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Innovative Approaches to Forest Fire Prevention: Integrating Technology and Ecological Strategies. A Comprehensive Review

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ABSTRACT

The problems associated with the advancement of technology and the environment are growing more complicated in recent years. Wildfires are one of the most important environmental challenges since they seriously endanger the world's ecosystems. There are many different types of damage done to forests, which result in both climate change and the devastation of terrestrial ecosystems. Consequently, the implementation of efficient strategies for early warning, prevention, the efficacy of ecological methods like fuel management strategies and green fire barriers in preventing wildfires and well-coordinated treatments is necessary to lessen their impact on both people and the environment. This overview examines the development of several technologies from previous years to the present with the purpose of detecting, tracking, and preventing forest fires. It draws attention to the advantages, restrictions, and potential advancements in this field of research. Because of their catastrophic effects on ecosystems and potential consequences on the climate, forest fires have become a major environmental concern. To create more potent plans for preventing and controlling wildfires, our research demonstrated the necessity for significant advancements in ecological methods, technological breakthroughs, and community involvement to strengthen wildfire preservation efforts.

Keywords: wildfire prevention techniques; satellites; AI; drones; ecological strategies; community engagement

INTRODUCTION

The intricacies associated with the widespread adoption of technology and its influence on the environment are growing in modern times. Wildfires present a substantial environmental dilemma as they represent a grave peril to the worldwide biosphere (Carta et al. 2023, Kreider et al. 2024). Given the substantial and diverse hazards posed by forest fires to terrestrial ecosystems and forests, it is imperative to adopt a proactive and timely strategy for their control (MacCarthy et al. 2023). Forest fires cause substantial damage to forested areas and have important ecological, economic, and societal consequences. Forest fires can be a result of both natural and anthropogenic causes (Arienti et al. 2006, Fried et al. 2008, Plucinski 2019, Kreider et al. 2024). Volcanic eruptions, lightning strikes, and spontaneous combustion are among various natural causes. Unregulated agricultural practices, alterations in land utilization, deliberate fire-setting, and negligence are instances of anthropogenic causes. Moreover, climate change amplifies fire conditions, hence heightening the probability and severity of wildfires (Blake et al. 2019, Winker et al. 2024).

The latest data on forest fires confirm our longstanding concerns: forest fires are expanding their reach more extensively compared to two decades ago, resulting in the destruction of at least double the amount of forested areas. In comparison to 2001, forest fires presently result in the annual loss of around 6 million hectares of tree cover (Tyukavina et al. 2022). Moreover, fire has a more prominent role in the depletion of global tree coverage compared to other processes such as mining and forestry. In 2001, fires accounted for around 20% of the whole forest cover loss. Currently, they constitute approximately 33% of the entire loss (MacCarthy et al. 2023). There has been a discernible surge in the incidence of fires in recent years, setting new records. Based on the rankings, it is evident that worldwide forest fires have been increasingly prevalent, with 2020, 2021, and 2023 being classified as the fourth, third, and first most severe years, respectively. In 2023, a land area about the size of Nicaragua, or nearly 12 million hectares, was consumed by fire, exceeding the previous record by approximately 24%. In Canada, almost 65% of the tree cover loss caused by fires in the preceding year may be attributed to catastrophic wildfires. Furthermore, these wildfires accounted for more than 27% of the overall tree cover loss globally (Flannigan et al. 2006, Wang et al. 2017, Hanes et al. 2019, MacCarthy et al. 2023). Climate change is a primary factor contributing to the increase in fire activity. Predictions indicate that severe heat waves will appear more often as global warming persists, with the current likelihood being five times higher compared to 150 years ago. Increased temperatures cause the terrain to become drier, creating optimal conditions for larger and more frequent forest fires (Carta et al. 2023, MacCarthy et al. 2023, Synolakis and Karagiannis 2024).

Recent technical developments have brought new instruments for detection, prediction, and reaction to wildfires, changing the management landscape. The fields of satellite technology and remote sensing are among the most promising for innovation. These technologies give authorities vital information on the health of the vegetation, moisture content, and fire behaviour, allowing them to properly monitor areas that are prone to wildfires. Modern sensors on satellites, like the Visible Infrared Imaging Radiometer Suite (VIIRS) (Schroeder et al. 2024, Setiawan et al. 2024) and the Moderate Resolution Imaging Spectroradiometer (MODIS) (Schroeder et al. 2024, Setiawan et al. 2024), make it easier to identify current fires and evaluate burned areas. This capacity is essential for comprehending the dynamics of fire and developing strategic reactions.

Furthermore, fire management and surveillance have undergone a radical change with the introduction of drones and unmanned aerial vehicles (UAVs) (Alon et al. 2021, Orgeira-Crespo et al. 2024, Wang et al. 2024, Wu et al. 2024). Drones with thermal imaging cameras are able to identify any fire outbreak early on because they can identify heat signatures that are invisible to the human eye. Their capacity to deliver real-time aerial data improves firefighting teams' situational awareness, empowering them to decide on containment tactics and resource allocation with knowledge. One example of how technology might enhance conventional firefighting techniques is the incorporation of drones into fire management operations.

The application of artificial intelligence (AI) (Cilli et al. 2022, Ahmad et al. 2023, Fan et al. 2024) to the forecast and management of wildfires is another noteworthy technological achievement. To identify high-risk locations and forecast fire behaviour, artificial intelligence (AI) algorithms examine enormous datasets, including past fire data, weather patterns, and vegetation conditions. AI can improve the accuracy of fire prediction models by using machine learning techniques, which will enable prompt responses. AI-powered systems, for example, can combine information from multiple sources, like weather stations and satellite photos, to offer thorough insights into changing fire conditions. This all-encompassing strategy helps with resource deployment and evacuation route planning in addition to increasing prediction accuracy.

Along with artificial intelligence, the creation of thermosensitive fire alarms (Doolin and Sitar 2005, Allison et al. 2016, Yu et al. 2021, Lv et al. 2022, Leslie et al. 2024) is a new method of detecting fires. By using materials that are sensitive to temperature changes, these alarms are able to identify sudden spikes in heat and provide early warnings that can stop small fires from growing into bigger catastrophes. In a similar way, autonomous systems and firefighting robots (Bogue 2021, Martinez-Rozas et al. 2021, Oliveira et al. 2021) are becoming important tools for fire management. These robots can operate in dangerous areas, lowering the risk to human firefighters while increasing operating efficiency. They are outfitted with cutting-edge sensors and firefighting abilities.

Technological advancements are important in preventing fires, but ecological solutions are still essential for managing fires sustainably. Prescribed fires and habitat restoration are examples of ecological practices that aid in lowering fuel loads and enhancing ecosystem resilience. These strategies reduce the severity of possible fires and establish firebreaks by carefully controlling vegetation. A comprehensive approach to fire management is facilitated by the fusion of ecological practices and technological advancements, which tackle the short- and long-term causes of wildfires (Brodie et al. 2024, Crockett and Hurteau 2024, Kokosza et al. 2024, Zald et al. 2024).

Furthermore, around 84% of wildfires are initiated by human action, with common causes including campfires, burning debris, and the usage of equipment (Kendell et al. 2023). Fostering a culture of readiness and resilience requires empowering local communities to take part in fire prevention initiatives. The community's ability to respond to wildfires can be greatly improved by educational initiatives that increase public knowledge of fire threats and preventative techniques. Involving the community in fire-safe landscaping and plant management initiatives not only reduces risks but also fosters community cohesion and encourages care of natural resources (Hensley 1975, Frandsen et al. 2011, Paton and Buergelt 2012, Amberson et al. 2023, Fazeli et al. 2024, Hostetter et al. 2024, Palsa et al. 2022).

Creating a thorough framework for preventing forest fires requires the convergence of ecological principles and technical developments. Every strategy works in concert with others to produce a synergistic impact that increases overall efficacy. For example, by identifying regions that need intervention, data gathered through remote sensing might inform ecological management approaches. On the other hand, ecological techniques, which offer insights into fire behaviour and vegetation dynamics, can improve the forecasting power of AI models.

Therefore, a cooperative strategy that makes use of the advantages of both ecology and technology is required due to the complex nature of forest fire prevention. The use of innovative approaches, such as artificial intelligence (AI), drones, remote sensing, thermosensitive alarms, and community involvement, will be essential for reducing the effects of wildfires as the wildfire landscape becomes more complicated. The purpose of this review is to compile advantages and limitations of these cutting-edge strategies in order to highlight their efficacy and potential for use in the future to avoid forest fires.

RESULTS OF RESEARCH

Remote Sensing and Satellite Technology

The field of remote sensing and satellite technologies has made substantial progress in the early identification and surveillance of wildfires. Due to the inadequate time interval between photos, proactive modeling using Landsat satellites has not been effective despite their decades-long deployment. Contemporary technology enables the monitoring of wildfires and the assessment of their expansion every 12 hours through the utilization of satellite imagery (Barber et al. 2024, Fraga et al. 2024, Liz-López et al. 2024, Synolakis and Karagiannis 2024). More often than ever, fire activity, growth, and behaviour are monitored using NASA's Fire Events Data Suite (Barber et al. 2024, Hunter 2024, Riris et al. 2024, Soja 2024). In 2024, the proposed synthetic aperture radar (SAR) constellations in Portugal, Spain, and Greece will provide high-resolution photographs every 4 hours (Garcia et al. 2024). From now on, the following images will provide estimates of how the fire perimeter will change over time. By combining thermal imaging and vegetation data with satellite photography, the accuracy of fire spread predictions can be greatly improved, leading to a transformative impact on the suppression of large-scale wildfires (Collins et al. 2024, Lee et al. 2024, Michaelides et al. 2024, Zhang et al. 2024). Satellite imaging is extensively employed globally for wildfire prevention. Synthetic aperture radar (SAR) devices possess more allure compared to optical and multispectral instruments due to their ability to operate in all weather conditions, both day and night, without being hindered by smoke or clouds in the presence of an active fire (Michaelides et al. 2024, Zhang et al. 2024). Geostationary satellites, such as those operated by the National Oceanic and Atmospheric Administration (NOAA), can track the boundaries of wildfires in real-time by consistently observing a certain area. Thermal infrared sensors are employed to identify heat irregularities associated with active flames. Geostationary satellites offer a notable advantage by providing regular updates, which are crucial for understanding the dynamics of fires and effectively coordinating firefighting efforts (Chen et al. 2024, Dong et al. 2024, Giorgi 2024, Kang and Im 2024). VIIRS (Visible Infrared Imaging Radiometer Suite) and MODIS (Moderate Resolution Imaging Spectroradiometer) (Setiawan et al. 2024, Schroeder et al. 2024) sensors, although carried on separate satellite platforms run by NASA and NOAA, respectively, are instruments that gather data about Earth observation. The MODIS sensor has several spatial resolutions and operates in 36 spectral bands, ranging from 0.4 to 14.4 µm in wavelength. There are three bands: two at 250 meters, five at 500 meters, and 29 at one kilometer. Numerous research projects have made extensive use of this cutting-edge technology. There are 22 spectral bands available with VIIRS, comprising 1 panchromatic day/night band (750 m), 5 imaging resolution bands (I bands, 375 m), and 16 moderate-resolution bands (M bands, 750 m) (Setiawan et al. 2024, Schroeder et al. 2024). The data collected by this technology, which is designed to capture images of the Earth from polar orbits, enables the development of applications for monitoring the Earth's land, atmosphere, cryosphere, and seas. Although they often revisit the same location every several hours, they send detailed information at a reduced rate of occurrence. Due to their short revisit periods, these satellites can rapidly detect and monitor the spread of fires. However, they are particularly valuable for recognizing larger fires and assessing the extent of the damage caused by burns (He et al. 2024, Sivakumar et al. 2024, Zhou et al. 2024). Since the 1980s, there has been extensive usage of the Advanced Very High-Resolution Radiometer (AVHRR) sensor on board NOAA satellites for the detection and monitoring of forest fires. AVHRR is appropriate for a range of fire-related applications due to its daily global coverage at moderate resolution (~1 km) and spectral coverage in the visible, near-infrared, mid-infrared, and thermal infrared (Li et al. 2001, Schiks et al. 2024). Among the main benefits of employing AVHRR for monitoring forest fires are: identifying burning fires – with its heightened sensitivity to fire radiation, mid-infrared channel 3 (3.55-3.93µm) enables the detection of even the smallest sub-pixel fires against a background that is cooler; tracking the spread of the fire – two daily revisits allow for the tracking of the growth and movement of big flames over several days; evaluating regions that were burned – using variations in surface reflectance, the visible and near-infrared channels can be utilized to map the extent of burned areas following a fire. Contextual data and dynamic thresholds are two features of more sophisticated fire detection algorithms. It has also been demonstrated that AVHRR data combined with better resolution sensors such as MODIS improves fire monitoring capabilities. Because of its coarse resolution, AVHRR sometimes detects fires only after they have spread, even though it offers a useful long-term record of worldwide fire activity. AVHRR works best when combined with other ground-based, aerial, and satellite monitoring systems to provide timely early warnings (Kim et al. 2016, Carta et al. 2023, Schiks et al. 2024). Sentinel-2 and WorldView-3 are two examples of satellites that have great spatial resolution (down to 30 cm) and frequent revisit durations (every 5 days for Sentinel-2). They are especially helpful for mapping and detecting small-scale fires locally, which makes it possible to identify flames that polar-orbiting satellites could overlook. Multispectral bands of Sentinel-2 are useful for identifying burn scars and evaluating the condition of the vegetation (James et al. 2023, Alonso et al. 2024, Panđa et al. 2024). Remote sensing and satellite technologies hold significant promise for wildfire prevention due to their ability to monitor fire-prone regions and provide early warnings. Modern satellites, such as those equipped with the Visible Infrared Imaging Radiometer Suite (VIIRS) and Moderate Resolution Imaging Spectroradiometer (MODIS), can detect vegetation stress and track atmospheric conditions conducive to wildfires. By integrating data from these satellites with predictive models, authorities can identify high-risk zones before ignition occurs. For example, synthetic aperture radar (SAR) technology enables consistent observation, unaffected by weather or smoke, making it an invaluable tool for preventive monitoring in vulnerable regions. Table 1 below shows various image sensors and their specifications.

Drones/UAVs

These tools are extremely helpful as they are equipped with high-resolution cameras and thermal image technology. They greatly improve aerial surveillance and real-time data collecting for wildfire management. This feature enables precise access to the dimensions, extent, and dynamics of a fire. Drones provide firefighters with comprehensive visual data, allowing them to make well-informed judgments on the allocation of resources, the selection of evacuation routes, and the development of firefighting methods. Drones can detect areas of intense heat and assess the strength of a fire, which is essential for effectively combating fires and allocating resources (Radu et al. 2019, Alon et al. 2021, Roldán-Gómez et al. 2021). Different types of drones as shown in Table 2 are used for firefighting, i.e. DJI Mavic 3 Thermal, DJI Matrice 300 RTK, and DJI Matrice 30T (Alon et al. 2021, Wu et al. 2024). The Zen Muse H20N camera is specially attached with Matrice 300 RTK drone, with its advanced imaging features which include dual thermal cameras, a laser rangefinder, and starlight sensors for low light. H20N is appropriate for a wide range of uses, including surveillance, search and rescue missions (Bhattarai and Lucieer 2024). These drones are also used for carrying firefighting equipment such as fire extinguisher balls (Valmiki et al. 2024, Wang et al. 2024). Drones are crucial for conducting search and rescue operations during wildfires, as well as for monitoring and observing the fires. Thermal cameras equipped on drones can detect heat signatures, facilitating the identification and assessment of stranded individuals. This capability enables rescue teams to effectively prioritize their actions and perhaps save lives in situations with limited sight caused by smoke or darkness. Drones are not only useful for determining the magnitude, precise location, spread, and behaviour of fires, but they are also effective in reducing the extent of fires during their early phases (Orgeira-Crespo et al. 2024, Wu et al. 2024). Drones are an essential instrument for conducting post-fire evaluations in the aftermath of a wildfire. By utilizing airborne imagery, they may acquire thorough documentation of the fire's impact on infrastructure, vegetation, and structures in the affected areas. This data facilitates a more comprehensive view on the extent of the damage and provides valuable insights for the development of future fire management strategies. Recovery planning, insurance claims, and post-fire investigations are all crucial aspects (Wang et al. 2024). These are also cost-effective alternatives to traditional firefighting methods (Orgeira-Crespo et al. 2024, Wang et al. 2024, Wu et al. 2024). Drones equipped with thermal imaging cameras can serve as on-demand surveillance tools, mapping fuel loads and identifying areas of concern in real time. Their flexibility allows for frequent, localized assessments, which complement satellite data by providing higher-resolution imagery for targeted interventions. For instance, drones can map the effectiveness of green fire barriers or assess the success of controlled burns, enabling continuous improvement in fire prevention measures.

Table 1. Review of the various image sensors used in satellites.

Image sensor	MODIS	VIIRS	AVHRR	SAR
Spectral band	36 (2 bands at 250 m, 5 bands at 500 m and 29 at 1 km resolution)	22 (16 moderate-resolution bands at 750 m, 5 image resolution at 750 m and 1 panchromatic day/night at 750 m)	6 (bands at 1 km)	L-band (1-2 GHz, 15-30 cm wavelength) C-band (4-8 GHz, 3.75-7.5 cm wavelength) X-band (8-12 GHz, 2.5-3.75 cm wavelength) P-band (0.3-1 GHz, 30-100 cm wavelength
Spatial resolution	1 km	750 m	1 km	1-30 m
advantages	Additional channels to provide more accurate earth mapping	The panchromatic day/night band provides a way to collect more precise data on forest fires.	infrared	All weather capability, longer wavelength for high surface penetration and interferometric capabilities.
Limitations	Earth mapping takes 99 minutes to be done.	Earth mapping takes 50 minutes to be done.	Earth mapping takes 102 minutes to finish.	Complex data interpretation, speckle noise, calibration requirements and limited penetrations in wet soils
References	(Setiawan et al. 2024, Schroeder et al. 2024)	(Setiawan et al. 2024, Schroeder et al. 2024)	(Kim et al. 2016, Carta et al. 2023, Schiks et al. 2024)	(Carta et al. 2023, Michaelides et al. 2024, Zhang et al. 2024)

Table 2. Review of the various types and specifications of drones used in wildfire fighting.

Drones	DJI Mavic 3 Thermal	DJI Matrice 300 RTK	DJI Matrice 30T
Image sensor	Wide camera: 1/2" CMOS, 48 MP Zoom camera: 1/2" CMOS, 12 MP Thermal camera: Uncooled Vox microbolometer, 640×512 px	Zen muse H20 series cameras available with various sensor options	Zen muse L1 lidar pod with 1" CMOS RGB camera Zen muse H20N hybrid sensor with 1/2" CMOS 48 MP visual, 640×512 thermal
Spectral band	Wide/zoom cameras: Visible spectrum Thermal camera: 8-14μm infrared wavelength	Depends on camera model, can include visible, thermal, and multispectral	Visual: Visible spectrum Thermal: 8-14μm infrared
Spatial resolution	Wide camera: 8000×6000 max image size Zoom camera: 4000×3000 max image size, 56x hybrid zoom Thermal camera: 640×512 resolution	Depends on camera model, up to 20 MP for visual, 640×512 for thermal	Visual: 8000×6000 max image size Thermal: 640×512 resolution
Advantages	Compact and portable design Thermal camera with temperature measurement capabilities Simultaneous zoom on thermal and zoom cameras Long 45 min flight time	Modular design allows using different camera payloads Supports RTK for precise positioning Long flight time up to 55 min	Lidar pod provides 3D data for mapping and modeling Hybrid camera provides both visual and thermal imaging Compact size for a professional drone
Limitations	Smaller sensor size compared to larger drones Lower thermal camera resolution than some competitors	Larger size and weight compared to Mavic 3 Thermal camera resolution limited to 640×512 on H20T	Thermal camera resolution limited to 640×512 Lidar pod adds weight and complexity
References	(Alon et al. 2021, Wu et al. 2024, Orgeira-Crespo et al. 2024, Wang et al. 2024)	(Alon et al. 2021, Wu et al. 2024, Orgeira-Crespo et al. 2024, Wang et al. 2024)	(Alon et al. 2021, Wu et al. 2024, Orgeira-Crespo et al. 2024, Wang et al. 2024)

AI in Wildfire Prediction

The AI data-driven approach (Haney 2019) constructs prediction models by leveraging extensive datasets, including historical fire data, meteorological data, and topographical parameters. The Fire Aid program in Türkiye employs machine learning algorithms to assess more than 400 factors from 14 datasets, enabling the anticipation of wildfires with a precision rate of 80% up to 24 hours in advance. Due to its predictive powers, authorities can proactively plan and implement preventive measures, significantly reducing the likelihood of injury and enhancing public safety (Sayad et al. 2019, Giannakidou et al. 2024, Okoro et al. 2024). Predicting fire behaviour, considering variables such as weather patterns and fuel moisture levels is essential for efficient deployment of resources and planning evacuations. Real-time monitoring and detection artificial intelligence systems have the capability to examine satellite imagery and aerial data in order to identify areas of intense heat caused by fires and continuously observe how fires are spreading and behaving (Czyczula Rudjord et al. 2022). AI combines data from multiple sources, including remote sensors and meteorological stations, to give a complete understanding of wildfire situations. This helps emergency responders make well-informed choices (Jaafari et al. 2019, Sayad et al. 2019, Carta et al. 2023). Artificial intelligence enhances the efficiency of allocating resources in wildfire scenarios. AI algorithms can enhance the allocation of firefighting resources by assessing up-to-date data and guiding them towards areas with the highest demand for assistance. This competence is crucial for minimizing reaction time and enhancing the effectiveness of firefighting operations. Artificial intelligence-powered early warning systems are crucial for effectively managing wildfires. These devices can rapidly alert authorities about the initiation of a wildfire by evaluating data from sensors and satellites. Swift detection is crucial in order to initiate early measures that can prevent fires from escalating (Jaafari et al. 2019, Sayad et al. 2019, Czyczula Rudjord et al. 2022, Carta et al. 2023, Boroujeni et al. 2024). Enhancing wildfire control capabilities can be achieved by integrating AI with other technologies such as smoke sensors, drones, and imaging satellites. While satellite systems analyze broader patterns and trends in fire behaviour, drones equipped with artificial intelligence (AI) capabilities can provide focused monitoring and detection. This comprehensive approach improves overall management methods and offers a more advanced comprehension of wildfire dynamics (Boroujeni et al. 2024).

AI-driven systems further enhance preventive strategies by analyzing large datasets to predict wildfire behaviour and identify risk factors. Machine learning models, such as FireNet, process historical fire data alongside meteorological inputs to forecast potential fire outbreaks. These forecasts allow for pre-emptive action, such as deploying resources to high-risk areas or conducting controlled burns to reduce fuel loads. Behavioural modeling with AI can also simulate human evacuation scenarios, improving preparedness and minimizing casualties.

Table 3. Review of the various AI models.

AI models	Convolutional neural networks (CNNs)	Recurrent neural networks (RNNs)	Hybrid models	Explainable AI (XAI)
Models	FireXnet, CNN-BiLSTM, spatial prediction CNN and multi-kernel CNN	Basic RNNs, long short-term memory (LSTM) networks, gated recurrent units (GRUs) and bi-directional LSTM (BiLSTM)	CNN-BiLSTM, MA-Net, DNN emulators and hybrid machine learning models	Random forest with Shapley values, SHAP (Shapley additive explanations), integrated feature engineering models and explainable deep learning models
Advantages	High accuracy, feature extraction, scalability and explainability	Temporal dynamics, flexibility, improved prediction accuracy and real-time analysis.	Improved accuracy, adaptability, robustness and explainability	Enhanced interpretability, improved decision support, bias detection and correction and facilitated communication
Limitations	Data requirements, computational complexity, overfitting and interpretability	Data requirements, computational complexity, overfitting and interpretability	Complexity, overfitting, interpretability and deployment challenges	Complexity, overfitting, interpretability and deployment challenges
References	(Zhang et al. 2019, Ahmad et al. 2023, Marjani et al. 2024)	(Kremens et al. 2010, Liang et al. 2019, Perumal and Van Zyl 2020, Marjani et al. 2024)	(Bui et al. 2016, Jaafari et al. 2019, Marjani and Mesgari 2023, Marjani et al. 2024)	(Cilli et al. 2022, Fan et al. 2024, Ahmad et al. 2023)

Table 3 shows various AI models used in wildfire prediction and prevention. Convolutional neural network systems (CNNs) are incredibly powerful image analysis tools, especially when it comes to the identification of wildfires using satellite imagery and aerial photographs. CNNs can automatically learn spatial hierarchies of features, which negates the need for manual feature extraction and allows them to identify complex patterns directly from raw data. CNNs can also learn from the data, which leads to significantly improved accuracy in image classification tasks, such as the identification of wildfires, often outperforming conventional detection methods. CNNs also operate well in unpredictable contexts, continuing to function even in the presence of unknown data. Applications like wildfire detection, where conditions might vary greatly and real-time analysis is necessary for efficient response and control, depend heavily on this robustness. CNNs are an effective method for detecting wildfires because they may improve forecast accuracy and dependability in the demanding and dynamic conditions by utilizing their strengths in image processing (Zhang et al. 2019, Ahmad et al. 2023, Marjani et al. 2024). Wildfire prevention and control is becoming more and more dependent on the application of recurrent neural networks (RNNs). Especially in conjunction with other machine learning approaches, RNNs offer robust tools for assessing wildfire risk data and enhancing detection strategies (Kremens et al. 2010, Liang et al. 2019, Perumal and Van Zyl 2020, Marjani et al. 2024). According to WEF (https://www.weforum.org/agenda/2023/09/ai-model-prevent-wildfires/) researchers from Finland's Aalto University developed the Fire CNN model, which is one noteworthy advancement. This model predicts locations at high risk for wildfires by analyzing weather data and satellite imagery using both convolutional neural networks (CNNs) and radial neural networks (RNNs). By simulating several land management techniques, such as turning shrubland into swamp forests and blocking drainage canals, the model has the ability to minimize wildfire occurrences by up to 76%. The use of hybrid artificial intelligence (Bui et al. 2016, Jaafari et al. 2019, Marjani and Mesgari 2023, Marjani et al. 2024) models is growing in the prevention and management of wildfires. These models combine different machine learning approaches to improve operational efficiency and predictive accuracy. These models analyze complicated datasets linked to wildfire risks and behaviours by combining several techniques, including convolutional neural networks (CNNs), recurrent neural networks (RNNs), and neuro-fuzzy systems. The application of explainable AI (XAI) in wildfire control is growing as a means of improving the interpretability of machine learning algorithms that forecast fire dangers. XAI assists in identifying important variables that influence the likelihood of wildfires, such as vegetation types and meteorological conditions, by revealing how models create predictions. A study that used a random forest model using Shapley values, for example, showed that it could detect high wildfire occurrence areas with 81.3% accuracy. It also highlighted important factors such as the Fire Weather Index and Normalized Difference Vegetation Index. Because of this openness, forest managers are better equipped to decide on fire control tactics, which eventually help to prevent and lessen wildfire disasters (Cilli et al. 2022, Ahmad et al. 2023, Fan et al. 2024).

Thermosensitive Fire Alarms

There has been a lot of discussion about how early-stage fire-warning systems (EFWSs) are better at spotting fire conditions that develop before they explode. Significant improvements in EFWSs over the past few years have raised the possibility of more time for evacuation in order to lessen the continuous risk of unintentional fires in our daily life (Lv et al. 2022, Li et al. 2022). Thermosensitive alarms, a recent innovation in early-stage fire warning systems, sense temperature changes to signal fire before combustion takes place. These alerts can offer vitally important extra time for evacuation and response in order to save lives, as well as assistance in implementing early firefighting measures in order to avert fire catastrophes (Li et al. 2022, Carta et al. 2023). While traditional smoke detectors may fail due to false alarms caused by dust or steam, thermosensitive fire alarms are more innovative to early fire detection. Some key advancements associated with thermosensitive fire alarms are reduced false alarms (Yu et al. 2021, Lv et al. 2022), real time monitoring and alerts (Lv et al. 2022), wireless communication (Liu et al. 2022, Carta et al. 2023, Alkhatib et al. 2024) and heat detection mechanism (Yu et al. 2021, Li et al. 2022, Alkhatib et al. 2024). Different thermosensitive fire alarms, their specifications and limitations can be seen in Table 4.

Firefighting Robots and Autonomous Systems

Human firefighters rely on firefighting robots developed in Japan to help them with dangerous and challenging tasks. Since these robots are well-equipped with a variety of sensors and firefighting devices, they can function in dangerous conditions like highly intense wildfires and toxic smoke (Guruprasad et al. 2020, Arora et al. 2023). Numerous firefighting robots are built to function independently. They can traverse over areas damaged by fires using sensors and algorithms, and they can collect and transmit data in real time, including temperature readings, smoke densities, and video feeds. These robots have fire suppression tools including foam dispensers, water cannons, and fire extinguishers installed. These robots can navigate challenging environments that are impossible for human firefighters to access, like rubble, steep inclines, and small places, thanks to advanced mobility technologies. Firefighters could remotely operate certain robots to facilitate coordinated efforts during rescue and firefighting operations (Guruprasad et al. 2020, Arora et al. 2023, Li et al. 2023, Talavera et al. 2023). Table 5 given below shows different types of firefighting robots and their specifications.

Case Studies of Forest-Ecological Techniques

Various contemporary ecological methods are employed to mitigate forest fires. Prescribed or controlled burns are deliberate, closely monitored low-intensity fires initiated with the aim of mitigating the risk of wildfires by minimizing the presence of hazardous fuels, such as dead vegetation and underbrush. This strategy can mitigate the challenges faced by firefighters in controlling wildfires by revitalizing ecosystems, promoting the establishment of fire-adapted species, and modifying future fire behaviour (Brodie et al. 2024, Krishnambika et al. 2024, Wang et al. 2024). Strategically implemented sections, referred to as "fuel breaks", disrupt the uninterrupted expansion of combustible vegetation and effectively reduce or extinguish fires. Implementing practices such as tree thinning, undergrowth clearance, and the protection of open spaces around infrastructure and communities in areas prone to high-risk situations are effective methods for their construction. Fuel stops provide firefighters with additional time to respond and protect vulnerable areas (Krishnambika et al. 2024, Wang et al. 2024). Implementing a deliberate tree spacing and thinning approach can effectively mitigate excessive growth and impede the progression of wildfires. Forest managers engage in brush clearing and tree spacing activities based on projected canopy dimensions in order to establish defensible areas, as excessive growth of trees, shrubs, and other plants can be susceptible to combustion. As a result, fires have a reduced likelihood of spreading and may be extinguished more rapidly (Brodie et al. 2024, Crockett and Hurteau 2024, Kokosza et al. 2024, Zald et al. 2024). Ensuring the prevention of wildfires necessitates the presence of forests that are in good health and possess the ability to recover quickly. By introducing tree species that possess greater resistance to disease, drought, and fire, forests become less susceptible to devastating fires. Research by Sharon Hood et al. provides a comprehensive assessment of the many tree species in the Northern

Table 4. Different thermosensitive fire alarms used in wildfire prevention.

Thermosensitive fire alarms	Fixed temperature sensors	Rate-to-rise sensors	Combination sensors
Sensor	Type: Heat-sensitive element (e.g., thermistor or eutectic alloy) Activation: Triggers an alert when the ambient temperature reaches a predefined threshold (e.g., 58°C).	Type: Rapid temperature rise detector based on heat sensitivity. Activation: Sets off an alarm in the event that the temperature increases rapidly (by, say, 10°C/min).	Type: Has integrated rate-of-rise detection and fixed temperature features. Activation: Sets off an alert in response to either gradual temperature increases or preset temperature thresholds.
Spectral band	Mostly works in the 8–14μm thermal infrared range.	Mostly works in the 8–14μm thermal infrared range.	Mostly works in the 8–14μm thermal infrared range.
Advantages	Cost effective, reliable and minimal maintenance	Quick response and effective in various environments	Versatile detection and enhanced safety
Limitations	Fixed threshold, slower response and limited detection	False alarms and limited to rapid changes	More complex and calibration needed
References	(Yu et al. 2021, Doolin and Sitar 2005, Lv et al. 2022, Leslie et al. 2024, Momeni and Al-e 2024)	(Doolin and Sitar 2005, Yu et al. 2021, Leslie et al. 2024, Lv et al. 2022)	(Doolin and Sitar 2005, Allison et al. 2016, Yu et al. 2021, Lv et al. 2022, Leslie et al. 2024)

Table 5. Type and specifications of firefighting robots.

Firefighting robots	Colossus (Shark Robotics)	Fotokite (Perspective Robotics)	THOR/Saffir	SmokeBot
Sensor	Cameras and thermal sensors	Thermal cameras and standard visual cameras	Equipped with advanced vision sensors and stereoscopic thermal LIDAR.	Gas sensors, laser scanner, and 3D thermal imager.
Spectral band	8-14μm	8-14μm	Visual sensors function within the visible spectrum, with a range of 8-14μm.	While gas sensors identify particular gas concentrations, thermal sensors function within the 8–14μm range.
Spatial resolution	High resolution imaging based on cameras	High resolution imaging based on cameras	For accurate fire detection and navigation.	Functions well in low-visibility environments.
Advantages	Capable of transporting equipment and navigating dangerous terrain. Offers video feeds and data in real-time to aid in combating fires. Operates in hazardous regions to lower the risk to human firefighters.	Gives a rapid overview of the situation for situation assessment. Minimizes water use by precisely focusing on fire hotspots. With just a start button, it is straightforward to use.	Suitable for risky tasks, designed for unstable situations. Able to navigate through small places and unlock doors. Permits remote operation, hence lowering the risk to human firefighters.	Has the ability to map in real time and navigate through thick haze. Identifies possible explosion hazards and gas concentrations. Wi-Fi enabled, enabling remote control operation.
Limitations	Limited operating time because of battery limitations. Susceptible to exposure to water and intense heat.	Restricted by the tether length, which could limit the practical range. Operation dependent on ground control.	Slower reaction time than other robots used in fighting fires and susceptible to high temperatures and water.	Information gathering and processing take between 20 and 30 minutes. It is still under development and not generally accessible for practical use.
References	(Bogue 2021, Martinez-Rozas et al. 2021, Oliveira et al. 2021)	(Dufek et al. 2017)	(Dhiman et al. 2020, Tephila et al. 2022)	(Sawant et al. 2020, Alrabia et al. 2021)

Rockies, focusing on their ability to adapt and regenerate in the aftermath of fires. The research emphasizes that particular species, such as ponderosa pine and western larch, exhibit exceptional fire resistance due to their large root systems and thick bark (Hood et al. 2018). According to (Alberta Government. 2012 aug 03) deciduous trees like trembling aspen can act as natural firebreaks, slowing fire spread due to their higher moisture content and different structural properties. Moreover, encouraging variety and avoiding monocultures increases the overall resilience of ecosystems (Shuhui et al. 2024, Speck and Speck 2024, Rhodes 2024). The utilization of livestock, specifically sheep and goats, for planned grazing can effectively mitigate the usage of detrimental fuels. Ruminants devour the vegetation such as grasses and bushes which is capable of igniting fires (Batcheler et al. 2024, Karp et al. 2024, Kerns and Day 2024, Schachtschneider et al. 2024). Mechanical methods, such as masticators and mulching machines, are used to decrease the density of plants and establish defensive areas (Calderon et al. 2024, Harrower 2024). Utilization of litter layer to grow mushrooms has also been found as a key factor to prevent wildfires, since fungal spread on the litter layer has several benefits such as nutritional cycling (Wade and Lundsford 1990, Adams and Neumann 2023), soil structure improvement (Hopkins et al. 2021, Adams and Neumann 2023), fire resilience (Hopkins et al. 2021, Espinosa et al. 2023), pest and pathogen control (Espinosa et al. 2023). Some studies used fertilizers on litter layer and achieved some outstanding results which are very effective in wildfire prevention such as: accelerated decomposition, promoting beneficial microbial activities, nutrient enrichment, improved soil quality and encouraging vegetation cover (Ferreira et al. 2015, Girona-García et al. 2021, Agbeshie et al. 2022, Song et al. 2022, Adams and Neumann 2023). Strategically positioned patches of vegetation that are resistant to fire are referred to as "green fire barriers" or "green firebreaks". They are employed to hinder or postpone the propagation of wildfires, especially when they are in proximity to buildings and other structures. Compared to traditional firebreaks, they are a more ecologically sustainable choice since they do not eliminate all organic matter until they reach mineral soil (Warnell et al. 2023). The primary goal of green fire barriers is to disrupt the continuity of flammable vegetation, thus reducing the severity of a fire. Planting low-flammability species can effectively decrease the amount of flammable material, thus slowing down the spread of flames. Studies have demonstrated that places with well-managed green firebreaks exhibit reduced severity and aggression of fires when compared to untreated areas (Li et al. 2024, Murray et al. 2024, Wang et al. 2024). Green fire barriers that employ indigenous plants with minimal flammability also promote biodiversity. By safeguarding indigenous plant species and providing habitats for wildlife, these barriers can contribute to the preservation of ecological balance. Strategically planting a diverse range of species can help to replace invasive plants that may increase the likelihood of fire (Weir et al. 2012, Ascoli et al. 2023, Warnell et al. 2023). Green fire barriers, particularly when positioned along topographic contours, can mitigate erosion and enhance soil stability. Fire activity can exacerbate the risk of erosion following intense rainfall, and vegetation roots play a crucial role in soil stabilization. This ecological advantage is particularly noteworthy in areas where wildfires frequently result in soil degradation (Warnell et al. 2023). These barriers offer protection to residents in places where urban areas meet wilderness areas. These barriers serve to safeguard homes from approaching flames by creating a protective boundary around residential zones. Moreover, they can provide firemen with a fortified zone to effectively combat flames, hence enhancing safety for both civilians and emergency personnel. The field data presented by Cui et al. (2019) demonstrate the efficacy of green firebreaks in putting out large, intense fires. The authors show the potential of these barriers as a biodiversity-friendly fire management approach by highlighting lessons learned from their implementation in China. Another researcher (Wang et al. 2024) also suggested using green fire barriers because of their ability to reduce wildfires. To improve these barriers' ability to guard against wildfires, it highlights how crucial it is to choose the right species.

Community Engagement and Education

Active community participation and education are necessary for promoting wildfire-safe behaviours and enhancing community resilience against fire dangers. This involves implementing initiatives to enhance public consciousness and executing successful community-driven endeavours (Elsworth et al. 2009). Community education: it is imperative to provide people with knowledge about the hazards of wildfires and the proactive measures they can use to mitigate those hazards. By implementing instructional programs, community members are more proficient in understanding fire safety protocols and recognizing the importance of promptly identifying and taking action in the event of a potential fire (Hensley 1975, Ryan et al. 2020, Palsa et al. 2022, Campbell et al. 2024). Promote a culture of preparedness: awareness initiatives play a crucial role in fostering a culture of preparedness and active engagement in fire safety measures by increasing community members' understanding of their responsibilities. This involves dispelling myths about wildfires and providing accurate information to empower residents to make informed decisions (Hensley 1975, Frandsen et al. 2011, Paton and Buergelt 2012, Palsa et al. 2022, Amberson et al. 2023, Fazeli et al. 2024, Hostetter et al. 2024). Encourage collaboration: effective campaigns often involve partnerships among community members, non-profit organizations, and local government institutions. Collaboration can enhance the efficient utilization of resources and offer tailored fire protection strategies to address the specific requirements of different communities (Hensley 1975, Palsa et al. 2022, Azevedo et al. 2024, Campbell et al. 2024, Hostetter et al. 2024, Shahi 2024).

Figure 1. Ecological techniques.

Figure 2. Community engagement.

Case Studies of Effective Community-Led Fire Safety Programs

Several successful community-led initiatives have demonstrated the significance of education and engagement in mitigating wildfires. Community workshops: utilizing interactive workshops has been effective in engaging residents and instilling in them a sense of satisfaction in their preparedness for wildfires. These programs often include presentations and interactive fire safety demonstrations, which promote community engagement (Eriksen 2013, Elliott 2022, Palsa et al. 2022, Vázquez-Varela et al. 2022, Elliott et al. 2023, Dobrich 2024). School programs can ensure that students are cognizant of the hazards of fire and equipped with the knowledge to mitigate them by incorporating fire safety instructions into the curriculum. This approach promotes the engagement of the younger population in advocating for safety protocols inside their households, while simultaneously providing them with knowledge and information (Eriksen 2013, Elliott 2022, Elliott et al. 2023). Neighbourhood watch programs: initiatives aimed at bolstering neighbourhood watch organizations to enhance community awareness and preparedness. These activities enhance response capabilities and community relationships by promoting neighbour vigilance, sharing information about fire threats, and participating in safety drills (Eriksen 2013, Elliott 2022, Palsa et al. 2022, Elliott et al. 2023, Dobrich 2024). Feedback mechanisms: soliciting community feedback on fire services and educational efforts facilitates the adaptation of plans to align with regional needs. This collaborative approach leads to the development of more efficient emergency response and fire prevention techniques (Eriksen 2013, Elliott et al. 2023,). The utilization of technology, such as social media and smartphone applications, has become imperative to disseminate fire safety messages to the broader population (Dobrich 2024, Isabella 2024). These technologies contribute to community engagement and awareness by delivering prompt information on fire incidents, offering safety guidance and giving educational resources (Eriksen 2013, Elliott et al. 2023, Wessinger 2024).

Integration of Technology, Land Management, and Community Education in Wildfire Prevention

Wildfire prevention requires a comprehensive approach that brings together technological advancements, ecological land management practices, and active community education. Modern technologies such as remote sensing, AI-driven models, and drones have transformed how wildfires are detected and managed. For example, satellite imaging identifies high-risk zones based on vegetation density, enabling targeted interventions like controlled burns or grazing (Carta et al. 2023). AI models analyze historical fire data to guide the strategic placement of green fire barriers and ecological buffers, while drones equipped with thermal sensors provide real-time monitoring of fuel loads, allowing for precise actions like tree thinning or undergrowth clearance (Wang et al. 2024). These tools not only detect risks but also inform about actionable land management strategies, creating a more proactive approach to wildfire prevention.

The successful adoption of these technologies hinges on an informed and engaged community. Educational initiatives, such as workshops, can teach residents how to use mobile wildfire detection apps and AI-driven alert systems (Elsworth et al. 2009). Involving communities in deploying and maintaining technologies, such as drones and early warning systems, fosters ownership and increases their effectiveness. Furthermore, mobile platforms can offer real-time fire risk updates while educating users on preventive measures and response strategies (Campbell et al. 2024). Empowering communities with technological knowledge ensures their active participation in wildfire prevention and strengthens overall resilience.

Community education programs can also integrate with land management practices to enhance ecological resilience. Citizen science initiatives enable local populations to monitor vegetation health and report high-risk areas using accessible platforms like smartphone apps (Frandsen et al. 2011). Training programs can focus on creating defensible spaces, managing fire-resistant vegetation, and implementing green fire barriers (Paton and Buergelt 2012). Collaborative fire drills involving community members, firefighters, and technology operators simulate real-world scenarios, improving preparedness and coordination. These efforts not only raise awareness but also ensure the long-term sustainability of ecological interventions.

By combining technology, land management, and community education, wildfire prevention becomes more effective. This integration creates a multiplier effect, reducing ecosystem and community vulnerability while optimizing resource allocation through data-driven insights (Brodie et al. 2024). Moreover, fostering community ownership promotes the adoption and sustainability of preventive measures. A cohesive strategy that links these elements offers a robust and sustainable pathway to mitigating the increasing risks of wildfires (Azevedo et al. 2024).

DISCUSSION

Drones and satellite monitoring systems are only two instances of advanced wildfire control technology that need substantial financial investments. Acquiring, running, and upkeeping these systems can be excessively costly, particularly for smaller organizations or communities with limited financial resources. The presence of this financial obstacle may restrict the efficacy of these devices in places with a high level of risk and impede their widespread acceptance (Webb et al. 2016, Fernández-Blanco et al. 2022). Technologies such as satellite imaging and remote sensing depend on optimal climatic conditions. Malfunctions in these systems, caused by factors like smoke, cloud cover, or atmospheric interference, can lead to delays in both detection and response. Moreover, the reliability of sensors and monitoring equipment can be affected by wear and tear, requiring frequent maintenance and calibration to ensure optimal performance (Esmzadeh 2024). The incorporation of artificial intelligence and machine learning (Czyczula Rudjord et al. 2022) in the control of wildfires produces copious volumes of data that require examination and interpretation (Gonzalez and Ghermandi 2024, Wang et al. 2024). The abundance of data can overwhelm decision-makers, hindering their ability to promptly derive practical insights. Furthermore, the influence of environmental elements and the complexity of fire behaviour might provide challenges to predictive modeling, potentially leading to imprecise estimates and erroneous actions (Neger et al. 2024). As wildfire prevention systems become increasingly interconnected, they are exposed to cybersecurity vulnerabilities. Cybercriminals can disrupt or disable fire detection systems, putting safety standards at risk and perhaps causing catastrophic consequences. Robust cybersecurity protections are essential; however, their implementation can pose challenges (Domínguez et al. 2017, McDermott et al. 2020). Dependence on contemporary technology has the danger of causing communities and fire management personnel to become self-satisfied. Excessive dependence on automated technologies can result in a deficiency of situational awareness and readiness, both of which are crucial in the case of a fire. Education and training remain crucial to ensure that individuals possess the necessary knowledge and skills to respond effectively, especially in the context of technology usage (Ali et al. 2024, Arango et al. 2024, Chen et al. 2024, Dong et al. 2024, Giorgi 2024, Kang and Im 2024, Tsujiguchi and Coraiola 2024, Silva et al. 2024).

For ecological practices to remain effective, regular maintenance is often required. Regular maintenance and vigilant monitoring are necessary for fuel breaks and green fire barriers to prevent the proliferation of flammable vegetation (Brodie et al. 2024, Krishnambika et al. 2024, Wang et al. 2024). These barriers may lose their effectiveness without regular maintenance, which could make it easier for flames to spread. Environmental factors (Drews et al. 2014) can affect how effective ecological strategies are. For example, certain climatic conditions (such as humidity and wind speed) are necessary for the safe execution of controlled burns (Davis et al. 2024). Uncontrolled burns can result from unfavourable conditions, which could increase rather than decrease the risk of fire (Davis et al. 2024). The effectiveness of ecological fire protection methods may be diminished by the introduction of invasive or non-native species. Invasive plants have the potential to replace native species, leading to an overall increase in flammability in a region and negating the benefits of efforts to minimize fuel (Wang et al. 2024). Managing these invasive species requires additional planning and allocation of resources. An obstacle that could impede progress is the community's endorsement of strategies such as controlled burns. Concerns about the potential for controlled burns to become uncontrollable and the impact on air quality may cause individuals to exercise caution when considering fire management measures. The public must be educated about the benefits and necessary safety measures of these technologies for them to be effectively implemented (Davis et al. 2024, Wang et al. 2024). Implementing and maintaining ecological technology can be financially burdensome, particularly for smaller towns or areas with little financial resources. There is a possibility that certain locations may not completely embrace these fire prevention strategies because of the costs associated with their design, implementation, and maintenance. Fire behaviour can be influenced by various elements, including vegetation type, soil moisture, and topography. The biological dynamics of forests are complex. Due to the complexity of the situation, accurately predicting the outcome of ecological processes can be difficult. Adapting strategies to specific ecosystems requires a thorough comprehension and examination, which may not always be readily available (Davis et al. 2024, Purnomo et al. 2024, Wang et al. 2024, Xu et al. 2024).

Obtaining reliable funding and resources is essential for engaging communities in wildfire prevention efforts, while it can be difficult to acquire them. Numerous municipalities encounter challenges in allocating sufficient funds for ongoing training, education, and mitigation endeavours, particularly smaller ones or those with limited financial resources. The lack of continuous support may undermine the effectiveness and long-term sustainability of engagement initiatives (Copes-Gerbitz et al. 2022, Palsa et al. 2022). Community involvement projects may face challenges due to institutional and cultural barriers. Implementing collaborative tactics can be challenging due to inflexible bureaucratic structures, segmented decision-making processes, and a lack of coordination among agencies and stakeholders. Moreover, the lack of trust between communities and authorities, together with cultural disparities, could hinder the ability to effectively act (Copes-Gerbitz et al. 2022, Mojir et al. 2023). Engaging a diverse range of stakeholders, including local communities, government agencies, landowners, organizations, and indigenous groups, could pose challenges. Managing a diverse range of interests, priorities, and opinions throughout decision-making procedures can be challenging and time-consuming. Although eliminating power inequalities and ensuring fair representation are crucial, they can sometimes be complex and challenging to achieve (Palsa et al. 2022). A significant portion of the population may lack full awareness regarding the hazards presented by wildfires or the critical importance of their involvement in preventive measures. Lack of awareness and information might lead to resistance or indifference towards participation. Effective educational projects require substantial resources and sustained effort to enhance awareness and promote active engagement (Palsa et al. 2022, Mojir et al. 2023). Assessing the importance and effectiveness of community involvement and educational programs can pose challenges. Quantifying the enduring effects of mitigating the risk of wildfires is challenging, and it could require several years to witness discernible enhancements. A lack of adequate measures and assessment mechanisms can make it difficult to justify the continuous spending on these activities (Copes-Gerbitz et al. 2022, Palsa et al. 2022, Mojir et al. 2023). Engaging diverse audiences, including underprivileged communities, non-native speakers, and hard-to-reach groups, can pose challenges. Some populations may not respond well to traditional outreach techniques. Adapting engagement strategies to suit the specific needs and preferences of different groups requires a greater investment of time, financial resources, and expertise. To overcome these challenges, as shown in Table 6, it is necessary to have a comprehensive plan that encompasses continuous funding, institutional support, collaborative decision-making, targeted educational initiatives, and innovative engagement methods tailored to the specific area conditions. Communities can enhance their resilience and proactively participate in initiatives aimed at wildfire prevention by addressing these challenges.

SUGGESTED AREAS FOR FUTURE RESEARCH AND DEVELOPMENT

Advancements in wildfire management strategies present several promising directions for further research and practical enhancement. To effectively mitigate wildfire risks, future efforts must integrate technology, ecological knowledge, and community engagement into cohesive frameworks. These initiatives should be supported by practical solutions and robust policymaking to address wildfire challenges holistically.

The adoption of remote sensing technology is vital for real-time monitoring of fire-prone regions. Future research should focus on enhancing space-based detection systems and equipping drones with advanced sensors to provide timely alerts and detailed assessments of fire dynamics. These technologies can significantly improve response times and optimize resource allocation for efficient fire management (Clements et al. 2011, Ciumasu et al. 2013, Pastor et al. 2020, Hötte and Jee 2022).

Developing smart sensor networks is another priority. Networks of intelligent sensors capable of continuously monitoring ambient temperature, humidity and wind speed can enhance situational awareness and improve decision-making during fire incidents. This scalable solution can greatly improve on-the-ground firefighting strategies (Clements et al. 2011, Ciumasu et al. 2013, Pastor et al. 2020, Hötte and Jee 2022)

Refining AI algorithms is essential for advancing wildfire behaviour prediction models. Research should aim to increase the accuracy of machine learning models by incorporating diverse datasets, including historical fire data and environmental factors. Additionally, behavioural modeling should be explored to simulate human responses in wildfire scenarios, aiding in evacuation planning and improving preparedness efforts (Clements et al. 2011, Ciumasu et al. 2013, Pastor et al. 2020, Hötte and Jee 2022)

Community engagement remains a critical element in wildfire prevention. Future efforts should investigate effective strategies for leveraging social media and technology to raise awareness of wildfire risks and promote preventive measures. High-priority initiatives should include educating residents on constructing defensible spaces and adhering to fire safety standards. Long-term educational programs, such as integrating wildfire lessons into school curricula, can foster a safety-oriented mindset in younger generations. These programs should be evaluated to measure their impact on improving community resilience and preparedness (Campbell et al. 2024, Hostetter et al. 2024, Sukawi et al. 2024).

Sustainable land management practices must balance ecological and economic considerations. Research should focus on analyzing the role of controlled burns and other fuel reduction measures in enhancing ecosystem health while reducing wildfire risks. Additionally, assessing the economic feasibility of these practices by exploring market opportunities for biomass and other forest products derived from fuel management operations will ensure long-term sustainability (Wang et al. 2024, Woolsey et al. 2024).

Transdisciplinary research initiatives are critical for fostering collaboration among disciplines such as forestry, meteorology, ecology, and fire science. Such multidisciplinary approaches can result in comprehensive fire management plans that address the complex factors influencing wildfire behaviour (Wang et al. 2024, Woolsey et al. 2024).

Furthermore, encouraging public-private partnerships can stimulate innovation in fire prevention technologies and promote resource sharing among government entities, non-profit organisations, and private enterprises. These partnerships can play a significant role in developing and implementing effective fire safety protocols (Barrett et al. 2024, Golleru 2024, Zulkarnaini et al. 2024).

The role of policy-making cannot be overstated in ensuring the integration of these strategies into actionable frameworks. Research should prioritize advocating for policies that promote sustainable land use and community-driven fire safety measures. Incorporating fire safety into broader land-use planning processes and evaluating the effectiveness of existing policies will help identify gaps and provide opportunities for improvement. Future policies must be adaptive, incorporating recommendations from this review to address the evolving dynamics of wildfire risks (Barrett et al. 2024, Shahi 2024, Sukawi et al. 2024, Zulkarnaini et al. 2024).

By addressing these research areas, future studies can significantly enhance wildfire prevention techniques, ensuring resilience and practical solutions to meet escalating wildfire risks. Supported by strong policies and collaborative efforts among stakeholders, these advancements will create a sustainable and effective framework for wildfire management.

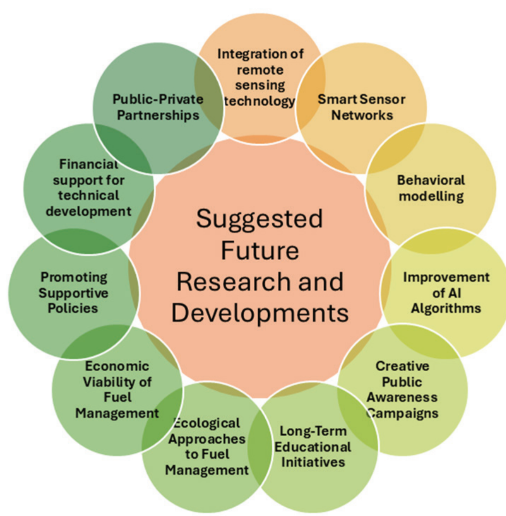

Figure 3. Suggested future research and development.

Table 6. Limitations and benefits of modern techniques.

Techniques	Types	Benefits	Limitations	References
Remote sensing and satellites	Technology	Early detection and wide area coverage	High initial cost and dependence on technology	(Clements et al. 2011, Ciumasu et al. 2013, Pastor et al. 2020, Hötte and Jee 2022, Barber et al. 2024, Soja 2024, Hunter 2024, Riris et al. 2024, Setiawan et al. 2024, Schroeder et al. 2024,)
Drones/UAVs	Technology	Real-time surveillance and data collection	Limited flight time and regulatory restrictions	(Alon et al. 2021, Bhattarai and Lucieer 2024, Wu et al. 2024)
Firefighting robots and autonomous systems	Technology	Enhanced safety for firefighters, autonomous operation, adoptability to various environments, continuous operation, rescuing and search operations, real time data collection and reduction of water usage	High initial costs, technical limitations and dependence on technology, limited decision-making capability, vulnerability to water and fire, public acceptance and trust, and the need for human oversights	(Guruprasad et al. 2020, Arora et al. 2023, Li et al. 2023, Talavera et al. 2023)
AI and machine learning	Technology	Predictive analytics and optimized response strategies	Requires extensive data and potential biases	(Ciumasu et al. 2013, Pastor et al. 2020, Hötte and Jee 2022)
Thermosensitive fire alarms	Technology	Early detection, reduced false alarms, adaptability to various environments, wireless communication and real time monitoring	Sensitive to heat only, response time to rapid fires, environmental influences, limited applications in hot environment and proper maintenance	(Clements et al. 2011, Liu et al. 2022, Carta et al. 2023, Alkhatib et al. 2024)
Fuel breaks	Ecological	Creates barrier to fire spread and enhances safety	Can alter the ecosystem and requires regular maintenance	(Wang et al. 2024, Krishnambika et al. 2024)
Green fire barriers	Ecological	Natural barrier creations and improves habitat	Slow to establish and effectiveness varies by species	(Weir et al. 2012, Ascoli et al. 2023, Warnell et al. 2023, Li et al. 2024, Murray et al. 2024, Wang et al. 2024)
Control burn	Ecological	Reduces fuel load and enhances biodiversity	Risk of escape and requires careful planning	(Wang et al. 2024, Woolsey et al. 2024)
Fungal spread	Ecological and community based	Nutrient cycling, soil structure improvement, fire resilience and pest, and pathogen control	Altered soil properties, sensitive to fire, dependence on environmental conditions, community composition changes	(Wade and Lundsford 1990, Hopkins et al. 2021, Adams and Neumann 2023, Espinosa et al. 2023)
Fertilizers spread on litter layer	Ecological and community-based	Accelerate decomposition, promote beneficial microbial activity, nutrient enrichment, improved soil quality, encourage vegetation cover	Risk of over fertilization, alteration to soil chemistry, increased fuel load, potential for increased erosion, microbial sensitivity and dependence on environmental conditions	(Ferreira et al. 2015, Girona-García et al. 2021, Agbeshie et al. 2022, Song et al. 2022, Adams and Neumann 2023)
Plantation	Ecological and community based	Fire retardation, ecosystem recovery, carbon sequestration, wildlife habitat, aesthetic and recreational values	Species selection, management challenges, ecosystem disruption, environmental conditions and long-term commitment	(Curran et al. 2017, Hood et al. 2018, Popović et al. 2021)
Community engagement	Community-based	Builds local resilience and promotes awareness and preparedness	Varies between community capacities and may require ongoing efforts	(Hensley 1975, Palsa et al. 2022, Azevedo et al. 2024, Campbell et al. 2024, Hostetter et al. 2024, Shahi 2024)

Author Contributions

Syed Shaheer Hassan and Guang Yang designed the article. Muhammad Sabir, Laila Noor, Haseeb Ahmad and Syed Shaheer Hassan wrote the research paper and interpreted the findings. Syed Shaheer Hassan, Sana Tahir and Guang Yang made corrections to the draft. All the authors have read the work and given their endorsement.

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Conflicts of Interest

The authors declare no conflict of interest.

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