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# Towards Intelligent Wildfire Detection: A Review of Hybrid WSN, AI, UAV, and IoT-Based Monitoring Systems

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**Abstract**

The problem of wildfires has become more common, leading to environmental degradation, loss of biodiversity, economic losses, and hazards to people's lives. The necessity to detect such wildfires quickly and effectively has led to the development and implementation of intelligent solutions that overcome the drawbacks of traditional approaches. This research study provides an analysis of the recent developments in Wireless Sensor Networks (WSNs), Internet of Things (IoT), Artificial Intelligence (AI), and Unmanned Aerial Vehicle (UAV)-based wildfire monitoring systems along with the underlying communication technologies and open source datasets used for intelligent fire detection. It has been found from the reviewed research papers that the technologies offer distinct advantages in terms of distributed sensing, communication, aerial imaging, and intelligent data analysis; nevertheless, the implementation of individual technology has certain limitations in terms of scalability, energy consumption, communication reliability, and adaptability. The analysis reveals that hybrid architectures integrating WSNs, IoT, UAVs, and AI make efficient use of the inherent capabilities of each technology to enhance accuracy in detection, coverage in monitoring, awareness in situational assessment, and decision-making. Lastly, this research study explores the critical research gaps,


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presents emerging challenges, and identifies promising areas for future research in wildfire monitoring.

**Keywords:** Wildfire Detection, Wireless Sensor Networks (WSN), Artificial Intelligence (AI), Unmanned Aerial Vehicles (UAV), Internet of Things (IoT), Machine Learning, Environmental Monitoring, Smart Sensor Systems, Disaster Management.

## 1. Introduction

Wildfires are becoming a serious threat to the environment, flora and fauna, human population, and key infrastructure in various parts of the world. Increasing incidents of wildfires can attribute to higher temperature levels, drought, changing vegetation structure, and human activities within wildland-urban interface areas. Apart from the destruction of forests and wildlife habitats, major wildfires cause high greenhouse gas emissions and have negative impact on the quality of air, socio-economic activities, and are financially costly for disaster management organizations. Hence, the importance of early detection of wildfires has now become a necessity in order to ensure that the wildfire does not spread much further, is economically cheaper to suppress, and enhances emergency response efforts. Traditional methods of monitoring, such as visual observation, lookout towers, and satellite images, have been used in the detection of wildfires over many years; however, these methods experience detection delay, low temporal resolution, low spatial resolution, and are dependent on weather conditions such as cloud cover and land cover [2], [3], [4], [5], [6].

The rapid advancement of sensing, communication technologies, and computing technologies has changed the perspective of wildfire detection technology. The initial WSN implementation made distributed environmental sensing possible by collecting parameters like temperature, humidity, smoke density, and gas emissions from the sensor nodes located across the geographical area [1], [7], [8]. Further advancements brought about by IoT technologies including connected sensing devices, data handling via cloud computing, and real-time communication that makes environmental monitoring possible [10], [14], [15]. Meanwhile, UAVs became flexible means of quickly surveying difficult-to-reach areas, taking high-resolution images, and conducting dynamic fire assessment [11], [16], [17]. In recent times, methods like AI, ML, and deep learning have made a great improvement in wildfire detection through automated feature extraction, detection of fire and smoke, risk prediction, anomaly detection, and decision-making based on diverse environmental data [12], [13], [21], [23].

Taken together, these technological developments have transformed the method of wildfire detection from individual sensing to intelligent systems for proactive disaster management.

However, there are some intrinsic drawbacks in the technologies used individually due to their specific nature. WSN based systems have certain limitations in the areas of energy expenditure, communication efficiency, and network scalability. The functioning of the IoT infrastructure depends on the reliability of communication infrastructure and data handling capabilities to function continuously. The UAV based monitoring is one of the best options in terms of mobility and spatial coverage; however, its use is limited by the duration of flight and weather factors. The advantages and disadvantages discussed above are complementing each other and have triggered the evolution of hybrid solutions to monitor wildfires using WSNs, IoT platforms, UAVs, and AI techniques together in one system. Such solutions allow gathering data from different sources, performing intelligent data fusion, adaptive monitoring, real-time analysis, and prompt decision making, which leads to higher accuracy of the wildfire detection and decreased response time [15], [16], [17], [19], [21].

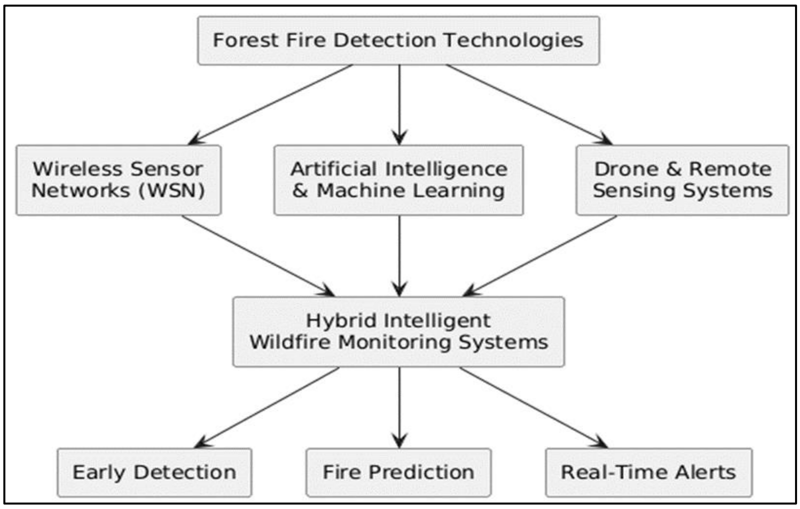


**Figure 1.** Conceptual framework of hybrid intelligent wildfire monitoring technologies

Figure 1 shows the evolution of intelligent wildfire monitoring through the application of WSNs, AI/ML, and UAV-based remote sensing technologies. It is noteworthy that all these technologies are interrelated and complement each other in the sense that they make up hybrid systems of wildfire monitoring, which increase the efficiency of detecting and forecasting wildfires.

Several review studies have explored different aspects related to technologies used for detecting wildfires. The existing literature surveys have thoroughly analyzed the application of

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machine learning in wildfire, IoT based sensing technologies, UAV-based monitoring, and remote sensing techniques [11], [13], [14]. While these research studies provide useful information regarding the particular fields, most of them focus on one specific technology or application scenario. Very few research works have been done on the integration of WSNs, IoT, UAVs, and AI in one intelligent monitoring framework. Moreover, the recent developments in hybrid sensor fusion approaches, cloud-fog-edge computing unification, explainable artificial intelligence, virtual sensing, multi-agent cooperation, standardization of benchmark datasets, and real-time implementation issues are addressed separately, rather than in a general technical context [18], [20], [23], [24], [25].

To address this research gap, this review study aims to provide an in-depth analysis on hybrid WSN-AI-UAV-IoT wildfire detection systems from the viewpoints of the sensor network architecture, communication system architecture, intelligent data analytics, and implementation aspects. This review summarizes the recent advancements in the areas of distributed sensing, intelligent predictive modeling, UAV-assisted fire monitoring, cloud-fog computing paradigms, explainable AI, and multi-agent decision support systems. Moreover, this review provides an analysis of the state-of-the-art techniques in terms of their limitations and current research gaps and suggests some future research directions.

## 2. Wireless Sensor Networks (WSNs) for Wildfire Detection

Wireless Sensor Network (WSN) is one of the well-known technologies used in intelligent fire detection due to its capability of continuously monitoring the environmental parameters of the vast geographic areas in the forests. Wireless Sensor Network (WSN) is composed of many nodes that have sensors to detect various environmental parameters such as temperature, humidity, smoke density, gases released, and wind speed. The data gathered by these nodes can be transmitted to sink nodes, which helps in continuously observing the condition of the forest and identifying any abnormalities linked to wildfires. Compared to the traditional methods, WSNs offer a self-reliant, inexpensive, and distributed system of monitoring and hence are ideal for use in remote regions where physical inspection is impossible. With recent developments in WSN technology, there has been an improvement in the efficiency of WSNs using energy-efficient communication protocols, smart routing techniques, and integration into IoT frameworks.

The WSN-enabled fire detection systems tend to utilize distributed sensing approaches whereby several sensor nodes are deployed across the forests for constant monitoring of important environmental parameters. The data collected from sensors will be transmitted using a multi-hop or clustering approach via communication channels to a central gateway or to cloud computing infrastructure for further processing. Machine learning, virtual sensing, and IoT technologies have recently been included in some research studies for better anomaly detection and decision-making. Moreover, research has been conducted on energy-efficient routing, adaptive topologies, and optimal placement of sensors to prolong the network lifetime while ensuring communication reliability in a changing environment. This progression of methodologies reflects the transition of WSNs from simple sensor-based networks into intelligent and scalable systems for forest fire monitoring [15], [18], [20], [22].

**Table 1.** Comparative analysis of WSN-Based wildfire detection systems

| Ref. | Method / Framework | Sensing Technology | Key Contribution | Strengths | Limitations |
|---|---|---|---|---|---|
| [1] | Modified LEACH Protocol | Environmental Sensors | Energy-efficient clustering protocol for WSNs | Reduces energy consumption and extends network lifetime | Not specifically designed for wildfire detection |
| [7] | FireWxNet | Temperature, Humidity, Wind Sensors | Multi-tier wireless monitoring platform for wildfire environments | Real-time environmental monitoring and distributed sensing | High deployment and maintenance cost |
| [8] | Forest Fire Detection WSN | Temperature, Smoke Sensors | Distributed WSN for early wildfire detection | Faster detection than conventional surveillance | Limited sensor battery lifetime |
| [15] | Intelligent IoT-WSN Framework | Temperature, Humidity, Smoke, Gas Sensors | Hybrid IoT-enabled WSN architecture for wildfire detection | Intelligent monitoring with real-time communication | Scalability and communication challenges |

| | | | | | |
|---|---|---|---|---|---|
| [18] | Smart WSN with Virtual Sensors | Environmental and Virtual Sensors | Machine learning-based wildfire evolution prediction | Improved prediction accuracy and adaptive sensing | Increased computational complexity |
| [22] | Optimized WSN Architecture | Multi-sensor Network | Cost-effective WSN deployment for wildfire mitigation | Energy-efficient network design and reliable sensing | Evaluated for specific deployment scenarios |

As summarized in Table 1, WSN based wildfire detection system has transformed itself from a basic sensing system to intelligent systems using IoT and machine learning technologies. Whereas earlier works mostly concentrated on environmental sensing and energy-efficient communications, modern works have been concentrating on improving prediction accuracy and adaptive sensing. Although these advancements have taken place, there are still some issues faced such as insufficient battery storage, reliable communication in the remote areas of the forest, and scaling for larger areas. This is why there has been a need to incorporate WSNs with other technology such as Internet of Things, drone-based monitoring, and AI- driven analytics for more robust hybrid wildfire monitoring systems.

## 3. IoT-Based Wildfire Monitoring Systems

Internet of Things (IoT) has significantly improved the wildfire monitoring process through the connection of sensor networks, cloud computing, and decision-making systems. In contrast to WSNs, the IoT systems make data transfer in a more constant and accessible way to monitor the connection of sensing devices in real-time. Continuous collection of environmental data like temperature, humidity, smoke, gas concentration, and wind are carried out by sensors and sent to the cloud or edge computing platform for storage, visualization, and alerts creation. The integration of IoT and WSNs has contributed to the efficiency of monitoring and has made IoT an essential element of smart wildfire detection systems [14], [15], [20].

IoT-based systems for wildfire monitoring typically adopt a layered design that includes sensing, communication, computation, and applications layers. The sensing nodes collect environmental data and forward it using various wireless communication protocols including Wi-Fi, LoRa, ZigBee, or cellular networks to cloud or fog computing systems. These computing systems analyze and visualize the collected data, while AI-powered decision-support tools produce fire warning alerts and risk assessment. Edge computing technology is also being integrated into the recent research to minimize communication delay and improve system responsiveness in remote forest environments [15], [20], [21].

**Table 2.** Comparative analysis of IoT-based wildfire monitoring systems

| Ref. | IoT Framework | Communication Technology | Key Contribution | Strengths | Limitations |
|---|---|---|---|---|---|
| [14] | IoT Ground Sensing System | LoRa, Wireless Networks | Comprehensive IoT sensing architecture for early wildfire detection | Large-scale monitoring and real-time data acquisition | Communication reliability in remote regions |
| [15] | IoT-WSN Framework | ZigBee, Cloud | Intelligent wildfire detection using IoT-enabled WSN | Real-time monitoring and automated alerts | Scalability challenges |
| [16] | UAV-Enabled IoT System | Wireless IoT Communication | IoT-assisted UAV framework for early wildfire prediction | Improved monitoring coverage and mobility | UAV flight limitations |
| [20] | Cloud/Fog IoT Architecture | Cloud–Fog Communication | Adaptive environmental monitoring based on wildfire risk | Reduced response latency and efficient data processing | Increased infrastructure complexity |
| [21] | IoT–ML Hybrid Framework | IoT with Machine Learning | Hybrid RF–XGB model for wildfire detection and prediction | High prediction capability and intelligent decision support | Requires extensive training data |

As shown in Table 2, recent IoT-enabled monitoring systems have evolved beyond merely connecting sensors to intelligent monitoring systems that use cloud, fog, and AI technologies. The current trend of research is mainly geared towards enhancing the real-time communication capability, scalability of data handling, and fast generation of alerts. However, the issues of network reliability, dependency on the infrastructure, and communication latency continue to be significant challenges, especially in the remote forest areas.

## 4. Artificial Intelligence-Based Wildfire Detection

The Artificial Intelligence (AI) technology is used for wildfire detection as it provides the possibility of automated processing of environment and image data in order to detect fires accurately and promptly. The machine learning and deep learning techniques are actively used for detecting smoke and flames, forecasting wildfires, analyzing satellite images, and detecting anomalies. The recent developments in computer vision and explainable AI have contributed to the improved model interpretability and reliability, which allows for enabling rapid wildfire management.

The AI-based wildfire detection consists of data collection, pre-processing, feature extraction, model development, and prediction. According to the nature of the application, the models are trained on sensor data, UAV images, or satellite images to detect fire incidents or estimate the probability of a wildfire. Nowadays, many research papers discuss the use of hybrid approaches that combine explainable AI with learning algorithms [21], [23], [24].

**Table 3.** Comparative analysis of AI-based wildfire detection methods

| Ref. | AI Model / Method | Data Source | Key Contribution | Strengths | Limitations |
|---|---|---|---|---|---|
| [12] | AI-Driven Prediction Model | Environmental Data | Intelligent wildfire prediction and monitoring | Early risk assessment | Limited validation |
| [13] | Machine Learning Review | Multi-source Data | Comprehensive review of ML applications | Broad coverage of AI techniques | Review study only |
| [21] | Hybrid RF–XGB | IoT Sensor Data | Wildfire detection and prediction | High prediction capability | Dataset dependency |
| [23] | AI-Based Wildfire Management | Multi-modal Data | AI framework from prediction | Comprehensive AI evaluation | Real-world deployment challenges |

| | | | | | |
|---|---|---|---|---|---|
| | | | to impact analysis | | |
| [24] | Explainable AI | Fire Image Data | Interpretable wildfire detection framework | Improved model transparency | Increased computational overhead |

As illustrated in Table 3, recent AI-based wildfire detection methods have been developed from traditional machine learning models to explainable and hybrid intelligent techniques that facilitate real-time monitoring and decision making. Recent research focuses on increasing prediction accuracy, model explainability, and the use of multiple sources of data. Nevertheless, the challenges associated with diversity of the datasets used, computational challenges, and large-scale deployment in practice still prevent the practical use of AI-based wildfire detection systems [12], [13], [21], [23], [24].

## 5. UAV-Based Wildfire Monitoring Systems

UAVs have proved to be efficient in firefighting with its rapid aerial reconnaissance, high-resolution imagery, and the ability to reach inaccessible areas. By incorporating the RGB, thermal, and multispectral sensors, UAVs has gained the ability to detect fires at the initial stage, find hotspots, and perform situational analysis. This type of technology outperforms the traditional methods of monitoring wildfires [11], [16], [17], [25].

UAV-based monitoring approaches usually include autonomous and planned missions for the collection of environmental data and subsequent processing of images on-board and/or ground-side and their transmission to the monitoring stations. In recent research work, AI methods have been incorporated into UAVs to detect fires and manage their flights and thereby improve wildfire monitoring [16], [17], [25].

**Table 4.** Comparative analysis of UAV-based wildfire monitoring systems

| Ref. | UAV Platform / Method | Sensor Type | Key Contribution | Strengths | Limitations |
|---|---|---|---|---|---|
| [11] | UAV Survey | RGB, Thermal Sensors | Comprehensive review of UAV-based wildfire monitoring | Covers monitoring, detection, and | Survey only |

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|---|---|---|---|---|---|
| | | | | firefighting strategies | |
| [16] | IoT-Enabled UAV Framework | Environmental Sensors | Integrated UAV-IoT system for early wildfire prediction | Enhanced monitoring coverage | Limited UAV endurance |
| [17] | Drone Network Early Warning System | Multi-Sensor UAV | Drone network for wildfire preparedness and response | Real-time aerial surveillance | Communication and deployment complexity |
| [25] | UAV Wildfire Dataset | RGB Imagery | Public UAV wildfire and smoke segmentation dataset | Supports AI model development and benchmarking | Dataset-specific applicability |

As summarized in Table 4, the UAVs used in wildfire monitoring have gone from surveillance through the use of smart UAVs with IoT and AI-enabled image analysis. The focus of today's researchers is on autonomous monitoring, quick data gathering and better situational awareness. Lack of endurance, reliable communication, and operation issues are among the main challenges faced by wildfire monitoring through UAVs.

## 6. Communication Technologies for Wildfire Monitoring

Efficient communication is very important when monitoring wild fires because it facilitates the real-time transfer of information from sensor nodes, unmanned aerial vehicles (UAVs), and IoT sensors to decision-making systems. Selection of the communication protocols to be used relies on aspects such as the transmission range, energy consumed, speed of data transfer, and the surrounding environment. LPWAN technology has recently attracted substantial interest by enabling long-range communications at lower energy consumption rates.

**Table 5.** Comparison of communication protocols for wildfire monitoring

| Protocol | Communication Range | Power Consumption | Data Rate | Suitability |
|---|---|---|---|---|
| ZigBee | 10–100 m | Very Low | Low | Dense WSN deployments |
| LoRaWAN | 2–15 km | Low | Low–Medium | Large-scale forest monitoring |

| | | | | |
|---|---|---|---|---|
| NB-IoT | 1–10 km | Low | Medium | Wide-area IoT systems |
| 5G | Several km | Moderate | Very High | Real-time monitoring |
| Wi-Fi | <100 m | High | High | Localized monitoring |

Table 5 describes a brief description of the different characteristics of the various communication technologies. LoRaWAN is used commonly for wildfire monitoring applications on a large-scale owing to the advantages associated with its long-range communication and lower power consumption, while NB-IoT and 5G provide improved connectivity for real-time applications. ZigBee and Wi-Fi, however, are more appropriate for short-distance or local application due to their short-range communication capabilities.

## 7. Publicly Available Wildfire Datasets

The performance of AI-driven wildfire detection systems is highly reliant on the accessibility of diversified datasets for training and testing purposes. Open wildfire datasets comprise satellite imagery, active fire data, and UAV-based image acquisition that are used to detect fires, segment smoke regions, classify wildfires, and estimate burnt areas. These open datasets allow developing and evaluating the performance of intelligent monitoring systems in varied environments [3], [4], [11], [25].

**Table 6.** Comparison of publicly available wildfire datasets

| Dataset | Data Type | Source | Primary Application |
|---|---|---|---|
| MODIS Fire Dataset | Thermal Satellite Images | NASA MODIS | Fire detection |
| FIRMS Dataset | Active Fire Records | NASA FIRMS | Fire monitoring |
| Landsat Fire Imagery | Multispectral Images | USGS | Burn area analysis |
| Sentinel-2 Dataset | Optical Satellite Images | ESA | Wildfire classification |
| Boreal Forest Fire Dataset | RGB and Smoke Images | UAV Platform | Fire detection and smoke segmentation |

As summarized in Table 6, the existing public wildfire datasets present useful tools for designing and testing AI-powered systems for monitoring. The satellite datasets feature large spatial coverage, while the UAV datasets feature high resolution of imagery in local fire identification tasks. However, the problem of data imbalances, geographic differences, quality of labeling, and scarcity of large multimodal datasets remains relevant [3], [4], [11], [25].

## 8. Hybrid WSN, AI, UAV, and IoT-Based Wildfire Monitoring Systems

The WSNs are capable of continuous monitoring of the environment but have limited capabilities in terms of communication and energy. The IoTs provide real-time connectivity but depend on the availability of the network infrastructure. The UAVs have flexibility in terms of monitoring from the air but have limited capabilities concerning flight endurance and costs. In the same way, AI models increase the precision of the detection but need data sets and computational resources.

The hybrid system for wildfire monitoring is a system that integrates WSNs in collecting environmental information, IoT in communication, UAVs in collecting aerial information, and AI in intelligent processing and decision-making. The environmental data collected from the various distributed sensors is communicated via IoT, and the UAVs complement this by making observations in inaccessible areas. The AI models integrate these different types of data in order to detect, predict and issue alerts about wildfires.

**Table 7.** Comparison of standalone and hybrid wildfire monitoring technologies

| Technology | Major Strength | Primary Limitation |
|---|---|---|
| WSN | Continuous environmental sensing | Limited communication range and battery life |
| IoT | Real-time connectivity and remote monitoring | Network dependency |
| UAV | Wide-area aerial surveillance | Limited flight endurance |
| AI | Intelligent detection and prediction | Dataset and computational requirements |
| Hybrid WSN + IoT + UAV + AI | Multi-source sensing, intelligent analysis, and real-time decision support | Higher system integration complexity |

As summarized in Table 7, the hybrid system of wildfire monitoring is efficient in overcoming the disadvantages that may arise using any of the technologies. WSNs ensure continuous ground-based detection, IoT helps with the effective communication of data, UAVs enhance the coverage areas of monitoring in areas that cannot be accessed, while AI helps in the intelligent interpretation of various forms of data to enable the effective detection and prediction of wildfires. As a result, hybrid approaches provide better solutions for intelligent wildfire monitoring when compared to WSN, IoT, UAV, and AI alone [15] – [25].

## 9. Research Gaps, Open Challenges and Future Research Directions

Despite significant advancements in WSN, IoT, UAV, and intelligent wildfire detection using AI, several issues have not been addressed by researchers yet. Some AI algorithms are trained using small or regional datasets, which makes the system unable to generalize in different environments. Besides, energy-efficient communication, scalability of sensors, data fusion from multiple sources, explainable AI, and benchmarks for evaluation are still underexplored. Field trials of developed intelligent monitoring systems in real wildfire situations are also insufficient [13], [14], [19], [21], [23], [24].

Future research works may focus on designing and developing a fully integrated hybrid systems, which would incorporate the above-discussed methods and tools in a unified ecosystem for wildfire monitoring. Edge artificial intelligence, federated learning, digital twin, autonomous multi-agent systems, and foundation vision-language model remain as some of the promising areas for research aimed at enhancing the precision of wildfire detection, decreasing communication delays, increasing scalability of the system, and developing autonomous management of wildfires [17], [19], [21], [23], [25]. Creation of benchmark multimodal datasets for wildfire detection will also contribute to the proper comparison and implementation of intelligent solutions in the real environment.

## 10. Conclusion

This research study has comprehensively examined the latest developments in intelligent wildfire detection through the analysis of the various contributions made by WSNs, IoT, AI, and UAV surveillance technologies. It has been identified from the comparative analysis that all four technologies provide their own strengths, such as distributed environmental sensing, effective communication, intelligent data processing, and swift aerial surveillance, but individually they have certain limitations in terms of energy consumption, communication, scalability, computational processing, and coverage. The review further highlighted that hybrid monitoring architecture for monitoring is well suited to meet these demands since it combines the strengths of WSN, IoT technology, UAV, and AI. Thus, such an approach helps to improve the precision of monitoring, increase its spatial scope, accelerate the discovery of wildfires, and make the decision making in time to act appropriately. Besides, the review considered communication techniques as well as publicly available datasets on wildfires, which are critically important for building intelligent monitoring systems. Lastly, the revealed research gaps stress the importance of researching scalable hybrid architecture, multimodal dataset standardization, edge intelligence, explainable AI, and autonomous collaborative monitoring. Developing these areas of research will help build next-generation wildfire monitoring systems.

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