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Prototypes of intelligent robots for first aid in natural disasters: A bibliometric analysis

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Abstract The increasing frequency and complexity of natural disasters have intensified global demand for intelligent robotic systems that can support first aid and emergency response. This study presents a systematic literature review (SLR) and bibliometric analysis of research on smart robots applied to disaster scenarios. Using the Scopus database, 153 records were initially retrieved with the keywords "disaster" and "smart robot." After applying PRISMA-based screening and inclusion criteria, 54 peer-reviewed publications were analyzed using the Bibliometrix R package. The analysis identifies key trends in robotic technologies, artificial intelligence algorithms, and design innovations for disaster response. Results highlight the growing research emphasis on unmanned aerial vehicles (UAVs), ground and snake robots, and the integration of sensors, IoT, and machine learning for real-time victim detection and navigation. Despite notable technological progress, critical challenges persist in field deployment, robot coordination, and human–robot interaction in crisis settings. This study contributes to the disaster robotics field by synthesizing existing knowledge, identifying underexplored areas, and proposing research directions to enhance the operational effectiveness of robotic systems in future emergencies.

Keywords: disaster robotics, first aid, unmanned systems, AI algorithms, bibliometric analysis, systematic review

1. Introduction

Natural disasters—ranging from earthquakes and floods to wildfires and tsunamis—continue to pose significant threats to human life and public infrastructure. These events frequently compromise access to medical services, particularly in remote or inaccessible areas (Syafitri et al., 2020), thereby elevating the importance of timely first aid and emergency response. Technological innovation has increasingly turned to robotics as a solution, with intelligent systems designed to assist in search-and-rescue operations, deliver supplies, and support preliminary triage tasks. Aligned with the third Sustainable Development Goal (SDG 3), robotic interventions in disaster contexts offer the potential to strengthen institutional resilience and improve health outcomes in vulnerable communities.

The past decade has seen rapid advancements in robotics, including the deployment of unmanned aerial vehicles (UAVs), ground-based mobile robots, and soft or snake-like robots in simulated disaster scenarios. These systems are often integrated with artificial intelligence (AI), the Internet of Things (IoT), and sensor networks to improve environmental awareness, obstacle avoidance, and victim detection. However, despite promising results in controlled environments, the transition to real-world deployment remains limited. Technical challenges such as unreliable connectivity, energy constraints, environmental unpredictability, and limited autonomy restrict the operational scope of these systems (Goncharov & Nechesov, 2023). Moreover, gaps persist in understanding how specific robot designs and algorithms align with the varied needs of different disaster contexts.

Existing literature on disaster robotics has predominantly focused on case studies, technological innovations, or algorithm performance, with limited effort to systematically synthesize cross-disciplinary insights. While prior reviews have provided valuable perspectives on AI and swarm robotics, they often lack a bibliometric foundation (Meyliana et al., 2021) or do not explicitly address the interplay between robotic architecture, sensor systems, and algorithmic control in first-aid settings.

This study aims to bridge that gap through a combined systematic literature review (SLR) and bibliometric analysis (Tan et al., 2024). Using PRISMA guidelines, we identified 54 relevant Scopus-indexed publications focused on smart robotic applications in disaster scenarios. Our study is guided by three research questions:

RQ1: What technologies are employed in disaster-response robots?
RQ2: What algorithms are commonly applied to enhance robotic functionality?
RQ3: What robot designs are most effective in different disaster contexts?

By addressing these questions, the study offers a comprehensive map of the current research landscape, identifies knowledge gaps, and proposes future directions for the development and deployment of intelligent robotic systems in emergency response.

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2. Materials and Methods

This study employed a Systematic Literature Review (SLR) combined with bibliometric analysis to examine the landscape of intelligent robotic systems designed for first aid in natural disaster scenarios. The methodology was structured following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines to ensure transparency and replicability. All data were retrieved from the Scopus database, selected for its comprehensive coverage of peer-reviewed journals and conferences in engineering, robotics, and disaster management. The search was conducted on January 20, 2024, using the following Boolean query applied to the article title field: TITLE("disaster" AND "smart robot").

Table 1 outlines the inclusion and exclusion criteria used to filter the literature. Only articles specifically addressing "disaster" contexts and "smart robot" applications were included, while works not meeting these topical requirements or not in article format (e.g., editorials, abstracts) were excluded.

Figure 1 shows after running the search query in Scopus, we identified 153 records. These records were exported in CSV format for screening. Duplicates and off-topic results were removed, and the remaining titles and abstracts were reviewed against the criteria. This screening process yielded 54 publications that met all inclusion criteria. We followed PRISMA guidelines to document the identification, screening, and inclusion of studies (the flow diagram indicated an initial yield of 153 records and a final set of 54 included publications). The bibliometric analysis was then conducted using the R bibliometrix package and its Shiny web interface. Key data such as publication years, citation counts, author affiliations, and keywords were extracted and analyzed. The results are presented through descriptive tables and figures. Statistical graphs (e.g., annual publication trends and citation analysis) were generated to quantitatively interpret the research development over time. All figures derived from Scopus data are labeled with their data source. Ethical considerations were observed by focusing on published research and properly citing all sources. exploration.

Table 1 Inclusion-exclusion criteria.

Inclusion Criteria	Exclusion Criteria
Topics involve "disaster" and "smart and robot"	Not related to "disaster" or "smart and robot"
Publications are article-based	Outputs like papers, books, or editorials

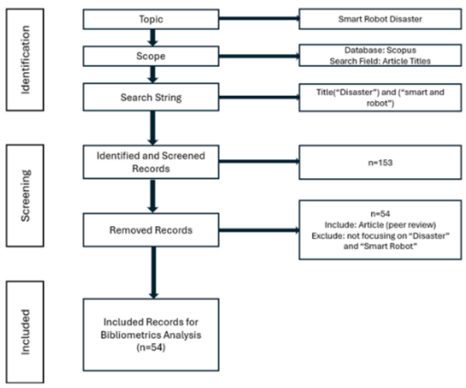

Figure 1 PRISMA diagram used in this review.

After finalizing the set of 54 relevant publications, we extracted detailed information from each. A summary of these key publications is provided in Table 2, which lists the authors, year, and a brief description of each study's focus. This summary highlights the diversity of research topics, ranging from the design of specific robotic systems to the application of AI algorithms for disaster response. By consolidating these references, Table 2 serves as a foundation for the subsequent bibliometric analysis and discussion, allowing us to identify common themes and gaps across the body of literature.

This study offers insights into the advancements and potential of smart robotic technologies in disaster response while emphasizing the ongoing challenges. The integration of cutting-edge sensors, AI, and IoT technologies shows promising results in enhancing disaster management efforts. However, addressing issues such as coordination, reliability, and technological limitations will be crucial for maximizing the effectiveness of these technologies in future applications.

Table 2 Key publications on disaster and smart robot.

No.	Author	Paper Title	Topics
1	(Murugan et al., 2020)	An IoT-Based Weather Monitoring System to Prevent and Alert Cauvery Delta District of Tamilnadu, India	This IoT-based weather monitoring system strengthens disaster preparedness in Tamilnadu's Cauvery Delta by providing real-time weather data and alerts, enhancing regional safety.
2	(Topal et al., 2023)	An Interpretable Environmental Sensing System with Unmanned Ground Vehicle for First Aid Detection	The Unmanned Ground Vehicle (UGV) for first aid is a critical advancement in emergency response, autonomously delivering medical aid in challenging terrains to boost survival rates.
3	(Nazarova & Zhai, 2019)	Distributed Solution of Problems in Multi-Agent Robotic Systems	Task distribution in Multi-Agent Systems (MAS) and Smart Electromechanical Systems (SEMS) is key to efficient search and rescue operations, balancing centralized and decentralized control.
4	(Bujak et al., 2011)	Applying military telematic solutions for logistics purposes	Advanced tech for logistics, transport, and disaster safety, with military tech transfer for logistics.
5	(Nan et al., 2012)	Design and realization of an intelligence mobile terminal on emergency response system for sudden affairs	Android-based emergency response system integrating GIS, voice, and data transmission for effective disaster management.
6	(Saeed et al., 2013)	Android, GIS and web base project, Emergency Management System (EMS)	Real-time Android, GIS, web system to enhance emergency response in fires, accidents, disasters.
7	(Bae et al., 2013)	A study of robot-based context-aware fire escape service model	Robot-based fire evacuation model using context-aware data for optimal escape routes via smartphone.
8	(Ahmed et al., 2022)	Domestic Smart Fire Fighting Robot with Multisensory Fire Detection and Warning System Using Python IDE	Raspberry Pi robot system to detect, extinguish home fires, with alerts via email and Bluetooth.
9	(Lowrance & Lauf, 2017)	Link Estimation in Robot Networks for Multi-Radio Control and Range Extension	Secondary radio and passive reflectors improve communication quality in remote robot applications, using fuzzy logic link estimators.
10	(Bae et al., 2022)	Review of the Latest Research on Snake Robots Focusing on the Structure, Motion and Control Method	Snake robot research focusing on structure, motion, control methods for applications in exploration and disaster recovery.
11	(Alsamhi et al., 2021)	Green internet of things using UAVs in B5G networks	UAV-based IoT for energy-efficient, sustainable applications in Industry 4.0.
12	(Saeed et al., 2021)	Smart delivery and retrieval of swab collection kit for COVID-19 test using autonomous UAVs	Drone deployment for emergency kits and medical sample collection in pandemic situations and developing regions.
13	(Xu et al., 2023)	Fluid-driven and smart material-driven research for soft-body robots	Development of soft body robots using intelligent materials for healthcare, agriculture, and disaster response.
14	(Manawadu et al., 2023)	Revitalize Aizu-Wakamatsu City Using Technologies of Disaster Response Robots	Integrating robotics in disaster management for urban resilience and community acceptance.
15	(García-Samartín et al., 2024)	Active robotic search for victims using ensemble deep learning techniques	Quadruped robot with AI-based search capabilities to locate disaster victims.
16	(Dimakis et al., 2010)	Distributed building evacuation simulator for smart emergency management	Multi-agent simulation for autonomous emergency management and building evacuation modeling.

17	(Tamilselvi et al., 2024)	IoT based Smart Robotic Design for Identifying Human Presence in Disaster Environments	Prototype for disaster victim detection using IoT and intelligent sensors for remote monitoring.
18	(Syamim et al., 2022)	Application of Fuzzy Logic in Mobile Robots with Arduino and IoT	Development of mobile robots with fuzzy logic, IoT, for industrial and disaster applications.
19	(Srivathsan et al., 2012)	Fuzzy-based automated mobile controlled rescue robot	Fuzzy-based robotic system for rescue operations in natural and human-made disasters.
20	(Sharma & Balamurgan, 2015)	Mobile robotic system for search mission	Robotic system designed for search and rescue in hard-to-reach locations.
21	(Telkar & Gadgay, 2020)	IoT Based Smart Multi Application Surveillance Robot	Surveillance robot with IoT applications to reduce casualties in combat zones.
22	(Agnes Shifani et al., 2020)	A Review on Smart Autobot in Building Eradication Using WSN Technology	Autonomous robot for rapid response in disaster sites or war zones, relying on quick victim identification.
23	(Kumar & Ilaiyaraja, 2015)	Smart interface for sensors in robot	Integration of robots with wireless sensor networks (WSN) for enhanced IoT data collection and processing.
24	(Khatib & Chung, 2014)	SupraPeds: Humanoid contact-supported locomotion for 3D unstructured environments	Humanoid robot designed for stability in complex disaster landscapes, introducing the SupraPeds concept.
25	(Xin et al., 2018)	Design and Implementation of Debris Search and Rescue Robot System Based on Internet of Things	Multifunctional rescue robot system for complex and hazardous environments in disaster scenarios.
26	(Baca et al., 2010)	A modular robot system design and control motion modes for locomotion and manipulation tasks	Modular robot design for versatile movement and task adaptability in emergency scenarios.
27	(Lin et al., 2023)	A 28nm 142mW Motion-Control SoC for Autonomous Mobile Robots	High-efficiency SoC designed to enhance autonomous mobile robot performance in critical missions.
28	(Breland et al., 2021)	Deep Learning-Based Sign Language Digits Recognition from Thermal Images with Edge Computing System	Edge computing system for sign language recognition in robots, utilizing thermal imaging for better communication.
29	(Cao et al., 2020)	Hybrid-Digital-Mixed-Signal Computing Platform for Accelerating Swarm Robotics	Computing advancements for swarm robotics, optimizing energy efficiency and scalability.
30	(Hussaini & Sundarambal, 2011)	Wireless control of humanoid robot using 3G	3G-based wireless control of humanoid robots for disaster and conflict response.
31	(Koeda & Murayama, 2017)	Translational slip movement with supine posture for humanoid robots	Innovative movement adaptation for humanoid robots in challenging rescue environments.
32	(Chu et al., 2015)	3D printed rapid disaster response	Cost-effective 3D-printed robotic systems for efficient disaster response.
33	(Rehman et al., 2020)	Trustworthy intelligent industrial monitoring architecture for early event detection by exploiting social IoT	Advanced IoT architecture for monitoring and early detection in high-risk industrial and disaster environments.
34	(Cardenas et al., 2021)	Reducing cognitive workload in telepresence lunar-Martian environments through audiovisual feedback in augmented reality	AR-based feedback system to enhance robot navigation and control in extreme exploration or disaster scenarios.
35	(Kim et al., 2018)	Smart disaster response in vehicular tunnels: Technologies for search and rescue applications	IoT and robotics for detecting and rescuing victims in vehicular tunnel disasters.
36	(Alam et al., 2021)	A Smart Approach for Human Rescue and Environment Monitoring Autonomous Robot	Autonomous robots for human rescue and environmental monitoring in challenging, inaccessible areas.

37	(Liu et al., 2023)	Review of the Research Progress in Soft Robots	Overview of soft robotics applications, especially in medical, agricultural, and disaster settings.
38	(Cheikhrouhou et al., 2020)	A cloud-based disaster management system	Cloud-integrated WSNs and 3D visualization for efficient disaster response planning and training.
39	(Maheswari et al., 2023)	Internet of Things and machine learning-integrated smart robotics	IoT and ML-enhanced robotics for various industrial and emergency applications.
40	(Mostafa et al., 2010)	Alternative gaits for multiped robots with leg failures to retain maneuverability	Multi-legged robots with adaptive gait for stability in adverse conditions.
41	(Divya et al., 2013)	Amphibious surveillance robot with smart sensor nodes	Amphibious robot for surveillance, tracking, and victim detection in disaster zones.
42	(Suba Raja et al., 2015)	Smart robot for disaster detection using Zigbee technology	Zigbee-enabled robotic systems to enhance efficiency in disaster rescue operations.
43	(Bourbakis et al., 2020)	Smart Cities-Detecting Humans in Regions of Disasters: Synergy of Drones, Micro-robots in Underground Tunnels	Tzitziki's micro robots can be used to address challenges in disaster rescue by collecting data under debris and collaborating with other technologies and rescue teams to improve the efficiency of rescue operations.
44	(Ramanathan et al., 2012)	Ontology-based collaborative framework for disaster recovery scenarios	How an adaptive framework based on semantic modeling can improve collaboration in public safety and disaster recovery missions, especially in situations where communication connections and resources may be affected by environmental changes and dynamic mission needs.
45	(Chakraborty et al., 2018)	A low cost autonomous multipurpose vehicle for advanced robotics	Development and application of multifunctional robots including disaster rescue, agriculture and factory surveillance with advanced technology in a single device that becomes the center of the system.
46	(Lee et al., 2017)	Reliable software architecture design with EtherCAT for a rescue robot	Design a software architecture for a rescue robot designed for tasks such as rescuing injured people and moving dangerous objects in disaster situations.
47	(Prabakaran et al., 2010)	Identification of explosives and disaster prevention using intelligent robots	Development of a multi-functional rescue robot system for disaster situations with complex and hazardous environmental characteristics.
48	(Billah et al., 2019)	Complex Terrain Negotiation Navigation: Survey on Different Robots	The ability of hexapod robots in disaster recovery missions by exploring difficult terrain efficiently and effectively.
49	(Nadiger et al., 2022)	IoT Based Alive Human Detection in War Field and Calamity Area Using Microcontroller	Development of robots designed to detect and transmit the location of living humans with advanced technology.
50	(Padmavathi & Vyasasreevedansh, 2024)	Smart Surveillence Drone with Navigation System	Smart Surveillance Drone with Navigation System program in advancing the field of surveillance and security through drone technology.
51	(Yang et al., 2014)	Autonomous mobile platform for enhanced situational awareness in Mass Casualty Incidents	The use of smartphone and RFID-based utonomous mobile platforms to improve the efficiency of search and rescue process in mass casualty incidents.
52	(Billah et al., 2016)	SMARS-I: Smart Material Actuated Robotic Snake (Ver-1)	Development of a snake robot using Ionic Polymer Metal Composite (IPMC) for flexible and lightweight movement, with specific applications in disaster recovery missions.
53	(Osaba et al., 2020)	Soft Computing for Swarm Robotics: New Trends and Applications	Development of Swarm Robotics, including the use of colony intelligence for the coordination of small robots in industrial and social applications such as structural health monitoring, complex manufacturing, logistics, and disaster management.
54	(Dwivedi et al., 2013)	Low-cost multiterrain rescuing 4-legged bot prototype	Arduino-based quad-robot with wireless communication and obstacle avoidance for versatile rescue operations.

3. Results and Discussion

This section synthesizes bibliometric results with a critical discussion on technological, algorithmic, and design trends in intelligent robots for first aid in natural disaster settings. Fifty-four articles published from 2010 to 2024 were analyzed after applying PRISMA 2020 screening. The discussion is structured around five dimensions: (1) publication trends, (2) keyword analysis, (3) prevalent technologies, algorithms, and robot types, (4) research gaps, and (5) future direction.

3.1. Publication trends and citation analysis

The evolution of research on intelligent disaster-response robots is reflected in the publication trends over time. Figure 2 illustrates the annual number of publications in this domain. The earliest relevant studies date to around 2010, with a modest output in the initial years of the decade. Publication counts grew steadily through the mid-2010s and surged toward 2020. The highest number of publications was recorded in 2020, indicating a peak in scholarly interest and activity. This surge coincides with the global COVID-19 pandemic and multiple large-scale disasters, such as the Beirut port explosion and Australian bushfires, which likely intensified the demand for autonomous and contactless support systems. The elevated interest may also reflect growing investments in AI and robotics under disaster resilience initiatives during that period.

After 2020, the number of publications has remained relatively high, though slight fluctuations occur year to year. While growth declined slightly in 2022, it resumed in 2023, indicating ongoing scholarly attention. These fluctuations suggest both episodic interest driven by major disaster events and a general upward trend driven by long-term technological innovation. Overall, the trend demonstrates significant growth in research output compared to a decade prior, highlighting that smart first aid and rescue robots have become an increasingly important and recognized field of study.

In addition to publication counts, we examined citation metrics to gauge the influence of the published works. Figure 3 shows the average number of citations per publication by year. Notably, papers from 2021 have the highest average citations, suggesting that the works published around that year have garnered significant attention from the research community. This spike in citations might reflect particularly impactful studies or reviews that year, or it may indicate that research from the early 2020s quickly became foundational for subsequent developments. Earlier years (e.g., 2010–2015) show lower average citations, which is expected given the smaller number of works and the nascent state of the field at that time. The upward trend in citations in later years underscores how the knowledge base has expanded and how newer studies are building upon and citing recent findings. This momentum in citations aligns with the growth in publications, reinforcing the view that smart robot applications in disasters have rapidly become a robust area of scholarly inquiry.

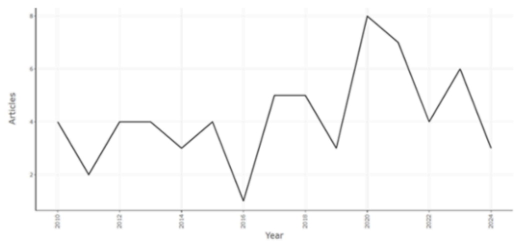

Figure 2 Annual Scientific Production plot. *Source:* Scopus Database.

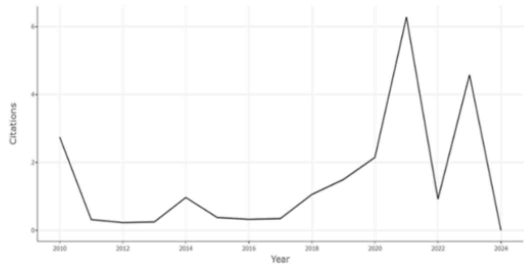

Figure 3 Average citations per year plot. *Source:* Scopus Database.

3.2. Keyword analysis

To further understand the direction of this research field, we analyzed the keywords and terms most frequently encountered in the selected publications. Table 3 presents the frequency of occurrence of important keywords across the 54 studies. The term "disaster" appears 26 times, confirming its centrality to all works in the dataset. The next most common term is "robots" (18 occurrences), underscoring that robotics is the core technological theme. "Disaster prevention" (12 occurrences) also ranks highly, indicating a significant subset of studies that focus on preventive measures and mitigating disaster impacts through robotic interventions. Other notable terms include "robotics" (11), "Internet of Things" (IoT) (10), and "machine design" (9), which suggest that many researchers concentrate on the integration of networked sensors (IoT) and the engineering design of robots for disaster contexts.

Table 3 Keywords frequency.

Words	Occurrences	Words	Occurrences	Words	Occurrences
Disasters	26	Unmanned Aerial Vehicles (UAV)	3	Navigation Systems	2
Robots	18	Affected aAea	2	Network Security	2
Disaster Prevention	12	Android	2	Object Detection	2
Robotics	11	Awareness	2	Optical Radar	2
Internet of Things	10	Biomimetics	2	Passive Infrared Sensors	2
Machine Design	9	Bombs (ordnance)	2	Remote Sensing	2
Agricultural Robots	8	Bridges	2	Robotic Systems	2
Intelligent Robots	8	Civil Defense	2	Search and Rescue Robot	2
Natural Disasters	8	Dommunication	2	Security Systems	2
Disaster Management	6	Computer Vision	2	Simulation	2
Smartphones	5	Data Analytics	2	Smart Sensors	2
Cameras	4	Data Handling	2	Smartphone	2
Drones	4	Deep Learning	2	Snake Robots	2
Aircraft Detection	3	Disaster Response	2	Social Robots	2
Antennas	3	Emergency Management	2	Software Architecture	2
Anthropomorphic Robots	3	Global System for Mobile Communications	2	Software Testing	2
Artificial Intelligence	3	Hi-tech	2	Surrounding Environment	2
DC Motors	3	Human Robot Interaction	2	Surveys	2
Decision Making	3	Infrared Detectors	2	snake	2
Disaster Recovery	3	Intelligent Materials	2	Telematic Systems	2
Disaster Situations	3	Intelligent Sensors	2	Testing	2
Efficiency	3	Internet of Thing (IoT)	2	Ultrasonic Applications	2
Embedded Systems	3	Logistics Control	2	Underground Tunnels	2
Emergency Response	3	Machine Learning	2	Unmanned Ground Vehicles	2
Fuzzy Logic	3	Maintenance	2	Unstructured Environments	2
Humanoid Robot	3	Mass Casualty Incidents	2	Wireless Sensor	2
Learning Systems	3	Mhealth	2		
Mobile Robots	3	Mobile Phones	2		
Monitoring	3	Multi-Agent Systems	2		
Risk Management	3	Multipurpose Robots	2		

The most frequent keywords— "disaster," "robot," "sensor," "IoT," and "machine learning"—highlight not only technological priorities but also the domain's interdisciplinary character. While "disaster" reflects the field's primary focus, its prominence may also signal a broad research framing aligned with risk mitigation and emergency response goals. The co-occurrence of "IoT" and "machine learning" points to increasing interest in networked robotic systems capable of autonomous decision-making. This aligns with a paradigm shift from manually operated rescue robots to context-aware intelligent agents.

The keyword analysis also reveals terms with moderate frequency that highlight specific technologies and methodologies. For example, “humanoid robot,” “embedded systems,” “emergency response,” and “fuzzy logic” each occur 3 times. Meanwhile, “machine learning,” “deep learning,” “swarm intelligence,” and “snake robots” appear with a frequency of 2–3. Although these counts are lower, their presence in multiple studies indicates emerging or specialized interests within the field: machine learning and deep learning represent the use of AI algorithms for perception and decision-making (Lin et al., 2023), swarm intelligence points to coordinated multi-robot systems (Osaba et al., 2020), and snake robots highlight a focus on robots designed for confined spaces (Agnes Shifani et al., 2020).

On the societal side, terms like “mass casualty incidents” and “civil defense” (each appearing twice) show that a few works explicitly address large-scale emergency scenarios and integration with public safety infrastructure. The breadth of keywords—from technical components like “sensors” and “communication systems” to application contexts like “search and rescue”—illustrates that the field is multidisciplinary. Researchers are not only building the technological capabilities of robots (e.g., mobility, sensing, AI) but also tailoring these capabilities to the unique demands of disaster scenarios.

However, the lack of emphasis on terms like “ethics,” “human–robot interaction,” and “field validation” suggests limited attention to sociotechnical dimensions. The dominance of certain keywords reflects past research focus, while areas with fewer mentions may represent underexplored topics. For instance, “swarm robotics” and networked robot coordination appear in only a handful of studies, suggesting opportunities for further exploration in multi-robot collaboration during disasters. Similarly, “social robots” (robots interacting directly with humans) and “anthropomorphic robots” are infrequently mentioned, implying that human–robot interaction in disaster relief is a niche that could benefit from more research.

By linking these keyword trends to broader technological and societal drivers, we observe that the increased focus on IoT and AI aligns with wider advancements in those domains during the last decade. At the same time, the persistent emphasis on terms like “emergency response” and “disaster management” underscores the driving societal need to improve how we handle crises. In summary, the keyword analysis reveals a field that is technologically driven by sensors, connectivity, and intelligent algorithms, and societally driven by the imperative to reduce disaster impacts. This convergence of drivers has shaped the research landscape, and recognizing less-studied areas (e.g., multi-robot systems, human–robot interaction in disasters) can guide future investigations.

3.3. Technologies utilized in smart rescue robots (RQ1)

This section addresses RQ1: What technologies are employed in disaster-response robots? A thorough review of the literature reveals a diverse range of technologies that enhance robot effectiveness in hazardous and unpredictable conditions. Central among these are sensors used for perception and victim detection. Most robotic platforms incorporate thermal cameras, LiDAR, ultrasonic sensors, and infrared detectors, which allow them to detect human presence in low-visibility environments. Wireless communication technologies, including Bluetooth, Zigbee, 4G modules, and long-range mesh networks, are widely implemented to support remote operation and real-time data transmission, even in infrastructure-compromised zones (Syafitri et al., 2020). When GPS signals are unavailable (e.g., indoors or underground), robots utilize SLAM or radio localization techniques for positional accuracy. These robust communication systems also facilitate multi-agent coordination and fleet control, which is essential for real-world disaster operations.

Mobility systems such as brushless DC motors, high-torque servos, and pneumatic actuators support diverse robotic forms—from wheeled tanks to snake-like robots. Power efficiency is also emphasized in the literature, with solar panels and modular battery packs designed to extend mission duration. In summary, RQ1 findings confirm that disaster robots integrate sensing, locomotion, communication, and computation systems into rugged platforms. The technical readiness of these components is high, but field integration remains limited, underscoring the simulation-to-deployment gap noted in later sections.

3.4. Algorithms and artificial intelligence in disaster robotics (RQ2)

To answer RQ2—What algorithms are commonly applied to enhance robotic functionality? —this section synthesizes findings from 54 studies. Artificial intelligence, particularly machine learning and deep learning, plays a central role. Convolutional neural networks (CNNs) are frequently used for image-based victim detection and environment classification (García-Samartín et al., 2024). These models process camera feeds to identify human shapes, dangerous debris, or access paths. Navigation remains a vital challenge. Algorithms such as A* and Dijkstra’s are common for route optimization, while dynamic window and potential field methods are employed for real-time obstacle avoidance. Fuzzy logic and rule-based systems are favored in uncertain conditions, enabling robots to navigate terrain with partial or ambiguous sensor input. Recent studies highlight the emergence of reinforcement learning (RL) and swarm intelligence models like particle swarm optimization and ant colony optimization (Osaba et al., 2020). These techniques show promise in simulations for learning adaptable behaviors or coordinating multi-robot teams.

Algorithm robustness remains a critical challenge in real-world deployment of disaster-response robots. Despite the availability of advanced models, performance in the field is often hindered by noisy sensor data and constrained training datasets. To address this, sensor fusion techniques are increasingly employed, integrating data from LiDAR, sonar, and visual inputs to build more reliable environmental representations. In parallel, emerging solutions such as blockchain-based communication frameworks have been proposed to enhance data security and trustworthiness in disaster-stricken areas (Goncharov & Nechesov, 2023), underscoring the importance of cybersecurity in autonomous robotic systems. Overall, algorithms function as the cognitive core of robotic decision-making, and current research is directed toward enhancing their adaptability and fault tolerance in unpredictable and high-stakes environments.

3.5. Robot types and their effectiveness in disaster scenarios (RQ3)

This section answers RQ3: What robot designs are most effective in different disaster contexts? Unmanned aerial vehicles (UAVs) are the most cited platforms due to their agility, speed, and ability to scan vast disaster areas quickly. Equipped with high-resolution thermal cameras, UAVs have proven critical in locating survivors in scenarios such as building collapses and floods (Alsamhi et al., 2021). However, their operational limitations include short battery life and susceptibility to adverse weather conditions.

Ground robots—particularly wheeled and tracked types—are commonly deployed for navigating rubble-strewn terrain and transporting emergency supplies. These robots, often modeled after compact tanks or rovers, have demonstrated effectiveness in earthquake simulations and volcanic zones due to their durability and load-bearing capacity. Legged robots, including spider-like and humanoid systems, are being explored for navigating uneven or unstable surfaces, although they continue to face challenges related to balance control and energy efficiency.

Snake robots, as highlighted in the works of Bae et al. (2022) and Billah et al. (2016), are uniquely effective for accessing confined or collapsed spaces. Their articulated bodies allow them to maneuver through debris and locate victims, often establishing communication with survivors in areas inaccessible to other platforms. Nevertheless, these systems still require enhancement in locomotion speed and directional control.

Amphibious robots appear in fewer studies but are highly relevant for water-related disasters, such as floods and tsunamis. Despite their potential, deployment in submerged environments remains limited, suggesting an opportunity for further exploration and development.

A key challenge across all robot types is the gap between technological readiness and field deployment. While many systems perform well in laboratory or simulated environments, real-world application remains constrained. Issues such as scalability, dynamic adaptability, and multi-agent coordination continue to hinder operational integration.

Literature increasingly supports the deployment of heterogeneous robot teams—combinations of aerial, ground-based, and subterranean platforms working collaboratively. While simulation studies demonstrate strong potential for such coordination, actual implementation in live disaster zones is still rare due to unresolved communication, synchronization, and command structure complexities.

In conclusion, context-driven deployment remains the most effective strategy. UAVs offer rapid aerial surveillance; tracked ground robots are well-suited for traversing debris; snake robots provide unique access to confined interior spaces; and amphibious systems offer untapped utility in aquatic disasters. A unified control and communication framework enabling these specialized platforms to function as an integrated response team represents the most promising direction for enhancing disaster robotics effectiveness in the field.

3.6. Research gaps

While the current body of literature shows considerable progress, it also highlights several under-explored areas that present opportunities for future research. A significant gap identified is the limited field deployment and validation of robotic prototypes. Many studies remain in the realm of simulation or lab-based environments, with few reporting large-scale deployment in actual disaster scenarios or full-scale field exercises. Most studies are simulation- or lab-based. Cost, ruggedness, energy consumption, and real-time responsiveness remain persistent barriers. Future research should focus on extended field trials to evaluate robot performance under authentic conditions. Such trials could uncover unforeseen operational challenges—such as sensor interference in dusty environments, battery degradation in cold climates, or communication lags during stress-intensive search missions—that are not adequately captured in laboratory settings.

Another under-developed area is multi-robot coordination in live disaster environments. While theoretical frameworks such as swarm robotics and decentralized multi-agent systems exist, their practical deployment remains rare. Very few articles address scalability and multi-agent coordination protocols under dynamic disaster conditions. Robust methods are needed for coordinating heterogeneous teams of robots—airborne, terrestrial, and subterranean—working collaboratively on a disaster site. This requires not only coordination algorithms but also resilient communication infrastructures capable of withstanding partial network failures and high-latency environments.

Human–robot interaction is another frontier with limited attention. Most systems operate either autonomously or via remote operators, but few studies explore direct collaboration between robots and human rescuers—or with disaster survivors themselves. Integration with human rescue teams and ethical considerations in victim prioritization are underexplored.

Moreover, the literature provides limited guidance on how robots should behave empathetically, communicate effectively in high-stress scenarios, or assist with psychological first aid.

From a technological standpoint, the field still requires improvements in autonomy, resilience, and energy efficiency. Many platforms lack the capacity to operate for extended missions in harsh, unpredictable conditions. Enhanced energy solutions, such as energy-scavenging mechanisms or field-rechargeable units, are urgently needed to extend robot mission lifespans.

3.7. Future directions

Based on the analysis, future research should focus on several critical areas:

• Deployable prototypes in real-world field trials, to validate system reliability and usability under operational stress.

• Integration with 5G and edge-AI computing, which could drastically reduce decision-making latency and enable real-time responses.

• Human–robot teaming frameworks, where robots collaborate dynamically with first responders and adapt to human commands or cues.

• Ethical guidelines and algorithms that prioritize aid delivery equitably, especially in mass-casualty incidents or triage situations.

• Cross-disciplinary collaboration, involving robotics engineers, disaster responders, psychologists, and ethicists to co-design effective and acceptable systems.

These future directions not only address the current limitations but also align with global policy calls for trustworthy and resilient AI systems in crisis settings. Furthermore, strengthening multi-agent deployment protocols, edge-based autonomy, and human-centered design will improve robot effectiveness and acceptance in disaster-prone regions.

3.8. Alignment with literature review

The findings of this bibliometric review affirm trends highlighted in previous studies, particularly the dominance of UAVs and visual sensors in disaster robotics (Syafitri et al., 2020; Ahmed et al., 2022). These platforms continue to lead in rapid deployment, aerial surveillance, and thermal detection. However, this study uniquely reveals the lag in real-world adoption despite technological readiness. This echoes similar concerns in AI safety and robotics ethics literature, where systems often prove effective in controlled settings but fail to scale reliably in dynamic, high-risk environments. This confirms the "simulation–deployment gap" previously noted in AI safety literature and highlights a need for more implementation science in robotics.

By identifying gaps in deployment, coordination, and human–robot integration, this study contributes to a more realistic appraisal of disaster robotics maturity. It calls for a shift toward implementation science, emphasizing how technologies can transition from prototypes to operational tools. As the demand for intelligent robotic systems grows in climate-exacerbated disaster scenarios, researchers and practitioners must focus not only on innovation but also on translation, adoption, and trustworthiness in the field.

4. Conclusion

This study presents a systematic literature review and bibliometric analysis of intelligent robotic systems designed for first aid and emergency response in natural disasters. Drawing on 54 peer-reviewed articles indexed in Scopus, the review synthesizes key technological trends, algorithmic approaches, and robot design innovations deployed over the past decade. The findings confirm the prominence of aerial drones (UAVs), thermal sensors, and AI-powered perception systems, especially convolutional neural networks (CNNs) in the development of smart disaster-response robots. These technologies enable enhanced situational awareness, victim detection, and autonomous navigation in hazardous and unstructured environments.

The keyword analysis reveals a strong research focus on technical enablers such as the Internet of Things (IoT), wireless communication, and machine learning, while highlighting a relative lack of emphasis on human–robot interaction, ethical deployment, and field validation. The review also identifies significant research gaps, including the limited deployment of prototypes in real-world disaster scenarios, insufficient attention to multi-agent coordination under dynamic conditions, and a lack of robust frameworks for human–robot teaming and ethical decision-making in triage situations. To address these limitations, future research should prioritize field-tested deployable systems, edge-AI architectures with low-latency decision-making, and interdisciplinary collaborations that incorporate insights from emergency responders, ethicists, and behavioral scientists. Emphasis should also be placed on developing scalable multi-robot systems and trust-centered design to ensure wider adoption and operational resilience.

In sum, while smart robotic systems have demonstrated substantial potential in simulated environments, a clear implementation gap remains. Bridging this gap will require not only technical refinement but also deeper integration with the human and institutional contexts of disaster response. By advancing both the technological capabilities and the sociotechnical readiness of disaster robotics, this field can make a meaningful contribution to saving lives and enhancing resilience in an increasingly risk-prone world.

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Ethical Considerations

Not applicable.

Conflict of Interest

The authors declare no conflict of interest.

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