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Smart and Sustainable Forest Fire Early Detection System Utilizing Solar Energy and Wireless Communication

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ABSTRACT

This study designed, developed, and evaluated a smart and sustainable forest fire early detection system utilizing solar energy and wireless communication. The system integrated ESP32-based sensor nodes, five digital flame sensors, MQ-2 gas/smoke sensors, SHT35 temperature and humidity sensors, solar charging modules, rechargeable batteries, ESP-NOW or ESP-Mesh wireless communication, a Raspberry Pi-based processing station, and GSM modules for real-time alert delivery. Using a design-and-development experimental methodology, the system was implemented as a functional prototype and evaluated through controlled fire-simulation testing, system monitoring, and deployment-feasibility analysis. The system architecture used sensing, communication, processing, and notification layers to support autonomous monitoring, multi-sensor fire verification, alert escalation, and event notification. Findings confirmed that the system provided timely and accurate fire detection with minimal false alarms, reliable low-power communication among distributed nodes, fast alert response through GSM-based SMS notification, sustainable solar-powered operation, and scalable deployment for small, medium, and large forest monitoring configurations. The study concludes that integrating renewable energy, embedded sensing, mesh communication, and automated alerting can strengthen forest fire early warning in remote and off-grid environments. The system offers a practical and adaptable technological solution for environmental protection, disaster-risk reduction, and sustainable forest management.

Keywords: *forest fire detection, solar-powered system, ESP32, GSM communication, wireless mesh network, environmental monitoring*

INTRODUCTION

Forest fires continue to threaten ecosystems, biodiversity, property, and human safety. In forested areas that are remote, difficult to access, or under-resourced, fire incidents can expand quickly before they are detected and reported. Traditional methods such as manual patrols and delayed visual confirmation often lack real-time, ground-level monitoring and therefore cannot always support rapid response. This problem is particularly important in developing-country settings where forest surveillance is constrained by geography, limited personnel, and communication challenges.

The study was framed around Philippine Forest conditions, with emphasis on the need for technologies that can operate in off-grid or remote environments. Mt. Arayat in Pampanga was identified in the source manuscript as an ecologically and culturally important forested area that is vulnerable to wildfire risk because of prolonged dry periods, deforestation, and climate change. These conditions justify the development of an early

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warning system that is autonomous, sustainable, and capable of transmitting alerts even when internet access is limited.

Recent developments in embedded systems, wireless sensor networks, and Internet of Things technologies have made it possible to design low-cost monitoring systems for environmental hazards. Wireless sensor networks can support distributed monitoring over large areas, while ESP32-based systems and GSM communication can provide practical alerting mechanisms for locations where conventional infrastructure is unavailable (Akyildiz et al., 2002; Borge et al., 2020; Daud & Abdul Rahman, 2025). Solar energy further extends the usability of such systems by allowing sensor nodes to operate with less dependence on grid electricity.

This study therefore developed and evaluated a smart and sustainable forest fire early detection system utilizing solar energy and wireless communication. Specifically, the system used solar-powered ESP32 nodes with flame, gas/smoke, temperature, and humidity sensors; an ESP-NOW or ESP-Mesh communication architecture; a Raspberry Pi-based monitoring station; and GSM-based SMS alerts. The study aimed to determine whether the integrated system could provide accurate, timely, scalable, and sustainable forest fire detection for remote monitoring applications.

Literature Review

Forest Fire Detection and Environmental Monitoring

Forest fire detection has evolved from manual observation and satellite monitoring toward sensor-based early warning systems. Alkhatib (2014) emphasized that early detection is central to reducing wildfire damage because rapid reporting enables faster response and containment. Wireless fire monitoring systems have also been shown to improve field-level detection because they can be deployed near the source of environmental change and can transmit measurements continuously (Hartung et al., 2006; Singh & Jain, 2017).

Sensor-based systems are especially useful when multiple environmental indicators are monitored together. Smoke, flame, temperature, and humidity data provide stronger evidence of fire conditions than any single sensor alone. Several studies have demonstrated the feasibility of ESP32- and IoT-based fire detection systems that use real-time sensing and alerting functions (Anand et al., 2020; Bakar et al., 2020; Hossain & Rahman, 2019; Kumar et al., 2021). These studies support the present system’s use of multi-sensor detection for early and more reliable fire-risk identification.

Wireless Sensor Networks and IoT Communication

Wireless sensor networks provide the communication foundation for distributed fire detection. Akyildiz et al. (2002) described wireless sensor networks as systems that combine sensing, computation, and communication across multiple nodes, making them appropriate for environmental monitoring. In forest applications, wireless sensor systems can expand monitoring coverage and reduce the need for continuous manual inspection (Borge et al., 2020; Manogaran et al., 2018).

The source system used ESP-NOW or ESP-Mesh communication to connect sensor nodes and transmit warnings toward the monitoring station. Khan et al. (2022) showed that ESP-Mesh-based wireless sensor networks can support efficient indoor and outdoor monitoring, while Daud and Abdul Rahman (2025) discussed ESP32-based IoT fire detection. These references justify the choice of ESP-based communication for low-power, scalable, and field-adaptable fire monitoring.

Renewable Energy and Autonomous Early Warning Systems

A major constraint in remote monitoring is power availability. Solar-powered systems help address this issue by supporting long-term field deployment with reduced dependence on grid electricity. The present design used solar charging modules, rechargeable batteries, and power-saving strategies such as deep sleep mode, duty cycling, and periodic voltage monitoring. These features are consistent with the requirements of autonomous systems deployed in forest or off-grid conditions.

IoT-based fire alerting systems are strengthened when sensing, processing, and notification are integrated. Patel and Shah (2020), Reddy et al. (2020), Pradeep et al. (2020), and Thakur and Joshi (2021) showed that ESP32,

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GSM, Firebase, cloud computing, or related IoT communication tools can support fire detection and alerting. In the present study, GSM communication was used to ensure that SMS alerts could still be sent in areas without stable internet connectivity.

Sensor Fusion, Alert Logic, and System Scalability

The effectiveness of early fire warning depends not only on sensor availability but also on decision logic. Single-sensor systems can produce false alarms when readings are affected by environmental variation. The use of sensor fusion, where flame, smoke/gas, temperature, and humidity data are interpreted together, can strengthen detection accuracy and reduce false positives. This logic is reflected in the source system's four alert levels: Normal, Warning, High Alert, and Critical.

Scalability is also essential because forest monitoring requires coverage across wide and irregular terrain. The system's scalability model classified deployment into small, medium, and large configurations based on node number and estimated range. Such a model supports gradual implementation, allowing additional nodes to increase coverage while retaining reliable alert transmission through mesh or low-power wireless communication.

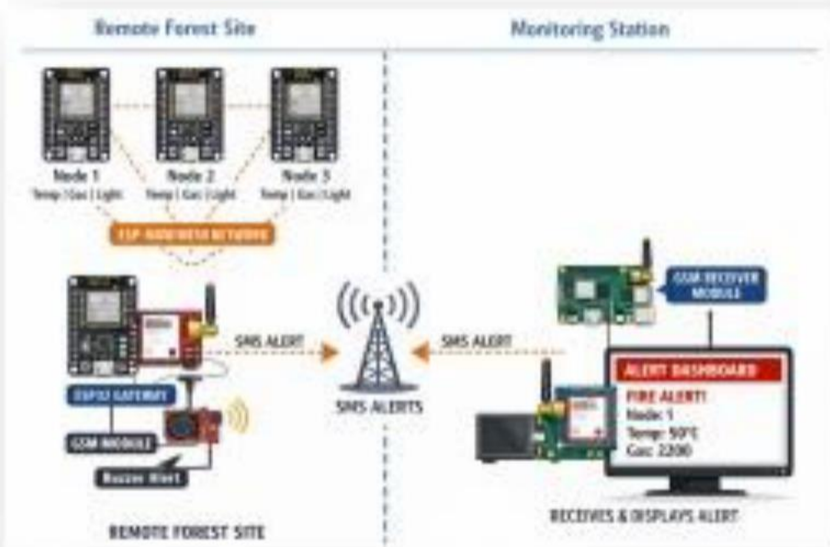

Figure 1. *Conceptual framework of the solar-powered wireless forest fire early detection system.*

METHODS

Research Design

The study employed a design-and-development experimental research methodology. It involved the design, construction, implementation, and evaluation of a solar-powered, multi-sensor forest fire early detection system. The methodology consisted of four major phases: system design and hardware development, wireless communication architecture implementation, alert and monitoring system development, and performance evaluation with deployment-feasibility testing.

Research Locale and Deployment Context

The system was designed for remote Philippine Forest environments where real-time monitoring and grid-based power supply may be limited. The source manuscript discussed Mt. Arayat in Pampanga as a relevant forest

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of Education, Research, and Innovation Perspectives
Volume 2 Issue 7 (July 2026)

context because of its ecological and cultural importance and its vulnerability to wildfire risk. System testing was conducted through controlled fire-simulation procedures and avoided sensitive ecological zones to prevent environmental harm.

System Architecture

The system followed a four-layer architecture consisting of a sensing layer, communication layer, processing layer, and notification and monitoring layer. The sensing layer collected flame, gas/smoke, temperature, humidity, and power-status data. The communication layer transmitted node readings through ESP-NOW or ESP-Mesh networking. The processing layer, supported by a Raspberry Pi-based local server, received and interpreted node data. The notification layer used GSM-based SMS communication and a user interface to deliver alerts, visualize readings, and log events.

Table 1. *Multi-Layered Fire Detection Architecture*

Layer	Main Function	Key Features
Detection layer	Monitors fire-related hazards at the node level	Multiple sensor nodes; flame detection; temperature, gas/smoke, and environmental monitoring
Communication layer	Transmits sensor data wirelessly across nodes	ESP-NOW/ESP-Mesh protocol; peer-to-peer or mesh transmission; scalable node communication
Processing layer	Analyzes readings and determines alert levels	Multi-criteria analysis; alert-level calculation; false-positive reduction; system health monitoring
Notification layer	Delivers alerts and supports remote monitoring	SMS alerts; real-time notifications; graduated response; event logging

System Components

Each detection node used an ESP32 microcontroller and was connected to five digital flame sensors, an MQ-2 gas/smoke sensor, an SHT35 temperature and humidity sensor, a solar charging module, a rechargeable lithium battery pack, and voltage-regulation circuitry. The gateway or monitoring node integrated an ESP32 development board, GSM module, SIM card, and external antenna to support SMS-based alert communication.

Table 2. *Hardware Components and Assigned Functions*

Component	Specification / Description	Function
ESP32 development board	Main controller for gateway and sensor nodes	Coordinates sensing, processing, and communication
Digital flame sensors	Five infrared flame sensors per node	Detects flame presence and triggers critical alert support
MQ-2 gas/smoke sensor	Analog smoke/gas sensing module	Detects smoke or gas concentration associated with fire
SHT35 temperature and humidity sensor	I2C temperature-humidity module	Monitors heat and environmental conditions
Raspberry Pi local server	Monitoring station / processing hub	Receives, processes, and displays sensor data
GSM module (SIM800L/SIM900)	SMS communication module	Sends real-time alert notifications to registered authorities
Solar power setup	Solar panel, charge controller, battery pack, regulator	Supports autonomous field operation

Sensor Fusion and Alert-Level Logic

A multi-criteria decision algorithm was implemented to classify sensor readings into four alert levels. Level 0 indicated normal readings; Level 1 indicated warning conditions; Level 2 indicated high alert conditions; and Level 3 indicated a critical fire condition. Alerts were triggered when multiple thresholds were satisfied, while any flame-sensor activation automatically triggered a critical alert regardless of other readings.

ISSN: 3116-3475
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Volume 2 Issue 7 (July 2026)

Table 3. *Alert Level Conditions*

Alert Level	Status	Temperature	Gas/Smoke Level	Flame Sensor Status	SMS Alert
Level 0	Normal	< 35°C	< 1000 PPM	All sensors clear	Sent only when recovering from alert
Level 1	Warning	35°C-44°C	1000-1499 PPM	All sensors clear	Alert level increased
Level 2	High alert	45°C-49°C	1500-1999 PPM	All sensors clear	Alert level increased
Level 3	Critical	≥ 50°C	≥ 2000 PPM	Any flame detected	Immediate alert sent

Wireless Communication and Scalability

The network architecture used ESP-NOW or ESP-Mesh to create a low-power and scalable wireless sensor network. Sensor nodes communicated directly or relayed data through other nodes toward the controller. When smoke, heat, gas, or flame conditions were detected, the alert was transmitted through the network to the monitoring station, where SMS or interface-based notification was generated.

Table 4. *Scalability Model*

Deployment Scale	Number of Nodes	Estimated Range
Small	1-5 nodes	30-50 meters
Medium	6-15 nodes	50-100 meters with repeaters
Large	16-20 nodes	100-220 meters outdoors

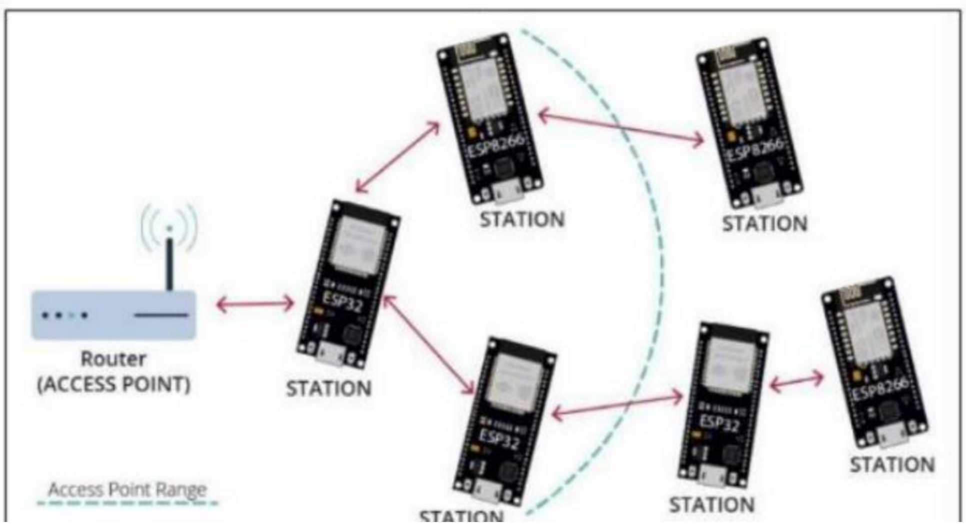

Figure 2. *ESP-Mesh or ESP-NOW network architecture for distributed fire-detection nodes.*

Data Gathering Procedure

The prototype was initialized and calibrated before testing. Sensor nodes continuously collected temperature, humidity, smoke/gas, flame, and battery-status data. The system transmitted readings to the monitoring station, classified conditions according to alert thresholds, generated SMS alerts when conditions changed or reached critical status, and logged events for monitoring and evaluation. Controlled fire-simulation tests were conducted with safety precautions and without exposing sensitive ecological zones to harm.

Data Analysis

System performance was evaluated descriptively in terms of detection accuracy, false alarm rate, communication reliability, alert response time, solar-power sustainability, and scalability. The analysis focused on whether the prototype could detect fire-related conditions, reduce false alarms through sensor fusion, transmit readings through low-power wireless communication, send timely GSM alerts, and sustain autonomous operation through solar power.

Ethical and Safety Consideration

All fire-simulation tests were conducted under controlled conditions with proper safety equipment. Outdoor testing avoided sensitive ecological zones and was carried out to prevent environmental damage. The research emphasized responsible testing, safe handling of fire-related simulations, and development of a system intended to protect environmental resources and nearby communities.

RESULTS AND DISCUSSION

System Design and Operational Integration

The developed system successfully integrated solar-powered sensing nodes, wireless communication, Raspberry Pi-based processing, and GSM notification into one early warning platform. This integration allowed distributed sensor nodes in a remote forest site to detect fire indicators and communicate alerts to a monitoring station. The conceptual architecture showed that remote nodes could send SMS-based alerts and monitoring data to receiving devices, supporting field-level detection and response coordination.

Multi-Sensor Detection and Alert Classification

The system used flame, smoke/gas, temperature, and humidity sensors to improve detection reliability. The alert-level model provided a graduated response, beginning with normal conditions, escalating to warning and high alert states, and reaching critical status when flame activation or severe sensor thresholds occurred. The decision logic reduced dependence on a single sensor reading and therefore helped minimize false-positive alerts. This design directly supports the source manuscript's finding that the system provided timely and accurate fire detection with minimal false alarms.

Wireless Communication Reliability and Network Scalability

The communication design supported low-power and stable data transmission among distributed sensor nodes. ESP-NOW or ESP-Mesh networking allowed sensor information to move from field nodes toward the gateway or monitoring station. The scalability model showed that the system could be expanded from small deployments of 1-5 nodes to large deployments of 16-20 nodes, reaching approximately 100-220 meters outdoors. This indicates that the prototype can be gradually expanded depending on the size and monitoring needs of the target forest area.

Solar Operation and System Lifecycle

Solar integration enhanced the system's sustainability by allowing nodes to operate independently from grid electricity. The design included solar panels, charge controllers, rechargeable battery packs, voltage monitoring, low-power communication, and deep sleep mode between readings. The system lifecycle showed a clear sequence from initialization to normal operation, alert state, critical state, and maintenance. This lifecycle supports continuous monitoring and orderly response when environmental readings become abnormal.

Figure 4. System lifecycle from initialization to normal operation, alert state, critical state, and maintenance.

Automated GSM Alerting and Deployment Feasibility

The GSM-based alerting mechanism provided direct communication even in locations without stable internet connection. Critical alerts were automatically generated when any flame sensor was activated, temperature exceeded 50°C, or gas/smoke level surpassed 2000 PPM. Users were also notified when alert levels increased, when a node went offline, when a new node was added, when an alert was cleared, and when the gateway initialized. These features strengthened the system's deployment feasibility for off-grid forest monitoring.

Summary of Findings and Practical Implications

The evaluation confirmed that the system demonstrated strong detection accuracy, minimal false alarms, reliable communication, fast alert response, sustainable solar operation, and scalable architecture for large forest coverage. Although the source manuscript did not provide detailed numerical test values for each metric, it clearly indicated that the prototype performed effectively under varying environmental conditions. The findings imply that solar-powered embedded systems and wireless communication can provide an affordable and adaptable solution for forest fire early warning, particularly in resource-limited regions.

Table 5. *Summary of System Performance Findings*

Evaluation Area	Observed Finding	Practical Implication
Detection accuracy	Timely and accurate fire detection was confirmed	Supports early fire recognition and faster response
False alarm control	Minimal false alarms through multi-sensor logic	Improves trustworthiness of alerts
Communication reliability	Stable low-power communication through ESP-based networking	Supports distributed monitoring in remote locations
Alert responsiveness	GSM alerts delivered critical notifications	Enables rapid decision-making even without internet access
Solar sustainability	Solar charging and battery operation supported autonomous nodes	Reduces dependence on grid power
Scalability	Architecture supports small to large node deployments	Allows expansion based on forest coverage needs

CONCLUSION

The study concluded that the smart and sustainable forest fire early detection system successfully integrated solar energy, ESP32-based multi-sensor monitoring, wireless mesh communication, Raspberry Pi-based processing, and GSM-based alert notification. The system responded to the need for real-time and field-level forest fire monitoring, particularly in remote or off-grid environments where manual patrols and delayed reporting may be insufficient.

The prototype demonstrated strong feasibility in terms of detection accuracy, false-alarm reduction, communication reliability, alert responsiveness, solar power sustainability, and scalability. The use of multiple sensors and alert-level logic strengthened the reliability of detection, while solar power and GSM communication increased practical applicability in resource-limited forest settings. Overall, the system represents a scalable technological contribution to forest fire prevention, environmental protection, and disaster-risk reduction.

Recommendation

Future development should expand the sensor suite by integrating advanced multi-gas sensors, thermal imaging, and more durable industry-grade components. These improvements may enhance detection accuracy and allow the system to operate more reliably under harsh environmental conditions.

Artificial intelligence and machine learning may be incorporated to analyze sensor patterns, predict fire-risk conditions, and further reduce false positives. The system should also be tested across wider and more diverse forest environments to validate its performance under different terrains, weather conditions, vegetation types, and communication ranges.

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International Journal
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Volume 2 Issue 7 (July 2026)

Collaboration with local disaster-risk reduction offices, forest conservation agencies, and local government units is recommended to integrate the system into existing fire prevention and response frameworks. Training materials and deployment protocols should also be developed so that local responders can operate, maintain, and interpret the system effectively.

References

Akyildiz, I. F., Su, W., Sankarasubramaniam, Y., & Cayirci, E. (2002). Wireless sensor networks: A survey. Computer Networks, 38(4), 393-422. https://doi.org/10.1016/S1389-1286(01)00302-4

Alkhatib, A. A. A. (2014). A review on forest fire detection techniques. International Journal of Distributed Sensor Networks, 2014, Article 597368. https://doi.org/10.1155/2014/597368

Anand, S., Rajendra, S., & Kumari, M. (2020). Fire safety system using IoT and ESP32. IEEE Xplore. https://ieeexplore.ieee.org/document/9452085

Bakar, B. A., Ibrahim, N., & Ismail, M. (2020). Fire detection system using ESP32 and IoT. International Journal of Advanced Research in Computer Science, 11(3), 28-34. https://www.ijarcs.info/index.php/ijarcs/article/view/2955

Borge, J., Go, H. D., & Poon, P. (2020). Development of a wireless sensor network system for forest fire detection. International Journal of Smart Computing and Artificial Intelligence, 4(1), 29-37. https://www.ijscaijournal.com/article_2020_4_1_29_37.pdf

Daud, S., & Abdul Rahman, R. (2025). IoT-based smart fire detection system using ESP32. ResearchGate. https://www.researchgate.net/publication/388173172_IoTBased_Smart_Fire_Detection_System_using_ESP32

Geronimo, J. P. A., & Mallari, M. O. (2025). Propelling rural communities: The impact of solar-powered irrigation systems. Iconic Research and Engineering Journals, 8(7), 108–122. https://www.irejournals.com/paper-details/1706886 (IRE Journals)

Hartung, C., Han, R., Seielstad, C., & Holbrook, S. (2006). FireWxNet: A multi-tiered portable wireless system for monitoring weather conditions in wildland fire environments. Proceedings of the 4th International Conference on Mobile Systems, Applications and Services, 28-41. https://doi.org/10.1145/1134680.1134685

Hossain, G. M., & Rahman, M. G. (2019). Fire detection system using IoT and ESP32. International Journal of Advanced Computer Science and Applications, 10(11), 307-312. https://thesai.org/Downloads/Volume11No6/Paper_27-Fire_Detection_System_Using_IoT_and_ESP32.pdf

Khan, A., Khan, M., Hasan, M., Zakri, W., Alhazmi, W., & Islam, T. (2022). An efficient wireless sensor network based on the ESP-MESH protocol for indoor and outdoor air quality monitoring. Sustainability, 14, 16630. https://doi.org/10.3390/su142416630

Kumar, A., Sharma, P., & Patel, M. (2021). Real-time fire detection system using ESP32 with wireless communication. Advances in Electrical Engineering and Computational Science, 10(2), 45-50.

Manogaran, S. R., Lakshmi, T. I., & Kumar, S. R. (2018). Wireless fire monitoring system using ESP32. International Journal of Pure and Applied Mathematics, 119(12), 953-960. https://www.ijpaa.com

Patel, N., & Shah, R. (2020). ESP32-based fire alerting system. In Proceedings of the International Conference on IoT and Applications (pp. 175-180). https://www.sciencedirect.com/science/article/pii/S1877050919300039

Pradeep, V., Kumar, V., & Ravi, S. (2020). Forest fire detection system using IoT and cloud computing. International Journal of Advanced Research in Computer and Communication Engineering, 9(3), 1123-1127. https://doi.org/10.17148/IJARCCE.2020.93012

Ramos, J. Z. M., Mallari, M. O., & De La Cruz, A. R. (2025). Experimental study on the adversary attack vulnerabilities in IoT and CPS actuators and sensors through electromagnetic fault injection. In R. U. Kumar (Ed.), Emerging technologies in sustainable innovation, management and development (pp. 248–255). Routledge. https://doi.org/10.4324/9781003684459-37

Reddy, V. K. R., Reddy, A. R. V. M., & Reddy, P. K. (2020). Fire detection and monitoring system using ESP32 and Firebase. In Proceedings of the International Conference on Control, Instrumentation, Communication, and Computational Technologies (pp. 88-93). https://ieeexplore.ieee.org/document/8393607

Singh, A., & Jain, S. (2017). IoT based forest fire detection system using wireless sensor network. International Journal of Engineering and Technology, 9(2), 192-197. https://doi.org/10.14419/ijet.v9i2.9207

Thakur, H. H. G., & Joshi, N. G. (2021). Fire detection system with ESP32 using GSM and IoT integration. In IEEE International Conference on Smart Technologies and Systems (pp. 123-128). https://ieeexplore.ieee.org/document/9401523