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Research Article

Advancing Early Warning Systems for Fire Detection: A Comprehensive Approach in Machine Learning

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ABSTRACT

This research conducts a comprehensive investigation of the efficacy of various machine learning algorithms for fire detection. The algorithms that were examined include logistic regression, decision tree, random forest, support vector classifier, gradient boosting, K-nearest neighbors, Gaussian naive Bayes, multilayer perceptron classifier, and XGBoost classifier. Through in-depth experiments, this study rigorously assesses the performance of these algorithms in identifying and predicting fires based on pertinent input features. Among the algorithms that were investigated, logistic regression is the best performer, with a high accuracy rate of 99%. The findings from this research offer valuable insights for optimizing fire detection systems, providing a nuanced understanding of the practical applicability of machine learning techniques in real-time fire monitoring scenarios. The primary objectives of this study are to elucidate specific challenges in fire detection, evaluate the performance of various machine learning algorithms, and contribute to the foundational knowledge that is essential for enhancing fire management strategies. The research addresses the limited precision of existing fire detection systems and aims to rectify this issue through a systematic exploration of advanced machine learning approaches. The overarching goal is to bolster the foundations of fire management, facilitating the development of proactive measures and prompt responses to mitigate the profound impact of wildfires. By presenting a detailed examination of the strengths and weaknesses of various machine learning algorithms, this research strives to foster a robust and effective approach to fire detection, thereby advancing the field and ensuring the safety of communities at risk.

Keywords:* *Decision Tree; Gradient Boosting; fire detection; SVC; Random Forest.

1. INTRODUCTION

Forest fires pose a multifaceted threat, disrupting the ecological balance, endangering human safety, and causing irreparable damage to vast landscapes and populated areas. The increasing frequency and intensity of these fires are the result of dynamic shifts in climate patterns, urbanization, and intensified human activities. This escalation highlights the urgent need for innovative strategies to immediately detect and manage forest fires effectively. Addressing the improvement of machine learning frameworks for timely and accurate detection of wildfires can highlight the problem at hand. Existing systems have limited accuracy and efficiency. Thus, better methodologies need to be explored. This research is consistent with the work of Al-Khatib et al. (2023) [1], who conducted a brief review of machine learning algorithms in the context of wildfires. They emphasized the importance of artificial intelligence (Artificial intelligenceAI) techniques, especially machine learning, in predicting and assessing forest fire risks. The ongoing problem of selecting the best prediction model has been noted, highlighting the need to explore different machine learning algorithms to enhance prediction power. The primary goal of this research is to evaluate and compare different machine learning algorithms within the specific context of fire detection. Logistic regression, decision tree, random forest, support Vector classifier (SVC), gradient boosting, K-nearest neighbors, Gaussian naive Bayes, multilayer perceptron classifier, and XGBoost classifier are examined carefully. This study explores related works such as that of Wang et al. (2023) [2], who conducted a deep learning experiment on forest fire detection in a machine vision course. Their interdisciplinary approach integrates digital image processing, machine learning, and deep

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learning techniques, addressing challenges such as high-resolution detection and practical application for students. The proposed algorithms, including reduced VGGNet for image classification and enhanced convolutional neural network (CNN) for region detection, show promising accuracy, reaching 91.20% and 97.35%, respectively. By synthesizing insights from existing work, this research contributes significantly to the broader narrative of smart disaster management. The combination of scientific rigor and technological advances in this study can potentially transform the fire management landscape, ensuring a proactive stance in protecting natural ecosystems and human communities.

2. RELATED WORK

Several significant contributions have been made in the field of early fire detection and warning systems, each offering unique insights and methodologies. Biswas, Ghosh, and Ghosh (2023) [3] presented a modified Inception-v3 model in a deep learning framework for early fire detection. Their model, applied to a dataset that includes smoke for fire image detection, obtained superior results, particularly in terms of minimizing false positives. Xiao, Wang et al. (2023) [4] proposed a hybrid feature fusion-based approach for high-sensitivity early fire detection in intelligent building systems. Utilizing temperature, smoke concentration, and carbon monoxide concentration as distinguishing attributes, their method, which combined backpropagation neural network (BPNN) and least squares support vector machine (LSSVM), achieved reliable early fire detection with an accuracy exceeding 96%. Chen et al. (2023) [5] focused on fire danger forecasting using machine learning-based models and meteorological observations in northeastern China. Combining data from the Canadian Fire Weather Index system, a long short-term memory (LSTM) network, and a random forest (RF) model, their two-stage approach demonstrated an accuracy of 87.5%, providing a robust forest fire danger warning system. Bhowmik, Jung et al. (2023) [6] contributed a multi-modal wildfire prediction and early warning system based on a novel machine learning framework. Integrating a comprehensive database and employing a U-convolutional LSTM neural network, their system achieved over 97% accuracy in predicting wildfires, surpassing traditional CNN techniques. This novel approach holds promise for anticipating and preventing wildfires, offering potential life-saving benefits, environmental protection, and economic damage avoidance.

Supriya and Gadekallu (2023) [7] introduced a particle swarm-based federated learning (FL) approach, leveraging FL with a particle swarm optimization algorithm (PSO) for efficient multidimensional forest fire image data processing. The proposed framework demonstrated improved performance, with a 94.47% prediction accuracy, offering potential for the development of robust early warning systems. Jana and Shome (2023) [8] contributed a hybrid ensemble-based machine learning model for smart building fire detection. The model combines logistic regression, SVM, decision tree, and naive Bayes classifiers, achieving higher classification accuracy and robustness than those in existing literature. Sathishkumar et al. (2023) [9] studied forest fire and smoke detection, addressing the challenges of training time and dataset availability by employing learning without forgetting (LwF) with CNNs, thus ensuring intact preexisting abilities while adapting to new tasks. Akyol (2023) [10] conducted a comprehensive comparison of traditional classifiers and deep neural networks for forest fire detection. The study highlighted the superior performance of the ResNet50+DNN-3 model, achieving 97.11% accuracy and demonstrating potential integration with real-time Internet of Things (IoT) and embedded system applications. Reis and Turk (2023) [11] focused on the detection of forest fires by using deep CNNs with a transfer learning approach, achieving a remarkable 99.32% accuracy with the DenseNet121 model. Abdusalomov et al. (2023) [12] presented an improved forest fire detection method based on the Detectron2 model, utilizing deep learning approaches. Their proposed model achieved a precision of 99.3%, thus being able to detect small fires over long distances during day and night. These works collectively contribute to the development of advanced forest fire detection systems, offering diverse methodologies and demonstrating substantial improvements in accuracy and efficiency.

Several innovative approaches have been introduced in the field of fire detection systems, particularly in scenarios involving autonomous vehicles and smart cities. Bishoyi et al. (2023) [13] presented a deep learning approach for fire object detection in autonomous vehicles, emphasizing the crucial role of object detection in autonomous driving infrastructure. The proposed prototype, controlled by a microcontroller, utilizes a deep learning model to detect fire objects from live video feeds, achieving high-speed and accurate recognition under diverse weather conditions.

Talaat and ZainEldin (2023) [14] contributed an improved fire detection approach for smart cities based on YOLO-v8. Their smart fire detection system (SFDS) leverages deep learning to enhance accuracy, reduce false alarms, and offer cost-effective solutions. The proposed framework, which incorporates fog and cloud computing along with the IoT layer, demonstrates state-of-the-art performance in precision and recall, providing an effective means for fire safety management in public areas.

Mozaffari, Li, and Ko (2023) [15] addressed the critical issue of real-time detection and forecast of flashovers using deep CNNs. Their FlashoverNet model leverages AI technologies to recognize vision indicators of flashovers,

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achieving a remarkable accuracy of more than 94% in full-scale actual room fire tests. This novel non-invasive prediction technique holds significant promise for enhancing firefighter safety. De Venâncio et al. (2023) [16] proposed a hybrid method for fire detection based on spatial and temporal patterns. This approach, utilizing CNNs for spatial processing and temporal analysis for dynamic events, achieves reduced false positive rates without compromising true positive rates or processing time. The cascading of these two stages offers a promising solution for early fire detection. Jagatheesaperumal et al. (2023) [17] introduced an automated fire extinguishing system using a deep learning-based framework. Their approach employs CNNs for fire and human presence detection and has the potential for early fire detection in its early stages. The experiments, which were conducted with a mobile robotic system, demonstrate the effectiveness of the proposed model in automatic and wireless control modes. Kim et al. (2023) [18] addressed rapid flame locating at construction sites by using a stochastic flame locating (SFL) method, which combines Kalman filter (KF) and deep neural network (DNN) to minimize uncertainty associated with ultraviolet radiation signals. This approach enhances the accuracy of flame location by updating the Kalman gain continuously, offering an effective solution for timely response to fires in construction sites. Table 1 summarizes the above work.

TABLE I. Summarizes The RELATED Work

Authors	Year	Title	Methodology	Key Findings/Results
Biswas, Ghosh, and Ghosh (2023)	2023	Modified Inception-v3 model for early fire detection	Deep learning framework; smoke for fire image detection	Superior results, especially in minimizing false positives
Xiao, Wang et al. (2023)	2023	Hybrid feature fusion for high-sensitivity early fire detection	BPNN and LSSVM; temperature, smoke, and CO concentration	Accuracy exceeding 96% in early fire detection
Chen et al. (2023)	2023	Fire danger forecasting using machine learning and meteorological observations	LSTM, RF, Canadian Fire Weather Index system	Two-stage approach with 87.5% accuracy in robust forest fire danger warning system
Bhowmik, Jung et al. (2023)	2023	Multi-modal wildfire prediction and early warning system	U-LSTM neural network; comprehensive database	Over 97% accuracy in predicting wildfires, surpassing traditional CNN techniques
Supriya and Gadekallu (2023)	2023	Particle swarm-based FL approach	FL with PSO; multidimensional forest fire image data	Improved performance with 94.47% prediction accuracy
Jana and Shome (2023)	2023	Hybrid ensemble-based machine learning model for smart building fire detection	Logistic regression, SVM, decision tree, naive Bayes	Improved classification accuracy and robustness compared with existing literature
Sathishkumar et al. (2023)	2023	Forest fire and smoke detection using learning without forgetting	LwF with CNN	Addresses training time and dataset challenges with intact preexisting abilities
Akyol (2023)	2023	Comprehensive comparison of traditional classifiers and deep neural networks for forest fire detection	ResNet50+DNN-3 model	97.11% accuracy; potential integration with real-time IoT and embedded system applications
Reis and Turk (2023)	2023	Forest fire detection using deep CNNs with transfer learning	DenseNet121 model	99.32% accuracy in forest fire detection
Abdusalomov et al. (2023)	2023	Improved forest fire detection method based on the Detectron2 model	Deep learning approaches	99.3% accuracy, capable of detecting small fires over long distances during day and night
Bishoyi et al. (2023)	2023	Deep learning approach for fire object detection in autonomous vehicles	Microcontroller-controlled prototype; live video feeds	High-speed and accurate recognition of fire objects in diverse weather conditions
Talaat and ZainEldin (2023)	2023	Improved fire detection approach for smart cities based on YOLO-v8	SFDS framework; fog and cloud computing, IoT layer	State-of-the-art performance in precision and recall; effective for fire safety management in public areas
Mozaffari, Li, and Ko (2023)	2023	Real-time detection and forecast of flashovers using deep CNNs	FlashoverNet model	Accuracy of more than 94% in full-scale actual room fire tests; significant promise for enhancing firefighter safety
De Venâncio et al. (2023)	2023	Hybrid method for fire detection based on spatial and temporal patterns	CNNs for spatial processing, temporal analysis	Reduced false positive rates without compromising true positive rates or processing time

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Jagatheesaperumal et al. (2023)	2023	Automated fire extinguishing system using a deep learning-based framework	CNNs for fire and human presence detection	Effective early fire detection in its early stages with a mobile robotic system
Kim et al. (2023)	2023	SFL method for rapid flame locating at construction sites	KF and DNN hybrid method	Enhances accuracy of flame location; effective for timely response to fires in construction sites

3. METHODOLOGY

Early fire detection using machine learning algorithms involves a systematic application of each algorithm to leverage its unique capabilities in modeling complex relationships within the input feature space. The following subsections provide detailed explanations of how each algorithm was specifically applied.

a. Logistic Regression

Objective: Binary classification to model the likelihood of fire occurrence.

Input features: Temperature, humidity, and wind speed.

Approach: Iterative optimization to learn a linear decision boundary distinguishing fire occurrence and non-occurrence.

$$P(y = 1lx) = \frac{1}{1 + e^{-(w^T x + b)}} \qquad (1)$$

b. Decision Tree

Objective: Constructing a hierarchical decision structure.

Input features: Temperature, humidity, and wind speed.

Approach: Recursive splitting based on feature values, forming if–then decision paths for fire detection.

c. Random Forest

Objective: Ensemble approach for enhanced predictive power.

Input features: Same as decision tree.

Approach: Construction of multiple decision trees on bootstrapped samples, aggregating predictions to mitigate overfitting.

d. SVC

Objective: Determine an optimal hyperplane for effective separation of fire occurrences.

Input features: Temperature, humidity, and wind speed.

Approach: Handling nonlinearly separable data for precise classification by identifying complex relationships.

$$W^T X + B = 0 \qquad (2)$$

e. Gradient boosting

Objective: Iterative construction of sequential weak learners (decision trees).

Input features: Same as decision tree.

Approach: Correcting errors made by predecessors for a refined and accurate fire detection model.

$$F(x) = \sum_{m=1}^{M} \alpha_m h_m (X) \qquad (3)$$

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4. IMPLEMENTATION DETAILS

This research uses Python as the primary programming language for implementation. Python, which is known for its readability and extensive libraries, plays a pivotal role in the exploration of machine learning algorithms. The scikit-learn library, a comprehensive toolkit for machine learning in Python, is used. This integration with scikit-learn not only facilitated a standardized and rigorous experimental setup but also ensured transparency and reliability in the evaluation of different algorithms. Using Google Colab, a cloud-based platform for Python that provides free access to graphical processing units, helped overcome computational limitations, enabling the efficient training and evaluation of complex machine learning models. This cloud-based approach not only streamlined the implementation process but also promoted reproducibility by providing a shared and accessible environment for collaborative work. Within the realm of machine learning algorithms, the study incorporated a diverse set of methodologies, including traditional models such as random forest and support vector machines. The scikit-learn library's versatile implementation of these algorithms ensured a robust and standardized comparison across different models.

4.1. DATA

The provided data consists of various geographical areas along with corresponding values for "Oxygen," "Temperature" "Humidity," and "Fire Occurrence." The attributes represent environmental conditions, and "Fire Occurrence" indicates whether a fire occurred (1) or not (0).

- Area: This column represents the geographical area or location. While it may not directly impact fire occurrence, it could be useful in identifying regions prone to fires based on historical data or environmental characteristics.

- Oxygen: Higher oxygen levels might contribute to fire ignition and spread because oxygen is necessary for combustion. However, excessively low oxygen levels might also inhibit fires. The relation depends on whether other factors such as fuel availability and ignition sources are present.

- Temperature: Higher temperatures generally promote fire risk by increasing evaporation, drying out vegetation, and enhancing fire ignition potential. Cooler temperatures are likely to reduce fire risk due to less evaporation and reduced flammability of vegetation.

- Humidity: Higher humidity levels tend to inhibit fires by keeping vegetation moist and reducing the chances of ignition. Lower humidity levels make vegetation more susceptible to ignition, increasing fire risk.

- Fire occurrence: This column is the target variable, indicating whether a fire occurred (1) or not (0). It is the outcome that should be predicted based on the other columns' values.

	Area	Oxygen	Temperature	Humidity	Fire Occurrence
0	Jharkand	40	45	20	1
1	Bangalore	50	30	10	1
2	Ecuador	10	20	70	0
3	a	60	45	70	1
4	Bangalore	30	48	10	1
5	c	50	15	30	0
6	de	5	35	35	0
7	asd	5	20	70	0
8	Ecuador	60	32	19	1

Fig. 1 Data columns

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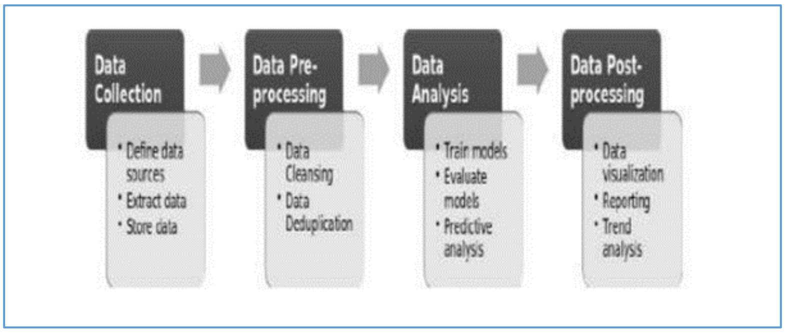

Fig. 2 Steps for Data Mining

4.2 RESULTS

The findings of this research were derived from a careful examination of different machine learning algorithms in the field of fire detection. This evaluation incorporates key metrics, including accuracy, F1-score, precision, and recall, ensuring a comprehensive assessment of the algorithms' efficacy. Logistic regression achieves high precision, with a score of 99.0. This result indicates the model's ability to accurately categorize instances of fire occurrence. The corresponding F1-score, precision, and recall values of 99.0 further corroborate the algorithm's precision and its careful handling of false positives and false negatives. The decision tree classifier model demonstrates robust performance, with an accuracy of approximately 0.83. The corresponding F1-score, precision, and recall metrics consistently parallel this accuracy level, proving the model's proficiency in discerning patterns within the data and making reasonable predictions. The random classifier attains an accuracy of approximately 0.92, highlighting its efficacy in generating precise predictions. Its high F1-score, precision, and recall values reflect its balanced performance, excelling in the precision and recall metrics.

The performance of the gradient boosting classifier aligns with that of the decision tree classifier, achieving an accuracy of approximately 0.83. The corresponding F1-score, precision, and recall values highlight the algorithm's capacity to make accurate predictions while ensuring a balance between precision and recall.

The SVC model performs similarly to the random classifier, achieving an accuracy of around 0.92. The corresponding F1-score, precision, and recall values verify the model's robust predictive capabilities and its well-rounded performance. These results are presented in Table 2.

TABLE II. Results

Algorithm	Accuracy	F1-Score	Precision	Recall
Logistic Regression	99.0	99.0	99.0	99.0
Decision Tree Classifier	0.83	0.83	0.83	0.83
Random Classifier	0.92	0.92	0.92	0.92
Gradient Boosting Classifier	0.83	0.83	0.83	0.83
Support Vector Classifier	0.92	0.92	0.92	0.92

TABLE III. COMPARISON WITH RELATED WORK

Model	Year	Approach/Methodology	Accuracy
Logistic Regression	ours	ML algorithms (best: logistic regression)	99%
Chen et al. (2023)	2023	Fire danger forecasting using machine learning and meteorological observations	87.5%
Bhowmik, Jung, et al. (2023)	2023	Multi-modal wildfire prediction and early-warning system	97%

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Supriya and Gadekallu (2023)	2023	Particle swarm-based FL approach	94.47%
Akyol (2023)	2023	Comprehensive comparison of traditional classifiers and deep neural networks for forest fire detection	97.11%

5. CONCLUSION

In summary, our research aims to enhance early warning systems for fire detection through a thorough exploration of diverse machine learning algorithms. Logistic regression exhibited outstanding performance, with an exceptional accuracy rate of 99%, thereby highlighting its precision in categorizing fire occurrences. This study contributes valuable insights for optimizing fire detection systems, emphasizing the practical applicability of machine learning techniques in real-time monitoring. This work achieved its primary objectives of addressing challenges in fire detection, evaluating various machine learning algorithms, and enhancing fire management strategies. Logistic regression's high accuracy sets a benchmark for precision in fire detection, offering proactive measures to mitigate the impact of wildfires. The comparison with related work underscores the effectiveness of different methodologies in accurately predicting fire incidents, contributing to the broader discourse on machine learning applications in disaster management. In essence, our findings provide a robust foundation for advancing fire detection systems, promoting proactive measures, and ensuring the safety of ecosystems and communities at risk.

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