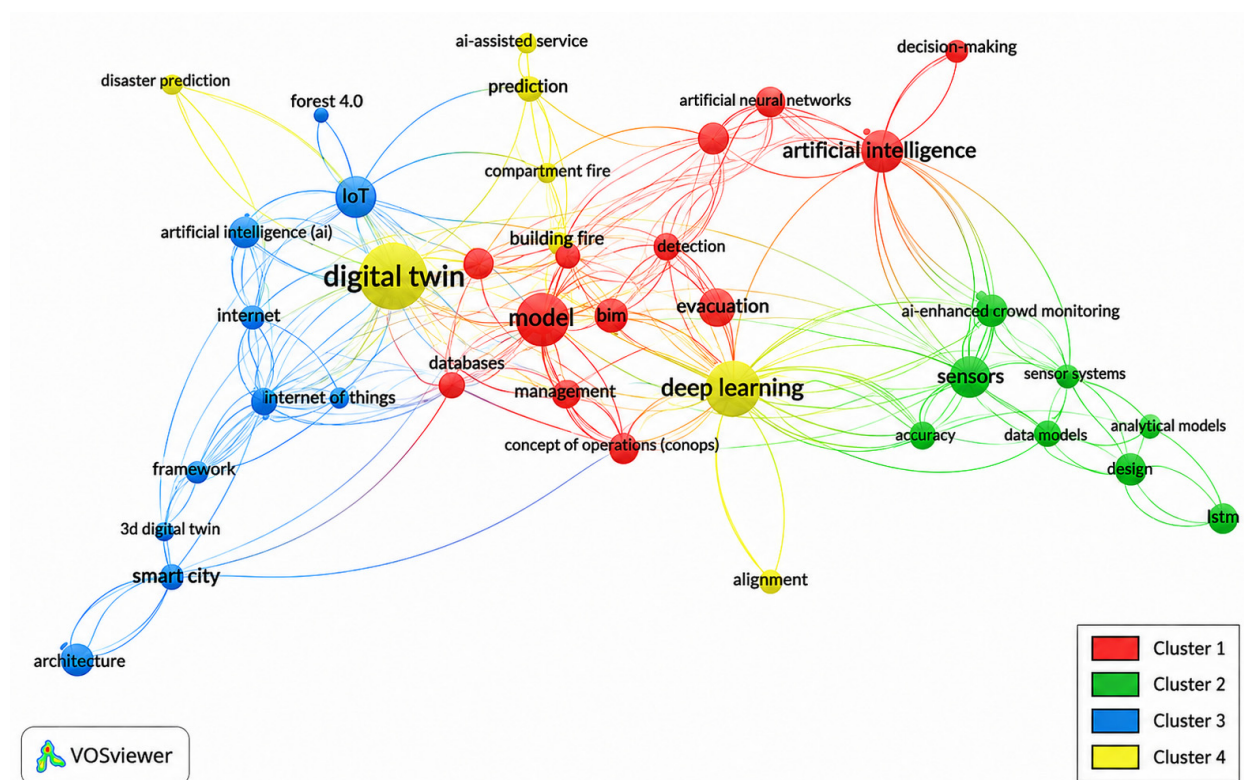


Figure 7. Conceptual relationships among the dominant technological themes.

The numbering of clusters presented in Figure 7 is based on the output from VOSviewer, which assigns cluster labels (Cluster 1–4) according to algorithmic grouping rather than a conceptual hierarchy or workflow sequence. As a result, the cluster numbering does not necessarily reflect the functional or logical relationships among the technological components.

To improve interpretability, Figure 8 reorganizes these clusters according to a functional architecture of digital twin systems, where Cluster 2 (sensing systems) represents the data acquisition layer, followed by Cluster 3 (IoT infrastructure) for data transmission and integration, Cluster 1 (AI models) for data processing and predictive analytics, and Cluster 4 (digital twin simulation) for decision support. This layered representation reflects the logical flow of information from sensing to decision-making in AI-driven digital twin systems.

The first technological domain focuses on AI-enabled fire risk modeling and intelligent decision support systems for emergency response operations. Research within this domain increasingly integrates machine learning, deep learning, and digital twin simulations to support real-time fire prediction, hazard assessment, and operational coordination [7,39,42,44,45,48–50,54,55]. Current developments demonstrate how AI algorithms can be integrated into digital twin environments to simulate fire dynamics, assess risk conditions, and support emergency response planning. For example, Tang et al. [44] developed a digital twin framework that uses deep learning and building-fire simulation models to improve fire prediction and emergency response strategies. Similarly, Xie et al. [42] integrated smart building and IoT data into predictive monitoring systems to improve situational awareness during emergency operations. These developments indicate that AI-driven fire modeling systems are becoming increasingly important for evacuation planning, disaster prediction, and real-time operational coordination in safety-critical environments.

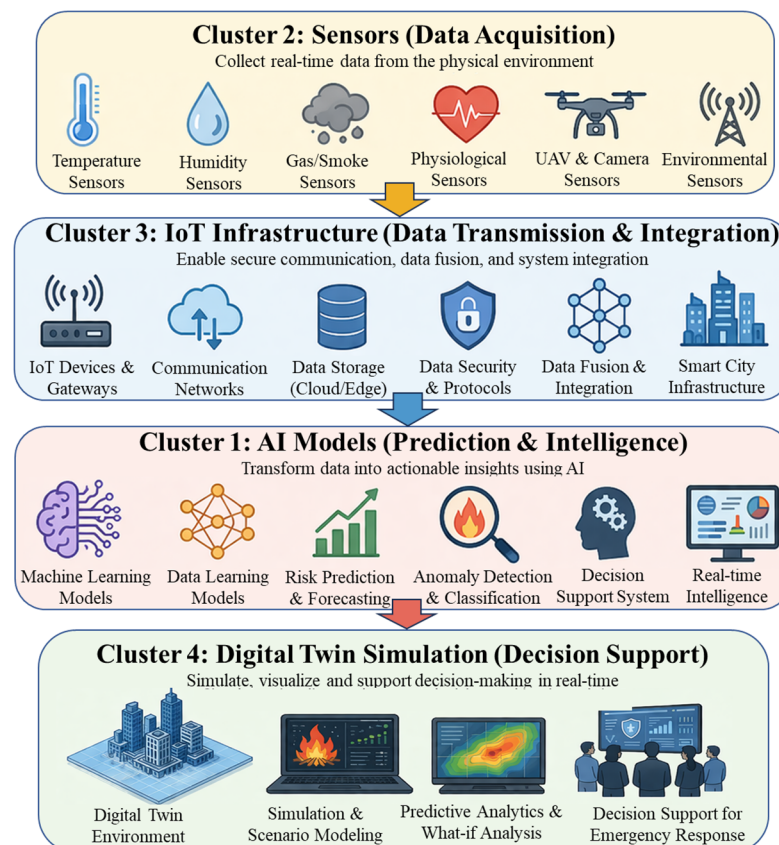


Figure 8. Conceptual Architecture of AI-Driven Sensing Technologies and Digital Twin Ecosystems for Firefighter Safety.

The second technological domain centers on sensor data acquisition systems and cyber-physical monitoring infrastructures that enable continuous real-time data collection within firefighter digital twin environments [35,36,38,47,56]. Research in this area

highlights the critical role of environmental sensors, wearable monitoring devices, wireless sensor networks, and edge-enabled cyber–physical systems in supporting intelligent digital twin ecosystems. These systems enable continuous monitoring of environmental conditions, physiological responses, and operational activities during firefighting operations. For instance, Gutiérrez-Rojas et al. [35] developed a wireless sensor network framework for cyber–physical systems that uses explainable artificial intelligence to detect anomalies in industrial environments. Their work demonstrates how sensor-generated data streams can support predictive analytics and real-time operational monitoring. Similarly, Hu et al. [36] proposed an AI-enhanced cyber–physical monitoring architecture that integrates IoT sensors, cameras, and edge computing to support real-time threat detection and situational awareness. These developments illustrate how sensing infrastructures increasingly serve as the foundational layer for intelligent firefighter digital twin systems.

The third technological domain emphasizes IoT-enabled digital infrastructures, smart-city integration, and distributed communication architectures that support large-scale environmental monitoring and emergency-response coordination [37,40,41,51–53]. Research within this area demonstrates how IoT frameworks, cloud computing systems, cyber–physical infrastructures, and data-fusion platforms enable the integration of heterogeneous environmental and operational datasets within digital twin ecosystems. Studies increasingly explore the role of smart-city infrastructure and urban digital twins in supporting environmental monitoring, disaster resilience, and emergency response management. For example, Shaikh et al. [37] examined cyber–physical architectures in healthcare and smart-city environments, emphasizing the importance of IoT communication networks, cloud platforms, and intelligent analytics for supporting real-time monitoring systems. The integration of smart infrastructure technologies with digital twin systems underscores the growing convergence between emergency response systems and intelligent urban environments [37,40,41,51–53].

The fourth technological domain focuses on predictive analytics, disaster simulation, and AI-driven forecasting systems designed to support proactive emergency-response decision-making [42,43,48,57]. Research within this area increasingly combines digital twin simulations with machine learning, computer vision, remote sensing, and predictive modeling techniques to forecast hazardous conditions and improve operational planning. Emerging systems continuously update digital twin environments using real-time environmental data, enabling dynamic hazard prediction and adaptive operational coordination. For instance, Zhang et al. [43] developed deep learning-enabled digital twin systems capable of predicting tunnel fire behavior using integrated AI-IoT frameworks. Other studies explore the use of computer vision, object detection, image fusion, and remote sensing technologies to monitor wildfire spread, structural fire progression, and environmental hazard evolution [42,48,57]. These developments demonstrate how predictive analytics increasingly function as the analytical intelligence layer of firefighter digital twin ecosystems, transforming sensor data and simulation outputs into actionable operational insights. Altogether, these technological domains illustrate the emergence of integrated firefighter digital twin ecosystems in which sensing infrastructures, cyber–physical communication systems, predictive analytics, and intelligent decision-support environments operate as interconnected layers within next-generation emergency-response platforms. As shown in Figure 8, sensing systems serve as the foundational data-acquisition layer; communication infrastructure supports real-time data integration and transmission; artificial intelligence models provide predictive analytics and operational intelligence; and digital twin simulations enable dynamic decision support for firefighter safety and emergency response management.

3.3. Evolution of Early and Emerging Research Directions

Research on AI-enabled digital twins for predicting firefighters' environmental and physiological risks has evolved rapidly in recent years, reflecting broader technological advances in sensing infrastructure, cyber-physical systems, artificial intelligence, and intelligent emergency-response platforms. The progression of research themes within the field demonstrates a clear transition from foundational digital monitoring infrastructures to predictive, AI-driven digital twin ecosystems that support proactive firefighter safety management and operational decision-making in hazardous environments (see Figure 9).

Early developments in the field primarily focused on establishing Internet of Things (IoT) infrastructures, cyber-physical communication systems, and distributed sensing architectures to support real-time environmental monitoring [7,37,40,41,52]. Initial studies focused on developing communication networks, data-fusion frameworks, cloud-enabled infrastructures, and smart-city monitoring systems to support digital data acquisition and real-time situational awareness in safety-critical environments. For example, Shaikh et al. [37] explored cyber-physical architectures that integrate IoT sensors, cloud computing, and machine intelligence to support intelligent monitoring and decision-support systems in smart environments. These foundational studies established the technological infrastructure necessary to integrate sensor networks, communication systems, and digital twin platforms into emergency-response ecosystems.

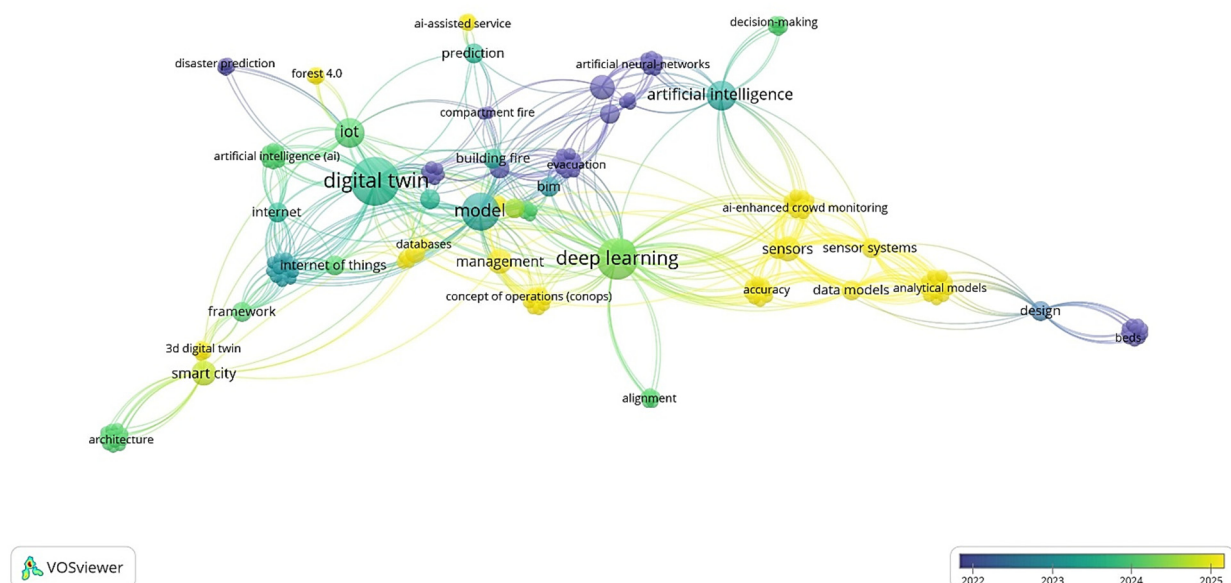


Figure 9. Evolution of Early and Emerging Research Directions in AI-Driven Firefighter Digital Twin Systems.

As the field matured, research increasingly shifted toward integrating artificial intelligence models into dynamic digital twin environments that support real-time operational monitoring and adaptive decision-making. During this transitional phase, digital twin architectures emerged as a central technological framework connecting sensing infrastructures, predictive analytics, and cyber-physical systems [47,50,53,56]. Research during this period focused on combining sensor networks, IoT communication systems, machine learning algorithms, and real-time simulation models to create intelligent monitoring environments that continuously update operational conditions and support situational awareness. For instance, Shaposhnyk et al. [53] developed a next-generation computing and communication framework for first responders in smart cities that integrates cyber-physical systems, real-time data exchange, and intelligent monitoring to enhance

situational awareness and operational coordination during emergency response scenarios. Similarly, Adibi et al. [47] demonstrated how sensor-enabled digital twin systems could support intelligent monitoring, system optimization, and data-driven decision-making within dynamic smart environments.

More recent developments increasingly emphasize predictive analytics, AI-enhanced monitoring systems, and intelligent digital twin environments capable of forecasting hazardous conditions before they escalate into critical incidents [35,36,38,39,42,44,48,54,57]. Current research demonstrates growing interest in deep learning, edge-enabled analytics, explainable artificial intelligence, and data-driven risk-prediction systems to support proactive firefighter safety management. These emerging systems integrate environmental sensing, physiological monitoring, predictive modeling, and real-time simulation to improve hazard forecasting and operational decision-making in complex firefighting environments. For example, Hu et al. [36] proposed an AI-enhanced cyber-physical monitoring framework that integrates IoT sensors, edge computing, and deep learning models to enable real-time threat detection and situational awareness in smart environments. Similarly, Alvaro et al. [38] developed a digital twin monitoring platform for firefighter training towers that integrates sensor data and predictive modeling to improve situational awareness during emergency scenarios. Gutiérrez-Rojas et al. [35] further demonstrated how explainable artificial intelligence integrated with wireless sensor networks can support anomaly detection and intelligent monitoring within cyber-physical systems.

Emerging interdisciplinary research directions increasingly combine computer vision, remote sensing, object detection, simulation modeling, and hybrid artificial intelligence techniques to enhance environmental monitoring and emergency-response planning [36,42,43,48,56]. In general, the evolution of research in this field can be divided into three major phases. The initial phase focused on establishing IoT infrastructures and cyber-physical communication systems for environmental monitoring and data acquisition. The second phase emphasized integrating digital twin architectures with artificial intelligence and sensor-driven monitoring platforms. The most recent phase highlights the emergence of predictive analytics, explainable AI, edge-enabled monitoring systems, and intelligent decision-support environments that enable proactive firefighter safety management and operational resilience. This progression illustrates how firefighter digital twin systems are evolving from infrastructure-oriented monitoring platforms toward intelligent cyber-physical ecosystems capable of supporting real-time hazard prediction, operational coordination, and adaptive emergency-response decision-making.

3.4. Sensing Technologies, Digital Twin Architectures, and Artificial Intelligence for Firefighter Safety Systems

Sensing technologies, digital twin architectures, and artificial intelligence collectively form the technological foundation of next-generation firefighter safety systems. These interconnected technologies enable continuous environmental monitoring, physiological assessment, predictive risk analysis, and real-time operational decision-making within hazardous firefighting environments. Current research increasingly demonstrates that integrated sensing infrastructures, cyber-physical systems, predictive analytics, and digital twin platforms can support intelligent emergency-response ecosystems that improve firefighter safety, situational awareness, and operational resilience (see Figures 10 and 11).

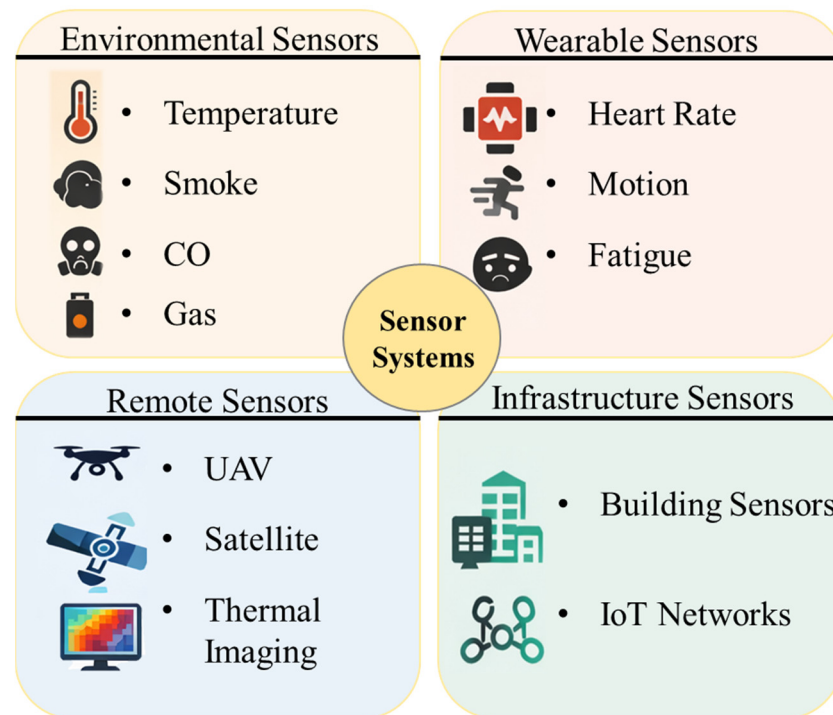


Figure 10. Sensing Technologies Supporting Firefighter Digital Twin Systems (Authors' Design).

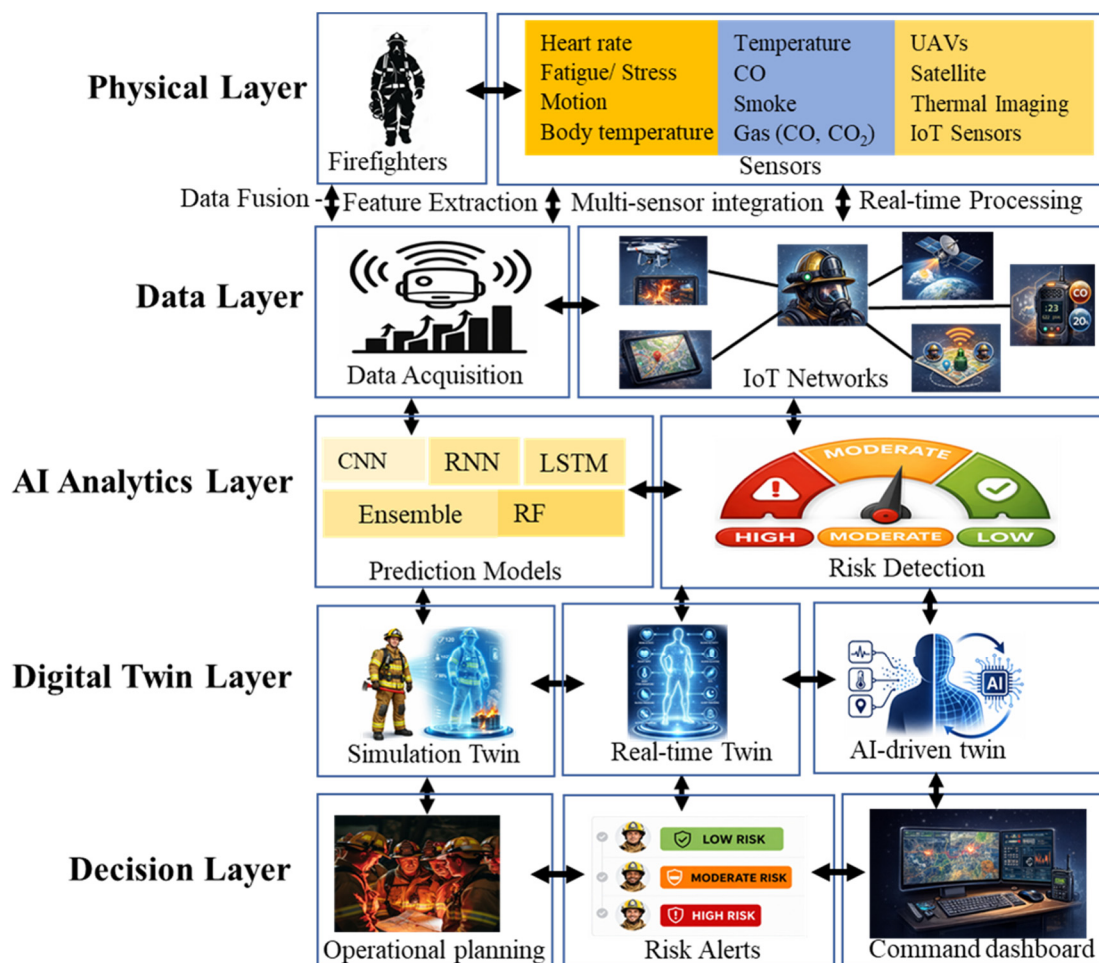


Figure 11. Conceptual Architecture of AI-Driven Digital Twin Systems for Firefighter Safety (Authors' Design).

3.4.1. Environmental Sensing Technologies for Hazard Monitoring

Environmental sensing systems are a foundational component of firefighter digital twin ecosystems. These technologies enable continuous monitoring of hazardous fire conditions, including extreme heat exposure, toxic gases, smoke density, structural instability, and wildfire dynamics. Current research increasingly integrates environmental sensing systems with digital twin platforms to support real-time situational awareness and predictive hazard forecasting within dynamic emergency-response environments [39,42,43,48,56,57].

Temperature-sensing technologies remain among the most widely implemented environmental monitoring tools in firefighter digital twin systems. Temperature sensors continuously track heat intensity and thermal variations within fire environments and are frequently integrated with digital twin simulations to model fire spread, heat propagation, and structural hazard evolution [42,43,48,58]. Smart fire-monitoring platforms increasingly combine temperature sensing with real-time simulation models and predictive analytics to improve hazard detection and operational coordination during emergency-response operations [59]. Similarly, wildfire digital twin systems integrate temperature monitoring with meteorological sensing and environmental data to support large-scale wildfire prediction and resource coordination [58].

Gas detection systems also play a critical role in firefighter monitoring environments. Carbon monoxide (CO) and carbon dioxide (CO₂) sensors are widely integrated into firefighter monitoring platforms to detect toxic combustion gases, oxygen depletion, and hazardous air-quality conditions during fire suppression activities [42,43,57,60]. Multi-sensor monitoring systems increasingly combine gas sensors with wearable sensing platforms to provide real-time alerts and predictive safety assessments during emergency operations [42,43,60]. These systems support intelligent monitoring frameworks that can identify dangerous environmental conditions before they escalate into life-threatening incidents.

Particulate matter sensing technologies have also become increasingly important within digital twin fire-monitoring systems. Fine particulate matter generated during combustion poses significant respiratory risks to firefighters and surrounding populations [42,48]. Current research explores integrating air-quality sensors, atmospheric monitoring systems, and urban digital twins to model smoke dispersion patterns and assess environmental exposure risks in densely populated environments [48]. These systems demonstrate how digital twin platforms can support both firefighter safety and broader urban disaster-management strategies.

Thermal imaging systems represent another important sensing technology increasingly integrated within firefighter digital twin environments [43,44,56]. Thermal imaging sensors provide spatial representations of heat distribution, enabling firefighters to identify hotspots, hidden fire sources, and structural hazards under low-visibility conditions. Current research demonstrates how thermal imaging data can be integrated with machine learning algorithms and digital twin simulations to dynamically update virtual fire environments and improve situational awareness during emergency-response operations [43,56].

Beyond conventional environmental sensing technologies, emerging firefighter digital twin systems increasingly incorporate remote sensing platforms, satellite monitoring systems, unmanned aerial vehicles (UAVs), humidity sensors, atmospheric pressure sensors, and wind-monitoring technologies [56–58]. The integration of ground-based sensing systems with remote sensing infrastructures enables digital twin platforms to capture the complex environmental dynamics that influence fire behavior across both urban and wildfire environments. These developments reflect the growing transition toward intelligent multi-layered sensing ecosystems capable of supporting large-scale environmental monitoring and adaptive emergency-response coordination.

3.4.2. Physiological Monitoring Technologies for Firefighter Health Assessment

In addition to environmental hazard monitoring described in Section 3.4.1, firefighter digital twin systems increasingly emphasize physiological monitoring technologies designed to assess firefighters' physical and cognitive conditions during emergency operations [47,53,57]. These sensing systems enable continuous monitoring of vital signs, workload levels, thermal stress, and fatigue, which may compromise firefighter safety and operational effectiveness.

Heart-rate monitoring systems remain among the most widely adopted physiological sensing technologies within firefighter monitoring platforms [47,53]. Wearable heart rate sensors enable digital twin systems to continuously monitor cardiovascular activity, workload intensity, and physiological stress responses during high-risk operations. Current research increasingly explores how heart-rate variability analysis and predictive AI models can identify early indicators of fatigue, overexertion, and physiological distress within firefighter digital twin environments [47,53].

Blood oxygen saturation (SpO₂) monitoring systems also represent an important physiological sensing capability integrated within firefighter monitoring frameworks. These sensors measure oxygen levels within the bloodstream and support the detection of hypoxia caused by smoke inhalation, toxic gas exposure, and oxygen depletion during emergency operations [47,53]. Current digital twin platforms increasingly integrate physiological monitoring systems with environmental sensing infrastructure to generate comprehensive representations of firefighters' health conditions in hazardous environments.

Skin temperature sensing technologies are similarly important for evaluating heat stress and thermal exposure during firefighting operations [47,53]. Firefighters frequently operate in environments with extreme temperatures that can cause heat exhaustion, dehydration, and heat stroke. Current research demonstrates how skin temperature monitoring integrated with environmental sensing and predictive analytics can support cumulative heat-exposure assessment and operational safety management [61].

Fatigue monitoring and cognitive workload assessment have emerged as important interdisciplinary research directions within firefighter digital twin systems. Advanced physiological monitoring frameworks increasingly combine heart-rate variability, movement patterns, biometric indicators, and behavioral analytics to detect fatigue, exhaustion, and reduced cognitive performance during emergency-response operations [47,53]. Artificial intelligence models are increasingly used to analyze physiological data streams and estimate workload conditions in real time, enabling intelligent digital twin systems capable of recommending operational adjustments and early intervention strategies [53].

Additional physiological sensing technologies reported across the literature include respiration sensors, electrocardiogram (ECG) systems, accelerometers, gyroscopes, magnetometers, inertial measurement units, and motion-tracking devices [12,53,57,60]. These technologies enable digital twin platforms to detect falls, abnormal movement patterns, physical incapacitation, and operational distress during firefighting activities. The integration of these physiological monitoring systems into digital twin ecosystems underscores the growing emphasis on human-centered firefighter safety systems that continuously evaluate environmental and physiological risk factors.

3.5. Digital Twin Architectures for Firefighter Monitoring and Emergency Response

Digital twin architectures can be more explicitly conceptualized as multi-layered cyber-physical systems consisting of four core components: (1) a data acquisition layer that captures real-time environmental and physiological data through sensing technologies, (2) a communication layer that enables data transmission via IoT and cyber-physical networks, (3) a data processing and analytics layer where artificial intelligence models perform predictive analysis and risk assessment, and (4) a virtual representation layer that

dynamically mirrors the physical environment and supports simulation and decision-making [48,61,62]. A key distinguishing feature of these architectures is the implementation of bidirectional data-flow mechanisms, in which real-time sensor data continuously updates the digital twin, while predictive outputs from the virtual model provide feedback to support operational decision-making [35,47,54,60]. This closed-loop interaction enables adaptive and responsive system behavior, differentiating digital twins from conventional simulation models.

Digital twin architectures serve as the integration layer that connects sensing technologies, artificial intelligence models, predictive analytics, and operational decision-support systems in firefighter safety environments [40,47]. These systems create dynamic virtual representations of physical environments that continuously fuse environmental conditions, firefighter physiological states, simulation outputs, and predictive AI models in real time [43,49]. By integrating sensing infrastructures with cyber-physical communication systems and intelligent analytics, digital twin platforms support hazard visualization, operational coordination, predictive simulation, and adaptive emergency-response decision-making [42,44].

Current research demonstrates several evolving categories of firefighter digital twin architectures, ranging from simulation-based training systems to real-time operational monitoring environments [38,45]. Many of these architectures adopt cyber-physical system frameworks in which environmental sensors, wearable devices, communication networks, and predictive analytics continuously update virtual operational models [37,41]. This continuous fusion between physical and digital environments enables digital twins to dynamically represent changes in fire behavior, environmental hazards, and firefighter health conditions [47,53].

3.5.1. Environmental Monitoring Through Digital Twins

Environmental monitoring digital twins increasingly integrate temperature sensing, gas detection systems, smoke-monitoring platforms, and predictive fire models to improve situational awareness during emergency operations [42,48]. Digital twin monitoring systems combine data from temperature sensors, gas detection devices, and environmental monitoring platforms to create a virtual representation of fire conditions within buildings or urban infrastructure [39,43]. These systems continuously update the digital model using real-time sensor inputs and predictive analytics to estimate fire spread and hazard exposure levels [44,48]. For example, digital twin-based fire monitoring systems have been proposed for smart environments, where sensor data from smoke detectors, temperature sensors, and other monitoring devices is transmitted to a virtual model that simulates fire dynamics and provides early warning alerts [59]. These systems demonstrate the ability of digital twins to support early hazard detection and improve situational awareness during emergency response operations [42,44].

3.5.2. Urban Digital Twin Platforms

Urban digital twin platforms extend these capabilities further by combining environmental monitoring systems with urban infrastructure models, evacuation simulations, smoke-dispersion analytics, and disaster-management systems [48,54]. These platforms combine real-time environmental monitoring data with digital representations of urban infrastructure to simulate fire spread, smoke dispersion, and evacuation dynamics [48,61]. By integrating urban data with fire behavior models, digital twins can support decision-making by predicting how fires may propagate across buildings, transportation systems, and critical infrastructure [43,54]. Studies on urban digital twin platforms highlight their potential to enhance emergency responders' situational awareness and predictive insights for managing large-scale fire incidents in complex urban environments [48,61].

3.5.3. Wildfire Digital Twin Systems

Similarly, wildfire digital twin systems increasingly integrate remote sensing platforms, satellite imagery, aerial monitoring technologies, meteorological sensing systems, and machine learning algorithms to forecast wildfire progression and support large-scale emergency coordination [56,57]. These digital twins continuously update fire models using environmental data such as temperature, wind speed, and vegetation conditions [57,58]. By combining machine learning algorithms with environmental monitoring data, wildfire digital twins enable emergency responders to assess fire risks and coordinate fire-fighting resources more effectively [57,58].

3.5.4. Human-Centered Digital Twins

Another important research direction involves human-centered digital twin systems capable of integrating firefighter physiological monitoring with environmental hazard assessment [47,53]. Wearable sensor technologies enable digital twin platforms to integrate physiological data, such as heart rate, oxygen saturation, and movement patterns, into the virtual representation of the firefighting environment [53]. This integration enables digital twins to monitor both environmental hazards and firefighter health conditions simultaneously [47,53]. Next-generation digital twin platforms designed for first responders incorporate artificial intelligence algorithms that analyze physiological sensor data to detect fatigue, stress, and other health risks [53].

3.5.5. Multi-Sensor Data Fusion in Digital Twin Systems

Current research also emphasizes the importance of multi-sensor data fusion within firefighter digital twin architectures [35,47]. Digital twin systems, as described in Section 3.5, often integrate heterogeneous data sources, including environmental sensors, wearable monitoring devices, remote sensing platforms, and simulation models [47,56]. Data fusion algorithms combine these diverse data streams to generate a comprehensive representation of fire incidents and operational conditions [35,54]. Multi-sensor data fusion systems designed for firefighter monitoring have demonstrated the ability to detect hazardous events, including firefighter falls, abnormal movements, and toxic gas exposure [60].

3.5.6. Digital Twin Simulation for Training and Preparedness

Digital twin simulation environments additionally play an important role in firefighter training, preparedness planning, and operational strategy evaluation [38,45]. Simulation-based firefighter digital twins replicate real-world fire conditions within controlled virtual environments, enabling responders to interact with dynamic hazard scenarios and predictive operational models. Machine learning algorithms embedded in these systems continuously improve simulation accuracy and optimize firefighting strategies using historical and real-time operational data [43,44].

In general, these developments demonstrate how digital twin architectures increasingly serve as intelligent operational ecosystems integrating sensing infrastructures, predictive analytics, cyber-physical communication systems, and real-time decision-support technologies. As sensing technologies and artificial intelligence continue to evolve, firefighter digital twins are expected to play an increasingly important role in improving firefighter safety, operational resilience, emergency preparedness, and intelligent disaster-response coordination.

3.6. Artificial Intelligence for Predictive Firefighter Digital Twin Systems

Artificial intelligence (AI) models represent the analytical engine of firefighter digital twin systems, transforming raw environmental and physiological sensor data into predictive insights that support operational decision-making and risk mitigation [42,44]. Current research increasingly integrates machine learning algorithms, deep learning architectures, predictive simulation models, and AI-enabled cyber-physical systems within firefighter digital twin environments to improve environmental risk prediction and firefighter safety monitoring [40,49]. Several categories of these AI techniques have been adopted to support fire risk prediction, environmental hazard detection, and firefighter health monitoring [39,43]. These approaches enable real-time hazard forecasting and dynamic risk assessment within complex fire environments [42,48].

3.6.1. Machine Learning Models for Firefighting Environments

Traditional machine learning algorithms, including Random Forest, Support Vector Machines (SVMs), and gradient-boosting methods such as XGBoost, are widely used for fire-risk classification, anomaly detection, and environmental hazard assessment [39,42]. These models are particularly useful for identifying patterns in multi-sensor data streams, including temperature, gas concentration, and smoke density measurements [42,43]. Machine learning-enabled digital twin systems increasingly support real-time environmental monitoring and intelligent operational decision-making within firefighting environments [59,61].

3.6.2. Deep Learning for Spatial Fire Detection

Deep learning architectures have further expanded the predictive capabilities of firefighter digital twin systems [43,44]. As discussed in Section 3.1, Convolutional Neural Networks (CNNs) are widely used for analyzing thermal imaging data, surveillance systems, remote sensing imagery, and computer vision applications associated with fire detection and environmental monitoring [44,56]. These models enable automated detection of fire hotspots, smoke propagation, structural hazards, and environmental anomalies, allowing digital twin environments to continuously update operational simulations and predictive fire models [41,43].

Recurrent Neural Networks (RNNs) and Long Short-Term Memory (LSTM) networks are increasingly applied to analyze temporal sensor data generated by firefighter monitoring systems [58]. Firefighter monitoring systems often generate continuous streams of physiological and environmental data, making temporal AI models essential for identifying emerging hazards or physiological stress patterns [47,53]. Current research demonstrates how LSTM-based predictive systems can estimate fire spread, smoke propagation, and hazard escalation using sequential sensor data collected from IoT-enabled monitoring environments [48,58].

3.6.3. Hybrid Models for Multi-Sensor Data Analysis

Beyond CNN and LSTM models, as discussed in Section 3.1, several studies highlight the role of hybrid deep learning architectures that combine multiple AI techniques to improve predictive performance [40,48]. These models integrate deep neural networks with traditional machine learning algorithms to analyze complex environmental datasets obtained from multiple sensor sources [40]. Hybrid modeling frameworks enable digital twin systems to integrate environmental monitoring data with simulation-based fire models, thereby improving the accuracy of fire dynamics prediction and associated safety risk assessment [48]. Such architecture demonstrates the potential of combining heterogeneous AI techniques to support complex firefighting decision-support systems [40,48].

3.6.4. Data-Driven Predictive Algorithms

Artificial intelligence is also increasingly applied to physiological risk assessment and firefighter health monitoring [47,53]. Machine learning algorithms analyze physiological data on heart rate, body temperature, fatigue levels, physical workload, and cognitive stress to identify early indicators of physiological distress during emergency response operations [53]. AI-enabled monitoring platforms designed for first responders increasingly support predictive health assessments and operational intervention strategies to reduce fatigue-related incidents and health risks in hazardous environments.

3.6.5. Integration of AI Models with Digital Twin Simulations

Current research additionally highlights the growing integration of AI models with simulation-based digital twin environments [43,49]. In these systems, computational fire dynamics models continuously update virtual operational environments using real-time sensor data, while machine learning algorithms interpret simulation outputs and forecast environmental risks [42,43]. Such integrated digital twin simulations support operational planning, evacuation modeling, wildfire forecasting, and firefighter preparedness training within adaptive emergency-response environments [58,62].

3.6.6. Edge AI and Cyber-Physical Systems for Real-Time Risk Prediction

Building on the sensing and AI frameworks described in Sections 3.4.1, 3.4.2 and 3.6, edge computing and AI-driven cyber-physical systems enable real-time hazard detection and operational decision-making [36,37]. Edge AI architectures deploy machine learning algorithms directly on connected sensing devices, enabling rapid local data processing and reducing communication latency during emergency operations [36]. These systems support real-time situational awareness and adaptive operational coordination within dynamic firefighting environments where network disruptions or communication delays may limit centralized processing capabilities [37,53].

The reviewed literature collectively demonstrates that artificial intelligence serves as the analytical engine driving predictive digital twin systems for firefighters. Machine learning, deep learning, hybrid AI architectures, predictive simulation models, and edge-enabled analytics increasingly support real-time hazard prediction, environmental monitoring, physiological risk assessment, and intelligent operational decision-making in complex emergency response environments. To synthesize the relationships among sensing technologies, artificial intelligence models, and digital twin architectures, Figure 11 presents an integrated conceptual framework that illustrates the flow of data from acquisition to decision support in AI-driven digital twin systems. This framework is discussed in greater detail in the subsequent section.

3.7. Technological Gaps and Emerging Research Opportunities

The following subsections in this results section present details of the identified technological gaps and emerging research opportunities based on the preceding bibliometric and content analysis. The study showed that despite significant advances in sensing technologies, artificial intelligence, and digital twin architectures, current firefighter digital twin systems still face several technological, operational, and implementation challenges that limit the realization of a fully integrated predictive safety ecosystem [42,48,59,61]. Figure 12 shows the emerging research directions and future opportunities in AI-driven firefighter digital twin systems [37,40]. Emerging research increasingly recognizes the need to move beyond isolated monitoring systems toward intelligent, interoperable, and human-centered digital twin platforms that support real-time operational resilience and adaptive emergency-response coordination [36,44].

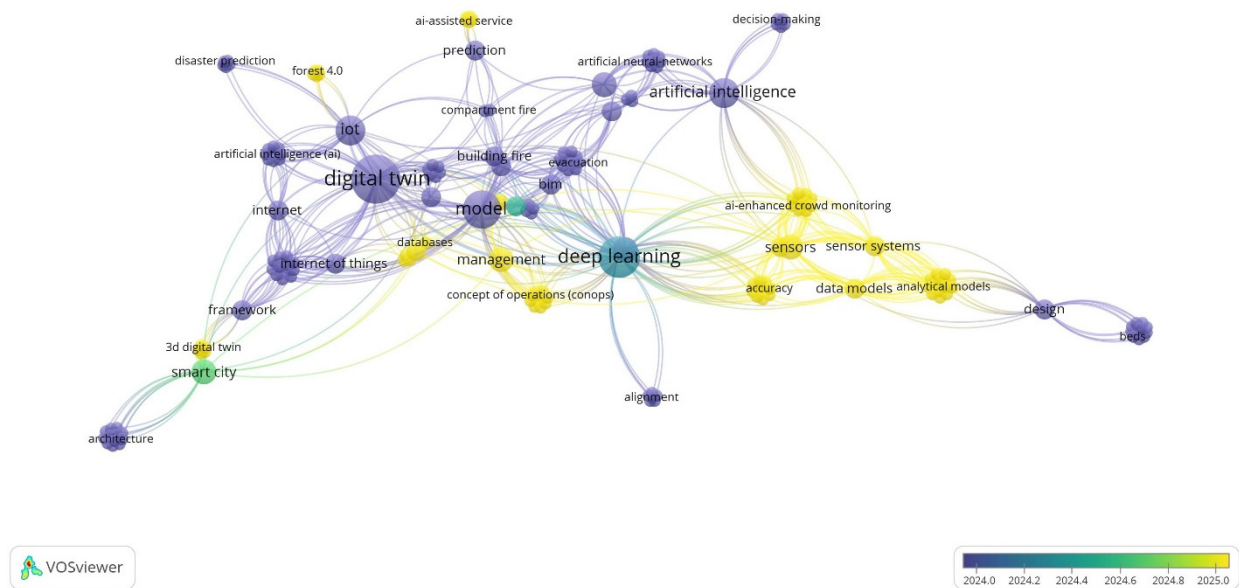


Figure 12. Emerging Research Directions and Future Opportunities in AI-Driven Firefighter Digital Twin Systems.

3.7.1. Lack of Integrated Environmental and Physiological Monitoring

One of the most significant challenges involves the limited integration of physiological and environmental monitoring data within digital twin systems [48,53]. Many existing systems focus on environmental hazard monitoring using sensors that detect temperature, smoke, and gas concentrations [58,59]. Other systems evaluate wearable sensor technologies for tracking firefighter physiological conditions, such as heart rate and oxygen saturation [47,48,53,58]. However, only a limited number of studies attempt to combine these two data streams within a unified digital twin framework [59,61]. The lack of integrated monitoring systems limits digital twins' ability to simultaneously assess environmental hazards and firefighter health risks, thereby constraining the development of comprehensive real-time risk prediction platforms [42,48].

3.7.2. Limited Predictive Capabilities of Current Digital Twin Systems

Another important challenge relates to the limited predictive capabilities of current digital twin implementations [59,61]. Although many digital twin systems provide visualization and monitoring functionalities, comparatively few platforms incorporate advanced AI-driven predictive analytics capable of forecasting fire progression, physiological distress, or operational risk escalation before hazardous incidents occur [40,49]. Current research increasingly demonstrates the importance of combining machine learning algorithms with dynamic digital twin simulations to support proactive risk management and adaptive emergency-response planning [44,62].

3.7.3. Absence of AI-Driven Risk Threshold Models

The literature also highlights the limited development of AI-driven risk-threshold models and automated operational intervention systems [39,42]. Machine learning models have been applied to analyze sensor data and detect anomalies in environmental or physiological conditions [39,53]. There is limited research on defining quantitative risk thresholds that can trigger automated safety interventions [59,61]. For example, sensor monitoring systems for firefighters have been designed to detect hazardous events such as high-temperature exposure or abnormal movement patterns [60]. However, translating these sensor measurements into standardized risk thresholds that support operational

decision-making remains an underexplored research area [39,42]. Developing AI-based risk assessment models capable of dynamically estimating safe exposure limits and predicting hazardous conditions represents a key research direction [44,48].

3.7.4. Limited Decision-Support Dashboards

A further technological challenge involves the limited integration of intelligent decision-support interfaces within firefighter digital twin systems [42,54]. While several systems propose digital twin architectures for monitoring fire environments or simulating fire spread scenarios [48,62], relatively few systems provide integrated decision-support interfaces specifically designed for emergency management operations [50,54]. Effective digital twin systems should not only collect and analyze data but also present actionable insights to incident commanders in real time [54]. Urban digital twin platforms demonstrate the potential of combining environmental monitoring, predictive modeling, and visualization tools to enhance situational awareness [48,61]. However, most existing systems remain focused on data monitoring rather than operational decision support [59,61].

3.7.5. Limited Human–Computer Interaction in Firefighter Digital Twin Systems

Human–computer interaction (HCI) and immersive operational visualization also represent important emerging research opportunities [50,62]. As digital twin technologies become increasingly complex, intuitive user interfaces and interactive visualization environments are critical [50]. Most existing platforms focus on modeling and simulation with limited attention to user experience [59,61]. Current research suggests that integrating AR/VR technologies with human-centered digital twin systems may significantly improve real-time firefighter decision-making and operational preparedness [62]. However, research on real-time interactive digital twin interfaces remains limited [53].

3.7.6. Emerging Research Opportunities

The identification of these technological gaps highlights several promising research opportunities for advancing digital twin systems for firefighter safety [42,48]. Cybersecurity, interoperability, and infrastructure resilience represent critical emerging challenges within firefighter digital twin ecosystems. Future systems will increasingly depend on interconnected sensing networks, edge computing architectures, cloud infrastructure, and AI-enabled cyber–physical communication systems [36,37]. Consequently, vulnerabilities stemming from communication disruptions, sensor spoofing, cyberattacks, and data integrity issues may significantly undermine the reliability of firefighter monitoring systems during emergency operations. Future research should therefore prioritize resilient cyber–physical architectures, secure communication protocols, explainable AI systems, and fault-tolerant emergency-response infrastructures that maintain operational continuity in hazardous environments.

Several other important research opportunities also emerge from the reviewed literature. One promising direction involves the development of multimodal sensor-fusion frameworks that integrate environmental and physiological sensor data in real time [53,58]. Such systems would enable digital twins to simultaneously model fire conditions and firefighter health status, thereby providing a more comprehensive representation of operational risk. Another emerging direction involves integrating explainable artificial intelligence (XAI) techniques into firefighter monitoring systems. Explainable AI models could improve transparency in predictive risk assessment algorithms and increase trust in digital twin decision-support systems among emergency responders [35,36]. Furthermore, future research should explore the development of predictive digital twin simulation environments that combine machine learning algorithms with computational fire dynamics models to forecast fire spread and hazard exposure levels [43,49]. These simulation

environments could be used not only for operational monitoring but also for firefighter training and preparedness planning.

Additionally, advances in edge computing and autonomous systems may enable the development of autonomous intervention mechanisms, such as automated hazard alerts or robotic assistance systems, that can support firefighters in high-risk environments [36,37]. This study posits that integrating immersive AR/VR interfaces with human-centered digital twin systems represents a promising approach to improving firefighter situational awareness and operational decision-making [62]. By enabling responders to interact with digital twin representations of fire environments through immersive visualization technologies, future systems could provide more intuitive and actionable insights during emergency operations. Addressing these gaps is essential for next-generation digital twin systems [42,48], with interdisciplinary research playing a critical role [37,40].

4. Discussion and Future Development

4.1. Discussion of Findings

Research on AI-driven digital twin systems for firefighter safety has evolved rapidly, driven by advancements in sensing technologies, cyber–physical systems, and artificial intelligence [48,58,59,61]. The field has transitioned from isolated monitoring solutions toward integrated digital twin ecosystems capable of fusing physical fire environments with virtual models in real time [36,59,61]. Early studies primarily focused on IoT-enabled sensing infrastructures and communication systems for data acquisition [35,37], while more recent work emphasizes predictive analytics, edge computing, and simulation-based digital twin platforms that support adaptive emergency-response coordination and proactive safety management.

Sensing technologies form the foundational data layer within these ecosystems, enabling continuous monitoring of environmental hazards and firefighter physiological conditions [58,59]. Environmental sensors, such as temperature, gas, and particulate monitoring systems, provide real-time situational awareness and support fire dynamics modeling [48,59], while wearable sensing technologies enable continuous tracking of physiological indicators such as heart rate, oxygen saturation, and fatigue [47,53]. Despite these advances, the integration of environmental and physiological sensing into unified digital twin frameworks remains limited, constraining comprehensive risk assessment and adaptive operational decision-making.

Artificial intelligence functions as the predictive intelligence layer, transforming multi-sensor data into actionable insights for hazard detection and operational planning [42,44]. Machine learning models such as Random Forest, SVM, and gradient-boosting methods support classification and anomaly detection [39,59], while deep learning architectures, including CNNs and LSTMs, enable spatial and temporal prediction of fire behavior and risk escalation [14,62]. Hybrid AI approaches further enhance predictive capabilities by integrating data-driven models with simulation-based digital twin systems [40,48]. However, challenges related to model interpretability, scalability, and real-time deployment persist, particularly in dynamic and high-risk firefighting environments.

Digital twin architectures serve as the integration layer that connects sensing systems, AI analytics, and simulation environments to support real-time decision-making [59,61]. These architectures enable continuous fusion between physical and virtual systems, facilitating hazard visualization, predictive modeling, and adaptive coordination. Applications span urban digital twins, wildfire monitoring platforms, and human-centered systems that integrate physiological and environmental data [47,53]. Nevertheless, many current implementations remain focused on monitoring and simulation, with limited development of fully integrated predictive and decision-support systems.

4.2. Future Research Directions

Future research should prioritize the development of integrated multimodal digital twin ecosystems capable of simultaneously analyzing environmental hazards, firefighters' physiological conditions, conducting predictive simulations, and coordinating operations within unified intelligent emergency-response environments [53,58]. Although current systems often focus independently on environmental monitoring or physiological sensing, integrating these heterogeneous data streams into unified predictive digital twin platforms would significantly improve operational risk assessment and emergency response effectiveness [47,48]. Another important research direction involves integrating explainable artificial intelligence (XAI) into firefighter digital twin systems [35,36]. As predictive AI models become increasingly complex, improving transparency, interpretability, and operational trust will become essential for ensuring effective emergency-response decision-making. Explainable AI frameworks could help incident commanders better understand the environmental and physiological factors contributing to predicted risk conditions during emergency operations. Future firefighter digital twin systems should increasingly incorporate predictive simulation environments that combine machine learning algorithms with computational fire dynamics models [49,58,62]. These systems could support proactive hazard forecasting, evacuation planning, operational strategy evaluation, and firefighter preparedness training within highly realistic simulation environments.

Advances in edge computing, autonomous systems, robotics, and cyber-physical communication technologies further present significant opportunities for next-generation firefighter digital twin ecosystems [36,53]. Autonomous hazard-alert systems, adaptive operational guidance platforms, robotic assistance technologies, and intelligent emergency-response coordination systems may significantly improve firefighter safety and operational resilience within hazardous operational environments. The integration of immersive augmented reality (AR), virtual reality (VR), and human-centered operational interfaces also represents an important emerging research opportunity. These technologies may significantly improve situational awareness, operational visualization, firefighter training, and real-time interaction with digital twin environments during emergency-response operations.

Finally, future firefighter digital twin systems should increasingly integrate with smart-city infrastructure, urban digital twins, resilient communication systems, and intelligent disaster-management ecosystems that support coordinated emergency response across large-scale urban environments. Addressing challenges in interoperability, cybersecurity, data fusion, predictive analytics, and human-computer interaction will be essential to developing next-generation intelligent firefighter digital twin ecosystems that support adaptive, resilient, and data-driven emergency-response operations.

5. Conclusions

This study provides a structured synthesis of the evolving research landscape on AI-driven digital twins for predicting firefighters' environmental and physiological risks. Using a combined bibliometric and content analysis approach, the study identified key technological domains, including sensing systems, artificial intelligence models, IoT infrastructures, and digital twin architectures. The findings reveal that although significant progress has been made in real-time monitoring and predictive analytics, critical gaps remain in system integration, predictive capabilities, and decision-support implementation. Addressing these challenges requires developing unified, data-driven digital twin frameworks that integrate environmental and physiological data and support real-time, adaptive decision-making. Several limitations should also be acknowledged. The reviewed literature was primarily identified through the Web of Science Core Collection database,

which may exclude relevant studies from other scientific databases and technical repositories. In addition, the rapid evolution of artificial intelligence, sensing technologies, and digital twin systems means that emerging developments may extend beyond the scope of this review. This work contributes to the field by providing a comprehensive analytical framework and identifying future research directions that support the development of scalable, intelligent, and human-centered digital twin systems for firefighter safety and emergency response.

Author Contributions: Conceptualization, A.A. and A.M.; methodology, A.A.; software, A.A.; validation, A.M., E.R., and N.M.; formal analysis, A.A.; investigation, A.A., A.M., E.R., and N.M.; resources, A.A., A.M., E.R., and N.M.; data curation, A.A.; writing—original draft, A.A.; draft preparation, A.A.; writing—review and editing, A.M., E.R., and N.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Texas A&M Engineering Experiment Station (TEES) through the 2025 TEES Annual Research Conference (TARC).

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Acknowledgments: The authors appreciate the funding support provided by Texas A&M Engineering Experiment Station (TEES) through the 2025 TEES Annual Research Conference (TARC). During the preparation of this manuscript, the authors used ChatGPT v5.5 (OpenAI, San Francisco, CA, USA) exclusively for preliminary language and grammar checks and for generating icons for some figures, which were then reviewed and edited as needed. No generative AI tools were used for data analysis, study design, interpretation of results, or the creation of scientific content. After using this tool, all authors reviewed and edited the content as necessary and take full responsibility for the final version of the manuscript.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

Abbreviation	Full Meaning
AI	Artificial intelligence
AR	Augmented reality
CNN	Convolutional neural network
CO	Carbon monoxide
CO ₂	Carbon dioxide
DT	Digital twin
ECG	Electrocardiogram
GIS	Geographic information system
HCI	Human–Computer Interaction
IEEE	Institute of electrical and electronics engineers
IoT	Internet of Things
LSTM	Long short-term memory
NFPA	National Fire Protection Association
PM _{2.5}	Particulate matter 2.5
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
RNN	Recurrent neural network
SpO ₂	Peripheral capillary oxygen saturation
SVM	Support vector machine
UAV	Unmanned aerial vehicle
VR	Virtual reality
VOSviewer	Visualization of similarities viewer
XAI	Explainable artificial intelligence

XGBoost

Extreme gradient boosting

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