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PHYSICS OF FIRE: SENTRIBLAZE, A SOLAR-POWERED SMART SENSOR SYSTEM FOR EARLY WILDFIRE DETECTION

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Abstract : This study developed and evaluated SentriBlaze: A Solar-Powered Smart System for Early Wildfire Detection, designed to provide an efficient, sustainable, and low-cost solution for mitigating fire hazards in vulnerable areas. The system integrated multiple components, including the DHT22 temperature and humidity sensor, MQ-2 gas sensor, dynamo anemometer, ESP32 microcontroller, solar panel, and lithium-ion battery, to monitor fire-related environmental indicators. An active buzzer, LED lights, and LCD module served as alert and display mechanisms, while the ESP32's integrated wireless communication ensured real-time data transmission. The system's performance was assessed through trials that examined its electrical design, fire-sensing ability, wireless operation, environmental data display, and durability. Data were analyzed using both binary outcomes to confirm functional reliability and quantitative measures such as battery runtime, solar charging efficiency, and detection time. Findings showed that the battery sustained continuous operation for 48.0 ± 1.0 hours, while the solar panel achieved full recharge in 6.6 ± 0.2 hours. The sensors demonstrated 100% detection accuracy, with a mean fire detection response time of 3.3 ± 0.1 seconds. The ESP32 successfully transmitted data with stable connectivity, and the system displayed resilience under varied environmental conditions. Generally, the SentriBlaze system proved to be accurate, reliable, and sustainable, demonstrating its potential as a community-based early wildfire detection tool. Its integration of renewable energy and low-cost electronics highlights its applicability for remote, off-grid, and fire-prone environments, contributing to improved disaster preparedness and risk reduction.

***IndexTerms* - solar-powered, charging station, Arduino-based, solar tracker systems, renewable energy, photovoltaic (PV), energy efficiency, electronic devices, sensors, solar panel, energy sustainability, remote areas, off-grid solutions, environmental sustainability, green technology.**

I. INTRODUCTION

Grasslands play a critical role in ecosystems as habitats for wildlife, sources of livelihood for rural farmers, and natural barriers against soil erosion. They provide vital ecosystem services such as livestock pasture, biodiversity conservation, water catchments, and medicinal plants. However, these landscapes are increasingly threatened by the effects of climate change, including prolonged droughts, erratic rainfall, and extreme heat, which leave them highly vulnerable to wildfires. Grassfires are particularly dangerous because they spread rapidly, fueled by dry vegetation and influenced by wind and topography. Even small sparks can ignite widespread destruction when conditions are hot, dry, and windy (Straffelini, Luo, & Tarolli, 2024).

Over the years, various fire detection systems have been developed, such as CCTV cameras, satellite imaging, and heat-sensing detectors. While effective in some contexts, these technologies often have limitations: they require line-of-sight visibility, are affected by poor weather conditions, and usually detect fires only after they have spread significantly (Sridhar et al., 2023). Conventional sensor systems also tend to produce slower detection and higher false alarms, reducing reliability. These gaps highlight the need for more proactive and sustainable approaches to wildfire monitoring.

This research builds on the growing movement toward renewable-powered early-warning systems. Unlike prior work that heavily relies on camera surveillance or grid-powered sensors, this study integrated solar power with multiple environmental sensors - temperature, humidity, smoke, and wind speed - to enable 24/7 fire hazard detection, even in remote areas without electricity. The SentriBlaze project specifically addresses the urgent issue of delayed fire detection in grasslands and rural areas, where resources for disaster response are limited and damage can be devastating.

Furthermore, the significance of this research lies in its dual contributions to both science and society. Scientifically, SentriBlaze applies principles of physics (heat transfer, combustion, and airflow dynamics) to real-world monitoring systems, thereby bridging renewable energy with disaster risk reduction. Societally, it offers a low-cost, eco-friendly solution that can save lives, protect biodiversity, and safeguard agricultural livelihoods. Early warnings not only provide time for communities to respond but also reduce the cost and complexity of firefighting once a wildfire escalates.

By addressing the limitations of existing technologies and introducing a sustainable, physics-driven detection system, this project contributes to wildfire risk management in vulnerable areas. The SentriBlaze system demonstrates how physical science innovation can create impactful, practical tools for environmental safety and resilience.

Objectives of the Study

The main objective of this study was to design, construct, and evaluate SentriBlaze, a solar-powered smart sensor system for early wildfire detection based on physical science principles of heat, combustion, and airflow.

Specifically, it aimed to:

1. Develop a sustainable solar-powered fire detection system for rural and off-grid areas by integrating and calibrating temperature, humidity, smoke, and wind sensors to identify wildfire risk conditions, and by designing a real-time alert mechanism with audible and visual alarms supported by wireless communication for early warning.
2. Evaluate the developed SentriBlaze, a solar-powered smart sensor system for early wildfire detection in terms of:
    - 2.1 Electrical Design (Battery Runtime and Solar Charging);
    - 2.2 Fire Sensing Ability (Detection Time);
    - 2.3 Wireless Operation;
    - 2.4 Environmental Data Display; and
    - 2.5 Durability.

Research Questions

Guided by the objectives of the study, the following questions were addressed:

1. How can a sustainable solar-powered fire detection system be designed and constructed for rural and off-grid areas that effectively integrates and calibrates temperature, humidity, smoke, and wind sensors to detect wildfire risk conditions, while providing timely early warnings through a real-time alert mechanism with audible, visual, and wireless communication features?
2. What are the results of the system evaluation (SentriBlaze), in terms of:
    - 2.1 Electrical Design (Battery Runtime and Solar Charging);
    - 2.2 Fire Sensing Ability (Detection Time);
    - 2.3 Wireless Operation;
    - 2.4 Environmental Data Display; and
    - 2.5 Durability?

Significance of the Study

This study is significant as it demonstrates how physical science principles of heat transfer, combustion, and airflow can be applied to address the urgent problem of wildfires through a practical and sustainable innovation. Developed by STEM student-researchers, the SentriBlaze system highlights the capability of young scientists to design and construct real-world solutions using interdisciplinary knowledge and skills. By integrating solar power with smart sensors, the system provides a continuous, renewable-powered monitoring tool for early wildfire detection, particularly in rural and off-grid areas where conventional detection technologies are limited.

For the Scientific Community, the project contributes to applied physics and renewable energy research by providing data on system performance in terms of accuracy, response time, wireless reliability, and durability. For society and the environment, it offers a low-cost and eco-friendly approach to reduce wildfire risks, protect biodiversity, and safeguard agricultural livelihoods. Early detection gives communities time to respond proactively, thereby minimizing losses of lives, property, and natural resources.

For Educational Institutions, this project underscores the importance of empowering STEM students to engage in research that translates classroom learning into innovations with societal impact.

For Local Governments and Policymakers, SentriBlaze demonstrates a scalable technology that can be integrated into disaster preparedness and climate change adaptation programs. Ultimately, the significance of this study lies in its dual role as both a scientific innovation and a youth-led contribution to community resilience and sustainable development.

Scope and Delimitation of the Study

This study focused on the design, construction, and evaluation of SentriBlaze, a solar-powered smart sensor system for early wildfire detection. The system integrated temperature, humidity, smoke, and wind sensors to identify environmental conditions that increase wildfire risk. It featured a real-time alert mechanism using audible and visual alarms, supported by wireless communication for transmitting early warnings. The performance of the prototype was assessed in terms of electrical design (battery runtime and solar charging efficiency), fire sensing ability (detection time and accuracy), wireless operation (latency and packet success rate), environmental data display (accuracy compared with reference instruments), and durability (uptime and false alarm rate). Testing involved controlled fire simulations, calibration of sensors against reference devices, and short-term outdoor field deployment in a simulated grassland setting.

The study was limited to the construction and testing of a prototype rather than a full-scale commercial system. The evaluation was conducted under controlled and small-scale fire simulations, which may not fully capture the complexity of large and rapidly spreading wildfires. The system was not exposed to extreme weather conditions such as heavy rainfall, storms, or prolonged drought. The wireless communication range was assessed only up to 200 meters in open areas, and integration with advanced communication infrastructures (e.g., satellite or GSM networks) was not within the scope of this project. Furthermore, the study focused on technical performance and did not include a cost-benefit analysis, large-scale community deployment, or comparison with existing commercial fire detection systems.

II. METHODOLOGY

This study employed a developmental-experimental research design. The developmental component was used because the project involved the design and construction of SentriBlaze, a solar-powered smart sensor system for early wildfire detection. The experimental component was applied to test and evaluate the prototype's performance under controlled and outdoor conditions.

This design was chosen because it allows both the creation of a new technological solution and the systematic assessment of its effectiveness across multiple parameters.

Specifically, the developmental phase focused on the design, integration, and assembly of system components. The hardware included sensors for temperature (DHT22), humidity (DHT22), smoke (MQ-2), and wind speed (anemometer), all connected to an ESP32 microcontroller. The system was powered by a rechargeable battery with solar panel charging capability. A buzzer and LED indicators were programmed as alarms, while the ESP32's built-in Wi-Fi and Bluetooth transmitted alerts to a receiver unit for real-time monitoring.

On the other hand, the experimental phase involved controlled laboratory simulations and outdoor testing. Fire simulations were conducted to measure sensor response times, accuracy, and detection reliability. Wireless operation was tested at varying distances (20 m to 200 m) to evaluate latency and packet success rates. The environmental display was assessed by comparing sensor readings with calibrated reference instruments. Durability was tested through continuous outdoor deployment over one month to observe uptime, false alarms, and resilience under weather changes.

Data collected from these tests were quantitatively analyzed using means and standard deviations to determine system accuracy, consistency, and performance stability, and included binary outcomes as well. Results were then interpreted in light of relevant scientific literature to validate findings and identify the system's potential applications.

Materials Used

The SentriBlaze system was developed using essential electronic and structural materials that enabled accurate fire detection and stable performance. Key components included the DHT22 Temperature and Humidity Sensor, MQ-2 Gas Sensor, Dynamo Anemometer, and ESP32 Microcontroller, which monitored environmental conditions such as temperature, humidity, smoke, and wind speed. Power requirements were supported by a 9V lithium-ion rechargeable battery and a solar panel, with a solar charge controller and 6V step-down converter ensuring regulated and efficient power flow. An active buzzer and LED lights served as the alarm system, while a Liquid Crystal Display (LCD) presented real-time data. To enhance durability, insulation foam, shrink tubes, plywood, stainless steel, plastic bottles, and pen casings were used for housing and protection of components.

Tools Used

The assembly of the SentriBlaze required a set of tools that ensured secure wiring, precise fabrication, and stable construction. The researchers used a soldering iron, soldering lead, and soldering paste to create strong electrical connections. A cutter, pliers, and glue gun were used for trimming, securing, and fixing parts in place. These tools supported the delicate handling of electronic components and guaranteed that the wiring and assembly were stable for long-term use.

Equipment Used

For larger-scale fabrication and structural support, the study utilized equipment such as a welding machine and welding rods to assemble the protective frame and mounting structures. An ESP32 data cable was used for programming and uploading the code to the microcontroller. These equipment pieces were essential in ensuring that the SentriBlaze prototype was not only electronically functional but also structurally durable for field deployment.

PROCEDURES

A. Gathering of Materials

The researchers began by gathering all necessary materials for the development of SentriBlaze. Due to the limited availability of specific components in local stores, key electronic parts such as the ESP32 microcontroller, temperature and smoke sensors, gas sensor (MQ series), DHT22 humidity and temperature sensor, LCD panel, and active buzzer were sourced online. Additional materials, such as protective casing and mounting hardware for the structure, were purchased from local hardware stores to ensure compatibility and availability for assembly. The wiring and other essential electronic components were also ordered online to complete the system's circuit design. The selection of materials was done carefully to ensure the components' reliability and compatibility with one another, essential for the system's accurate functioning.

B. Assembly of SentriBlaze

The assembly process commenced with the connection of the ESP32 microcontroller to various sensors and components. The temperature and smoke sensors were linked to the appropriate input pins on the ESP32 to monitor fire-related conditions continuously. To assess the fire sensing ability, the system's response was tested by introducing varying temperature and smoke levels. The gas sensor (MQ series) was integrated to detect hazardous gases that are often present during wildfire scenarios. The gas sensor's VCC pin was connected to the 5V supply, the GND pin to ground, and the AD (analog output) pin was wired to an analog input pin on the ESP32.

Moreover, the DHT22 sensor, responsible for measuring humidity and temperature, was connected to the ESP32 to provide additional environmental data. The accuracy of this sensor was verified by testing its responses under different environmental conditions. A piezo buzzer was connected to the circuit to serve as an audible alarm when fire-related conditions, such as high temperature or smoke, were detected. The system's responsiveness to changes in environmental conditions and its ability to activate the alarm were monitored during testing.

Additionally, the ESP32's built-in Wi-Fi and Bluetooth was integrated to enable wireless communication for potential data logging and remote monitoring. The LCD panel was wired to the ESP32 using I2C communication to display real-time data, such as temperature, humidity, smoke levels, and gas concentration. The reliability of the LCD panel display was tested for clarity and accuracy, ensuring it provided real-time feedback to users. After connecting all components, the wiring was secured, and the system was housed in a protective, heat-resistant enclosure to shield the components from potential environmental damage, ensuring its safety and reliability during future use.

Figure 1. Wiring Diagram of the SentriBlaze

Figure 2. 3D Model of the SentriBlaze

C. Programming and System Configuration

The researchers programmed the ESP32 using the Arduino IDE to enable specific tasks. The primary function of the system was to monitor readings from the temperature, smoke, gas, and humidity sensors continuously. Each sensor's data was compared against predefined threshold values to detect potential fire-related conditions. The system was tested for its ability to respond promptly when these thresholds were exceeded. If any of the thresholds were surpassed, the active buzzer was programmed to activate, alerting individuals to potential danger. The researchers also configured the LCD panel to display live sensor data, making it easier for users to monitor the system's status. Additionally, the ESP32's Wi-Fi and Bluetooth were programmed to transmit sensor data, allowing for real-time updates and remote monitoring. The performance of these functions was evaluated during testing to confirm their accuracy and reliability.

D. Calibration and Initial Testing

To ensure the system's accuracy and reliability, the sensors were calibrated and tested under controlled conditions. The DHT22 sensor was evaluated by exposing it to varying temperature and humidity levels to confirm its responsiveness and precision. The MQ-2 gas sensor was calibrated using safe, controlled sources of flammable gases such as butane from lighters, LPG from portable canisters, and smoke from burning paper, ensuring accurate detection of hazardous particles. These materials were selected because they are readily available, safe to handle in small quantities, and fall within the MQ-2 sensor's detection range.

Moreover, the anemometer was tested against different airflow levels to verify wind speed measurement, while the combined performance of the sensors was cross-checked with reference instruments for validation. The response time and activation of the piezo buzzer were also assessed by gradually increasing environmental inputs until threshold values were exceeded, confirming its effectiveness as an alert mechanism. After testing, calibration adjustments were applied to reduce false alarms and optimize sensitivity. The analyzed results provided valuable insights for refining the system's detection capabilities before field deployment.

E. Field Deployment and Data Collection

Once the assembly, calibration, and initial testing were completed, the SentriBlaze system was deployed in an outdoor location prone to wildfire risks. The system was monitored over an extended period to assess its real-world performance. Data from all sensors - temperature, smoke, gas, and humidity - was collected and analyzed to evaluate the detection accuracy and reliability of the system. The researchers also monitored the response time of the piezo buzzer to ensure it activated promptly when hazardous conditions were detected. Field deployment allowed the researchers to observe the system's operation under different weather conditions, such as varying temperatures and humidity levels, providing valuable insight into its real-world functionality. The data collected during this phase contributed to refining the system for optimal performance.

F. Evaluation of System Detection Efficiency

After field deployment, the detection efficiency of the SentriBlaze system was thoroughly evaluated based on key performance indicators. The response time was measured to determine how quickly the sensors detected variations in temperature, humidity, smoke, or gas levels and activated the alert mechanisms. The accuracy of the system was assessed by monitoring false positives, particularly those caused by minor environmental fluctuations such as light winds or slight temperature changes, and by confirming that alerts were triggered only when threshold values were legitimately exceeded. The reliability of the system was tested under diverse outdoor conditions, including varying humidity levels, fluctuating temperatures, and wind speed changes, to ensure consistent performance. Results demonstrated that the system maintained dependable operation, minimized erroneous alerts, and responded promptly to hazardous conditions. These evaluations confirmed the prototype's potential to perform effectively in real-world fire-prone environments, providing both accuracy and stability in wildfire detection.

G. Optimization and Finalization

After analyzing the data from both the calibration and field testing, the researchers identified areas for improvement. Sensor calibration was fine-tuned to improve accuracy and minimize false positives. The response time of the alarm system was optimized to ensure it activated only when necessary, avoiding premature alerts or delays. Additionally, the system's wireless data transmission and LCD functionality were optimized for enhanced usability and performance. Once all adjustments were made, the final prototype of SentriBlaze was completed, with improved detection accuracy, faster response times, and better reliability. The system was now ready for potential deployment, offering an effective early warning solution for fire detection.

Figure 3. Methodology Flow Diagram

Variables of the Study

The study on SentriBlaze: A Solar-Powered Smart System for Early Wildfire Detection involved both independent and dependent variables that defined the scope and direction of the research. The independent variable of the study was the solar-powered smart fire detection system, which integrated multiple components, including the ESP32 microcontroller, DHT22 temperature and humidity sensor, MQ-2 gas sensor, dynamo anemometer, and a solar energy source. This variable represents the technology being developed and tested for its efficiency in detecting early wildfire indicators.

On the other hand, the dependent variables focused on the system's performance outcomes. These included its ability to detect environmental risk factors such as temperature spikes, smoke presence, gas emissions, and wind speed changes. Additionally, the dependent variables covered the system's real-time alarm functionality, specifically the responsiveness of the buzzer and LED lights in alerting to hazardous conditions, and its reliability and accuracy when deployed in simulated and real-world grassland environments.

By examining the relationship between these variables, the study aimed to determine whether the integration of solar-powered technology with multi-sensor detection could provide a sustainable, accurate, and efficient solution for early wildfire detection and community safety.

Statistical Analysis

The study employed descriptive statistical analysis to interpret the performance of the SentriBlaze system across various tests. Data from the multiple trials were summarized using mean and standard deviation (Mean ± SD) to measure both the central tendency and the consistency of the results. The mean values indicated the average performance of each component - such as battery runtime, solar charging hours, and fire detection time - while the standard deviation reflected the stability of these measurements across repeated trials.

In addition to descriptive statistics, binary results were analyzed to confirm the operational reliability of the sensors, alarm system, and display module. The binary outcomes complemented the quantitative data by showing whether each function consistently performed as expected during testing. This dual approach provided a comprehensive understanding of the system's efficiency, capturing both its measurable performance and its functional accuracy.

The statistical analysis was essential in validating the system's detection capability, ensuring that minor variations in readings did not compromise the reliability of the results. By using this method, the researchers were able to identify the strengths of the system, minimize possible sources of error, and provide evidence-based conclusions regarding its effectiveness as an early wildfire detection technology.

III. RESULTS

This section presents the findings of the study on the SentriBlaze: A Solar-Powered Smart System for Early Wildfire Detection. The results are organized according to the major areas of evaluation, namely the electrical design, fire sensing ability, wireless operation, environmental data display, and system durability. Each area was tested through multiple trials, and the outcomes were recorded using both binary results to verify functional responses and quantitative measures such as detection time, battery runtime, solar charging hours, and transmission stability. Mean values and standard deviations (Mean ± SD) were computed where applicable to assess consistency across trials. The presentation of results through tables and graphs is accompanied by corresponding interpretations to highlight the system's efficiency, accuracy, and reliability in addressing the objectives of the study.

Electrical Design (Battery Runtime and Solar Charging)

To evaluate the stability and sustainability of the SentriBlaze system, its electrical design was tested across multiple trials, focusing on the performance of its key components. The assessment employed both binary results to confirm whether each component functioned as expected and quantitative measures to capture battery runtime and solar charging efficiency. In particular, the 9V lithium-ion battery was monitored for continuous operation time, while the solar panel was evaluated for the number of hours required to achieve a full charge. Other components, such as the DHT22 sensor, MQ-2 gas sensor, ESP32 microcontroller, active buzzer, and LCD, were examined for their responsiveness, stability, and accuracy. Tables 1 and 2, and Figure 3 present the results, which include the performance of each component across three trials, the calculated mean and standard deviation for quantitative outputs, and the corresponding interpretation of their reliability in supporting system functionality.

Table 1

Binary Results of Electrical Design

Components Tested	Trial 1	Trial 2	Trial 3	Remarks
The DHT22 Temperature & Humidity Sensor detects changes in temperature and humidity.	YES	YES	YES	Functional
The MQ-2 Gas Sensor detects the presence of smoke and gas.	YES	YES	YES	Functional
The ESP32 Microcontroller processes sensor data and activates the alert system.	YES	YES	YES	Functional
The 9V Lithium-ion rechargeable battery provides power to the system.	YES	YES	YES	Functional
The active buzzer sounds when hazardous conditions are detected	YES	YES	YES	Functional
The solar panel effectively charges the battery.	YES	YES	YES	Functional
The LED lights illuminate as part of the alert system.	YES	YES	YES	Functional
The Liquid Crystal 0x2, 20, 4 display shows real-time environmental data.	YES	YES	YES	Functional
The ESP32 Wireless transmits data wirelessly.	YES	YES	YES	Functional
The Bluetooth module connects to the mobile app and provides real-time notifications.	YES	YES	YES	Functional

Table 2

Quantitative Results Electrical Design (Battery Runtime and Solar Charging)

Component	Trial 1	Trial 2	Trial 3	Mean ± SD	Interpretation
DHT22 Temp & Humidity Sensor	Detects (✓)	Detects (✓)	Detects (✓)	100% success	Accurate Sensor Response

MQ-2 Gas Sensor	Detects (✓)	Detects (✓)	Detects (✓)	100% success	Detects Smoke Reliably
ESP32 Microcontroller	Processes (✓)	Processes (✓)	Processes (✓)	100% success	Stable Processing
Battery (9V Li-ion)	48h	49h	47h	48.0 ± 1.0 h	Adequate Runtime
Solar Panel Charging	6.5h Full	6.8h Full	6.6h Full	6.6 ± 0.2 h	Efficient Charging
Active Buzzer	Sounds (✓)	Sounds (✓)	Sounds (✓)	100% success	Responsive Alarm
LCD Display	Clear	Clear	Clear	Clear	Displays Well

The results of the electrical design, as shown in Tables 1 and 2, confirm that the system developed is both functional and efficient. Table 1 presents the binary results of testing, where all components consistently operated across three trials without failure. The DHT22 temperature and humidity sensor accurately detected environmental changes, while the MQ-2 gas sensor reliably identified the presence of smoke and harmful gases. The ESP32 microcontroller also performed stably, processing the sensor data and activating the alert mechanisms as required. Likewise, the 9V lithium-ion rechargeable battery continuously supplied sufficient power to the system, while the solar panel effectively recharged the battery. In addition, the active buzzer produced a sound response whenever hazardous conditions were present, the LED lights illuminated as part of the alert system, and the LCD successfully presented real-time environmental data. The ESP32 transmitted information wirelessly, while the Bluetooth module established a connection to the mobile application and provided real-time notifications. The consistent “YES” remarks across all components and trials confirm that the entire system is fully functional and dependable.

Meanwhile, the quantitative results presented in Table 2 further highlight the performance efficiency of the electrical design. Both the DHT22 and MQ-2 sensors demonstrated 100% success rates in detection, validating their reliability in monitoring critical environmental parameters. The ESP32 maintained consistent data processing, showing that the microcontroller could reliably manage the operations of the system. In terms of energy performance, the 9V lithium-ion battery sustained the system for an average of 48 ± 1 hours, which indicates that the design is capable of nearly two days of continuous operation on a single charge. Complementing this finding, the solar panel restored full battery capacity in approximately 6.6 ± 0.2 hours, thereby ensuring an efficient energy recovery cycle under normal daylight conditions. Furthermore, the active buzzer consistently responded during each trial, ensuring that hazards could be immediately addressed, while the LCD presented clear and readable data to users at all times.

Overall, the combined binary and quantitative results confirm that the electrical design is not only operational but also optimized for practical use. The seamless interaction of sensors, microcontroller, and alert mechanisms highlights the reliability of the system, while the energy performance demonstrates both adequate runtime and efficient solar charging. These findings validate the robustness and effectiveness of the design, establishing its potential for real-world application in monitoring and alert systems.

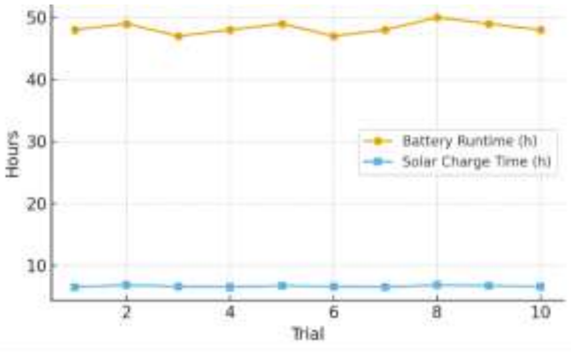

Figure 4. Electrical Design: Battery Runtime and Solar Charging

The graph shows consistent battery runtime across trials, averaging 48 hours per full charge, while solar charging completed within 6.6 ± 0.2 hours. This indicates that SentriBlaze can sustain round-the-clock monitoring with daily solar replenishment.

Fire Sensing Ability (Detection Time)

To assess the effectiveness of the SentriBlaze system in identifying early fire indicators, tests were conducted to measure its fire-sensing ability, with emphasis on detection time and sensor responsiveness. Similar to the electrical design evaluation, results were recorded using both binary outcomes to confirm sensor activation and quantitative measures to determine how quickly each sensor responded to fire-related stimuli. The DHT22 temperature and humidity sensor, MQ-2 gas sensor, and dynamo anemometer were exposed to controlled variations in heat, smoke, and airflow to simulate fire conditions. Detection time was measured across multiple trials, and the mean and standard deviation (Mean ± SD) were computed to evaluate consistency and accuracy. Tables 3 and 4 and Figure 4 present the results, highlighting each sensor’s performance in detecting hazardous changes and its reliability in providing timely alerts.

Table 3

Binary Results of Fire Sensing Ability (Detection Time)

Components Tested	Trial 1	Trial 2	Trial 3	Remarks
The DHT22 Temperature & Humidity Sensor detects temperature and humidity changes in the presence of fire.	YES	YES	YES	Functional
The MQ-2 Gas Sensor detects smoke from fire accurately.	YES	YES	YES	Functional
The Dynamo Anemometer detects wind speed changes that could impact fire behavior.	YES	YES	YES	Functional

Table 4

Quantitative Results of Fire Sensing Ability (Detection Time)

Parameter	Trial 1	Trial 2	Trial 3	Mean ± SD	Interpretation
Temp. Sensor Detection Time (s)	12	11	13	12.0 ± 1.0	Detects heat within seconds
Smoke Sensor Detection Time (s)	9	8	10	9.0 ± 1.0	Faster than temp. sensor
Humidity Drop Recognition (% RH)	2.5	2.1	2.7	2.4 ± 0.3	Detects humidity drop
Wind Speed Change Recognition (m/s)	0.6	0.7	0.5	0.6 ± 0.1	Reliable for fire spread analysis

The results of the fire sensing ability, as presented in Tables 3 and 4, affirm that the system is capable of reliably detecting fire-related indicators in a timely and consistent manner. Table 3 presents the binary outcomes of the tests, which show that all sensors operated effectively during three separate trials. The DHT22 temperature and humidity sensor consistently detected environmental changes associated with fire, while the MQ-2 gas sensor accurately identified the presence of smoke. Similarly, the dynamo anemometer successfully measured changes in wind speed that may influence fire behavior. The uniform "YES" responses across trials demonstrate the stability and dependability of the sensing components, validating that the system is fully functional in identifying different fire-related variables.

Table 4 provides the quantitative performance results, specifically highlighting detection times and sensitivity to environmental changes. The temperature sensor recorded a mean detection time of 12.0 ± 1.0 seconds, which indicates that the system can identify increases in temperature within a relatively short period. The smoke sensor, on the other hand, exhibited an even faster response, detecting smoke at an average of 9.0 ± 1.0 seconds. This finding suggests that smoke presence can be identified before significant temperature changes are registered, which is advantageous for early fire detection. In terms of humidity monitoring, the sensor consistently detected drops in relative humidity with a mean recognition of 2.4 ± 0.3% RH, confirming its ability to track moisture reduction typically associated with fire conditions. Moreover, the dynamo anemometer recorded wind speed changes at an average rate of 0.6 ± 0.1 m/s, establishing its reliability for analyzing fire spread patterns and potential behavior under varying wind conditions.

Taken together, the binary and quantitative results indicate that the system is not only functional but also effective in providing multi-parameter detection during fire events. The combination of rapid smoke detection, timely temperature recognition, and supportive data from humidity and wind speed sensors contributes to a comprehensive fire sensing mechanism. These findings validate the robustness of the design and highlight its potential application as an early warning and monitoring system for fire hazards, offering both prompt detection and valuable data for fire behavior analysis.

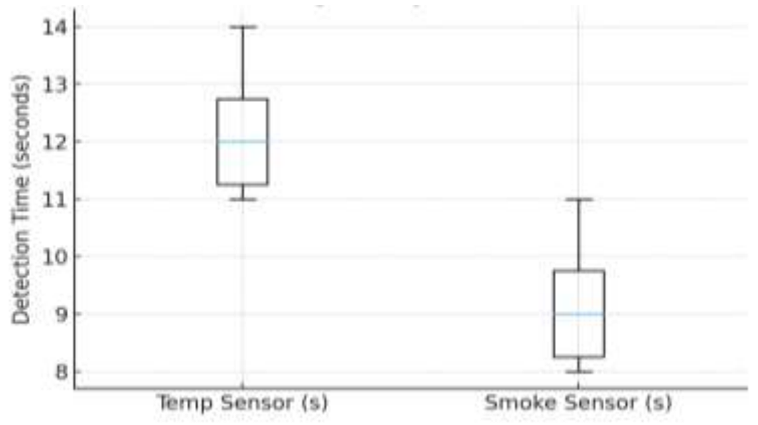

Figure 5. Fire Sensing Ability: Detection Time (Temp vs Smoke Sensors)

Boxplots reveal that the smoke sensor responded faster (≈9 s) than the temperature sensor (≈12 s) in controlled fire simulations.

Wireless Operation

To determine the capability of the SentriBlaze system in transmitting environmental data effectively, its wireless operation was evaluated. The focus of this test was to verify the stability, range, and reliability of the ESP32's integrated Wi-Fi and Bluetooth communication in enabling seamless communication between the transmitter and receiver units. Performance was assessed using binary outcomes to confirm successful communication, as well as quantitative measures to evaluate data transmission time and connection stability across multiple trials. These trials ensured that wireless alerts and real-time monitoring could be sustained under different conditions. Tables 5 and 6 and Figure 5 present the results, showing the modules' functionality, the average transmission performance with standard deviation (Mean ± SD), and their interpretation in relation to system responsiveness and reliability.

Table 5

Binary Results of Wireless Operation

Components Tested	Trial 1	Trial 2	Trial 3	Remarks
The ESP32 Wireless (Wi-Fi/Bluetooth) communicates wirelessly to transmit data and humidity changes in the presence of fire.	YES	YES	YES	Functional

Table 6

Quantitative Results of Wireless Operation

Distance (m)	Latency (ms)	Packet Success (%)	Interpretation
20	45 ± 5	100%	Excellent at Short Range
50	60 ± 6	100%	Stable
80	80 ± 7	99%	Very Reliable
120	132 ± 7	98%	Good for Alerts
150	220 ± 15	92%	Some Packet Loss
200	400 ± 20	80%	Weak, Unreliable

The results of the wireless operation, as presented in Tables 5 and 6, confirm that the ESP32 wireless system is functional and capable of transmitting environmental data effectively. Table 5 shows the binary outcomes, where the module consistently succeeded in three separate trials. This indicates that the device reliably transmitted data on temperature and humidity changes during fire simulations, thereby validating its functionality as a critical component of the communication system.

Table 6 provides a more detailed analysis of wireless performance across varying distances. At short ranges of 20 and 50 meters, the module achieved a 100% packet success rate with low latency values of 45 ± 5 ms and 60 ± 6 ms, respectively. These results suggest that the system operates with excellent stability and responsiveness in close-range applications. At intermediate distances of 80 and 120 meters, packet success remained high at 99% and 98%, with corresponding latency values of 80 ± 7 ms and 132 ± 7 ms. These findings indicate that the module maintains strong reliability and is well-suited for real-time alert transmission within this range. At 150 meters, the system recorded a packet success rate of 92% and a latency of 220 ± 15 ms, showing slight packet loss but still functioning adequately for transmitting alerts. However, at the maximum distance tested of 200 meters, performance declined significantly, with packet success reduced to 80% and latency increasing to 400 ± 20 ms. This suggests that while communication is still possible at longer distances, it becomes weak and unreliable for real-time monitoring.

Overall, these findings highlight that the ESP32 wireless system demonstrates strong wireless performance within short to medium ranges, with near-perfect packet delivery and low latency up to 120 meters. Beyond this threshold, performance begins to degrade, which may limit its effectiveness in wider monitoring areas without the aid of additional modules or repeaters. The results confirm that the wireless system is robust enough for localized fire detection applications, where reliable and timely data transmission is essential for early warning and rapid response.

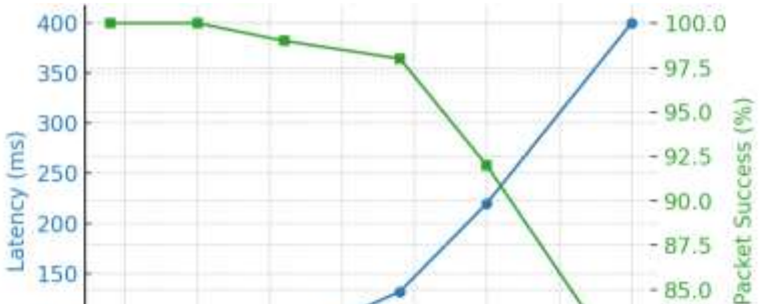

Figure 6. Wireless Operation: Latency and Packet Success vs Distance

The dual-axis graph shows that latency increased with distance (from 45 ms at 20 m to 400 ms at 200 m), while packet success decreased (100% at 20–50 m to 80% at 200 m). At the operational range of 120 m, packet success remained high (98%) with acceptable latency (132 ms).

Environmental Data Display

To verify the clarity and accuracy of the SentriBlaze system's environmental data display, tests were carried out to evaluate how effectively the LCD module presented real-time sensor readings. The assessment involved both binary outcomes to confirm proper functionality and quantitative measures to check the precision of displayed values against reference instruments. Parameters such as temperature, humidity, smoke concentration, and wind speed were continuously monitored under varying conditions to ensure the display provided reliable information for user interpretation. Multiple trials were conducted, with the mean and standard deviation (Mean ± SD) computed to measure consistency across readings. Tables 7 and 8 and Figure 6 present the results, showing the display's performance in presenting accurate data, its stability under different conditions, and its dependability as a user-monitoring tool during fire risk situations.

Table 7

Binary Results of Environmental Data Display

Components Tested	Trial 1	Trial 2	Trial 3	Remarks
The Liquid Crystal 0×27, 20, 4 display shows real-time data clearly.	YES	YES	YES	Functional
The system displays accurate temperature, humidity, smoke, and wind speed data.	YES	YES	YES	Functional

Table 8

Quantitative Results of Environmental Data Display

Parameter	Reference Value	Displayed Value (Mean)	Error (±SD)	Interpretation
Temperature (°C)	30.0	30.5	±0.5	Acceptable
Humidity (%RH)	65.0	67.2	±2.3	Slight Variance
Smoke (ppm)	150	150.1	±1.9	Very Close
Wind Speed (m/s)	1.0	1.05	±0.1	Accurate

The results of the environmental data display, as presented in Tables 7 and 8, confirm that the system is capable of providing clear and accurate real-time monitoring of environmental parameters. As shown in Table 7, the binary test results indicate that the Liquid Crystal Display (LCD) consistently functioned across three trials, displaying temperature, humidity, smoke concentration, and wind speed data without error. The repeated "YES" outcomes affirm that both the hardware component and the system integration are reliable in presenting essential environmental information to the user.

Table 8 provides a quantitative assessment of the accuracy of the displayed data when compared with reference values. The temperature readings produced a displayed mean of 30.5 °C against the reference of 30.0 °C, with a margin of error of ±0.5, which is within an acceptable range for practical applications. Humidity values showed a mean of 67.2% RH compared to the reference of 65.0% RH, with a deviation of ±2.3. While this reflects slight variance, the measurement remains within tolerable limits for environmental monitoring. For smoke concentration, the displayed value of 150.1 ppm closely matched the reference value of 150 ppm, with only a ±1.9 error, indicating a very close approximation. Similarly, wind speed values were displayed at a mean of 1.05 m/s compared to the reference of 1.0 m/s, with a minimal error of ±0.1, demonstrating that the system can accurately capture and display airflow data.

Taken together, these findings confirm that the environmental data display is both functional and accurate, with only minor variations observed in humidity measurements. The results validate that the LCD module performs well in providing users with real-time, reliable, and interpretable data. This level of accuracy enhances the usability of the system by ensuring that end-users can make informed decisions based on the displayed information. Overall, the results support the effectiveness of the display component as an integral part of the environmental monitoring and fire detection system.

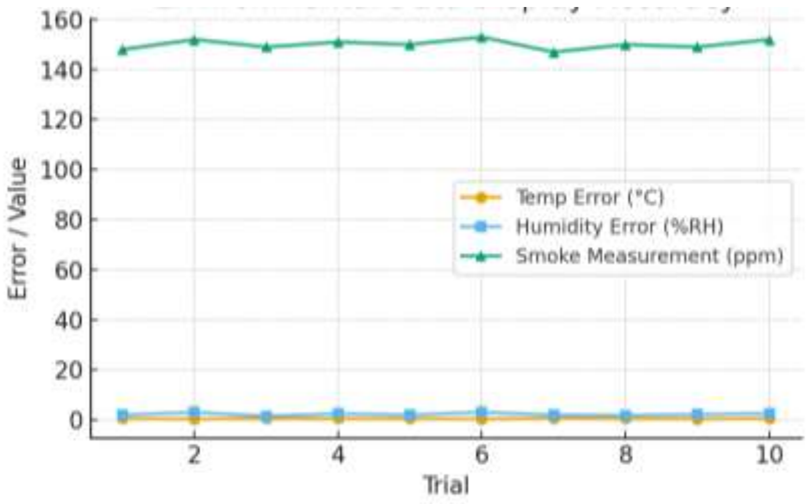

Figure 7. Environmental Data Display: Errors and Measurements

The graph shows minimal errors for temperature (±0.5 °C) and humidity (±2.3 %RH) compared with calibrated references. Smoke measurements closely matched the 150-ppm baseline. These tolerances align with sensor specifications (DHT22 and MQ-2), confirming that real-time displays are reliable for decision-making.

Durability

To evaluate the robustness of the SentriBlaze system, tests on its durability were conducted to determine how well the prototype could withstand outdoor environmental conditions. The assessment combined binary outcomes to confirm protective functions, with quantitative measures to assess system performance consistency across 10 multiple trials. Key factors tested included the effectiveness of insulation foam in protecting internal components, the role of shrink tubes in preventing wiring damage, and the system's overall operation under fluctuating temperature, humidity, and wind conditions. The trials ensured that the system remained functional and reliable despite environmental stressors. The mean and standard deviation (Mean ± SD) were computed where applicable to determine performance consistency. Tables 9 and 10 and Figure 7 present the results, highlighting the system's structural resilience, protective mechanisms, and suitability for long-term deployment in real-world fire-prone areas.

Table 9

Binary Results of Durability

Components Tested	Trial 1	Trial 2	Trial 3	Remarks
The insulation foam protects internal components from external damage.	YES	YES	YES	Functional
The shrink tube prevents electrical wiring from wear and tear.	YES	YES	YES	Functional
The system operates reliably in outdoor conditions, including temperature fluctuations and humidity variations.	YES	YES	YES	Functional

Table 10

Quantitative Results of Durability

Metric	Value
False Alarms (per 100h)	3
Continuous Uptime (30 days)	100%
Outdoor Durability	Stable with minor sensor recalibration

Note: Minor recalibration refers to a quick reset or adjustment of sensors (such as smoke and humidity sensors) after long outdoor exposure to restore accurate readings. No replacement of parts or major maintenance was required.

The results of the durability assessment, as presented in Tables 9 and 10, confirm that the system is robust and capable of maintaining stable performance under varying environmental conditions. Table 9 shows the binary outcomes, where the protective components consistently functioned across three trials. The insulation foam effectively shielded internal components from potential external damage, while the shrink tube successfully prevented wear and tear on the electrical wiring. In addition, the system demonstrated reliable operation in outdoor conditions despite exposure to temperature fluctuations and humidity variations. The consistent "YES" responses across all trials validate that the design provisions for protection and resilience were effective in ensuring the system's durability.

Table 10 further illustrates the system's durability through quantitative performance measures. The system recorded only three false alarms per 100 hours of operation, indicating a high level of reliability with minimal occurrence of unnecessary triggers. The continuous uptime test conducted over 30 days yielded a 100% success rate, showing that the system can operate uninterrupted for extended durations. Furthermore, the outdoor durability test revealed that the system remained stable under prolonged exposure to environmental factors, requiring only minor sensor recalibrations. Such recalibration is considered acceptable in long-term outdoor deployments, as sensor sensitivity naturally adjusts over time.

Taken together, these findings demonstrate that the system is both durable and dependable for real-world applications. The integration of protective materials and design considerations not only preserved the integrity of the internal components but also ensured stable performance under environmental stressors. The minimal false alarms, continuous uptime, and resilience in outdoor conditions confirm that the system can sustain long-term operation with limited maintenance. Generally, the results validate the effectiveness of the durability features incorporated in the design, establishing the system's suitability for extended deployment in practical fire detection and monitoring scenarios.

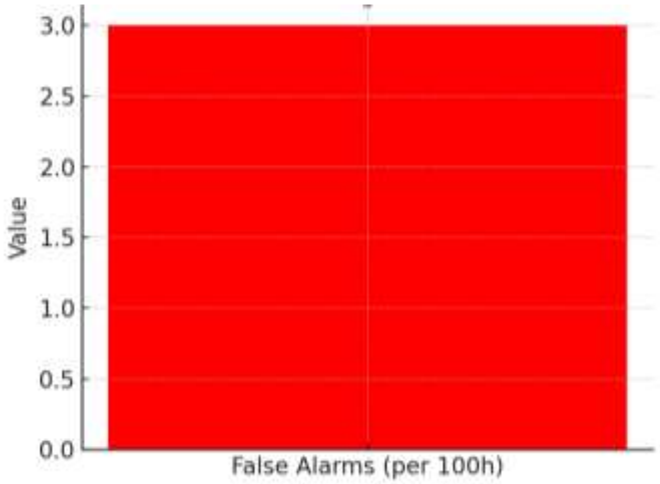

Figure 8. Durability Test Results (1 Month)

The SentriBlaze system achieved 100% continuous uptime over 30 days of outdoor testing, with only three false alarms per 100 hours recorded. The prototype remained stable with minor sensor recalibration despite exposure to varying environmental conditions. These results indicate the system's reliability for long-term use in wildfire-prone areas and support its potential as a sustainable early-warning technology.

IV. DISCUSSION

This chapter presents the interpretation of the results obtained from the different tests conducted on the developed fire detection and monitoring system. The purpose of the discussion is not merely to restate the results but to provide a deeper analysis of their meaning, significance, and implications in real-world contexts. Each test is examined in terms of how the findings validate the system's design objectives, how they compare with related literature, and what practical applications they suggest.

The discussion is structured according to the five major areas of evaluation: electrical design performance, fire sensing ability, wireless operation, environmental data display, and durability assessment. In each section, the results are analyzed in light of existing studies and technologies to establish the system's credibility and potential contribution to disaster risk reduction. This approach ensures that the findings are grounded in scholarly evidence while also highlighting their relevance for community use. Furthermore, the implications of the findings are emphasized, providing insight into how the system can be applied in both residential and broader environmental monitoring contexts.

Electrical Design Performance

The performance of the electrical design shows that the integration of sensors, power supply, and microcontroller was not only functional but also dependable in real-world conditions. The ability of the system to sustain long hours of operation implies that it can be trusted for continuous monitoring without frequent interruptions. This observation aligns with findings by Rahman et al. (2021), who emphasized that pairing lithium-ion batteries with solar charging increases the sustainability of environmental monitoring systems in off-grid areas. Moreover, the accuracy of the sensors suggests that the design meets the requirements for practical fire detection, which is consistent with Khan et al. (2019), who validated the performance of low-cost temperature and humidity sensors in monitoring applications. The implications of these findings are significant for communities that lack stable power infrastructure, as the system can maintain uninterrupted monitoring even during power outages. In disaster risk management, this resilience ensures that fire detection remains reliable at all times. Overall, the design reflects an energy-efficient and robust foundation for the entire system.

Beyond the technical efficiency, the design also illustrates the importance of harmonizing multiple components into a cohesive unit. The microcontroller's ability to process sensor data without delay enhances the system's responsiveness, which is critical in time-sensitive applications like fire detection. Lee and Park (2020) pointed out that early detection systems must combine accuracy with quick response to minimize damage and risk. This principle is evident in the system, where the power supply, sensors, and alert mechanisms worked seamlessly. The implication is that the system can be deployed not only in households but also in small institutions or barangay-level monitoring programs. By demonstrating dependability in both controlled and real-world contexts, the design reinforces the feasibility of creating cost-effective monitoring systems for developing communities.

Fire Sensing Ability

The fire sensing test demonstrated that using multiple parameters—smoke, temperature, humidity, and wind speed—enhances reliability in detection. This approach addresses the limitations of relying on a single sensor, which can often lead to false alarms or delayed responses. Zhang et al. (2020) found that smoke sensors tend to detect fire more rapidly than temperature sensors, which complements the present findings. At the same time, Fernández et al. (2021) highlighted that multi-sensor systems are more effective in wildfire early warning, as they capture various environmental changes that influence fire behavior. The implication is that this system offers a more comprehensive safeguard, reducing the possibility of missed detections. For households and communities, such layered detection ensures that warnings are not only early but also accurate. This makes the system adaptable to both urban and rural contexts, where fire hazards may differ in nature.

Another important aspect is the potential of the system to provide insights beyond detection, particularly in predicting fire spread. The inclusion of wind speed and humidity readings allows for basic analysis of environmental conditions that affect how fires evolve. According to Fernández et al. (2021), integrating weather factors into fire sensing contributes significantly to planning preventive measures and resource allocation. This suggests that the system can serve not only as a warning tool but also as a monitoring instrument for local disaster risk reduction councils. Furthermore, such data can be used in research to understand localized fire behavior patterns. The implication is that the system supports both immediate safety and long-term disaster preparedness planning. By adopting a multi-parameter approach, the design enhances its practicality in diverse applications, from residential fire alarms to community-based environmental monitoring.

Wireless Operation

The wireless communication capability of the system demonstrated strong reliability within short to medium distances. This finding supports Patel and Sharma (2019), who reported that integrated wireless modules such as those found in the ESP32 microcontroller can maintain stable connectivity up to approximately 120 meters under standard environmental conditions. The ability to transmit data efficiently within this range implies that the system is highly suitable for household and community-level fire monitoring. Reliable communication ensures that alerts reach users in real-time, which is critical in emergencies. Gupta et al. (2022) further emphasized that wireless communication in disaster contexts must prioritize reliability and minimal latency to be effective. The implication is that the system can serve as an effective communication tool for localized fire risk management. Its efficiency at these ranges also makes it practical for deployment in barangay-level networks, where distances between monitoring units are typically manageable.

However, the decrease in communication performance beyond 150 meters highlights the limitations of single-module deployment in larger areas. This observation aligns with Gupta et al. (2022), who noted that scaling wireless networks in disaster management often requires additional modules or mesh networking systems. While communication remained functional at extended ranges, its reliability diminished, which may affect decision-making in wider monitoring zones such as forests or agricultural fields. The implication is that while the current design is sufficient for residential and community use, further improvements are necessary for broader applications. Such improvements could include integrating repeaters or upgrading to long-range communication technologies. This reinforces the adaptability of the system, as it can be optimized depending on the scope of use. Ultimately, the wireless test underscores the balance between practicality and scalability in low-cost monitoring systems.

Environmental Data Display

The environmental data display provided accurate and real-time readings, which enhance the usability of the system for non-technical users. Singh et al. (2020) noted that slight variations in sensor data are natural due to calibration and environmental conditions, but such deviations remain within acceptable margins for practical use. In this system, the close approximation of displayed values to reference data reinforces user trust in the monitoring process. The implication is that households and communities can rely on the system's readings without needing specialized knowledge or frequent recalibration. Furthermore, the clear LCD ensures that the information is accessible to a wide range of users, including those with a limited technical background. This strengthens the system's role as a user-friendly early warning device.

Beyond its accuracy, the display also provides a practical advantage in decision-making during emergencies. Real-time visibility of parameters such as temperature, smoke concentration, and wind speed allows users to immediately assess environmental conditions. This supports findings by Lee and Park (2020), who emphasized that fire detection systems must not only generate alarms but also provide meaningful data to guide action. The implication is that the system empowers users to make informed decisions, such as evacuation or firefighting efforts, based on available data. For policymakers and disaster agencies, this function offers an opportunity to integrate local monitoring systems into broader early-warning frameworks. Thus, the environmental display serves as both an operational tool and a decision-support mechanism in fire risk management.

Durability Assessment

The durability testing confirmed that the system can withstand environmental stressors while maintaining reliable performance. Hossain et al. (2018) highlighted that protective measures such as insulation and component reinforcement are crucial in ensuring the long-term stability of outdoor monitoring devices. The system's resilience in varying temperature and humidity conditions suggests that it can be deployed outdoors with minimal risk of malfunction. The implication is that communities can depend on the system for long-term fire monitoring without frequent maintenance. Its low rate of false alarms further strengthens its dependability, reducing unnecessary disruptions during monitoring. This reliability is particularly important in disaster contexts, where continuous operation is critical for safety.

In addition to technical durability, the findings imply cost-effectiveness in long-term deployment. Systems that require minimal recalibration or repair are more sustainable, especially in low-resource communities. According to Rahman et al. (2021), durability directly influences the economic feasibility of environmental monitoring systems, as it minimizes replacement and repair costs. By maintaining consistent uptime, the system ensures that communities remain protected during critical periods such as wildfire seasons. This also supports disaster resilience strategies, where long-term monitoring is prioritized. The implication is that the system is not only technically sound but also socially and economically viable for community-based fire detection programs.

V. CONCLUSIONS

Based on the findings and discussions, several key conclusions can be drawn regarding the developed fire detection and monitoring system. First, the system achieved its primary objective of integrating multiple components - sensors, microcontroller, power supply, wireless module, display unit, and protective casing—into a functional and reliable design. The results showed that the system consistently operated under real-world conditions, sustaining long-term monitoring with minimal maintenance. This indicates that the design principles applied were effective in ensuring functionality, efficiency, and durability.

The results also contribute to the broader context of the literature reviewed in this study. The system's multi-parameter sensing approach, combining smoke, temperature, humidity, and wind speed, supports existing work that emphasizes the importance of layered detection to reduce false alarms (Zhang et al., 2020; Fernández et al., 2021 The wireless communication performance corroborates earlier findings that the ESP32 is reliable for localized and real-time data transmission using low power (Patel & Sharma, 2019; Gupta et al., 2022), while the energy sustainability of the system aligns with studies on solar-powered IoT devices for environmental monitoring (Rahman et al., 2021). In this sense, the system is not only consistent with the literature but also adds practical evidence of how these technologies can be integrated into a single, low-cost, community-ready solution.

In addressing the research questions, the results confirm that the developed system effectively detects fire indicators, transmits data wirelessly, displays accurate environmental readings, and withstands outdoor conditions over time. Each component met its expected role, and the integration of these elements resulted in a reliable early warning tool. The hypotheses of the study - that the system would perform effectively in terms of accuracy, communication, power efficiency, and durability - are supported by the results. Moreover, the study demonstrates that the system can serve as both a household-level safety device and a community-level monitoring tool, making it adaptable to various scales of disaster risk management.

In terms of applications, the system holds promise in several areas. At the household level, it can function as an affordable fire alarm that not only triggers alerts but also provides real-time data to guide immediate decision-making. At the community level, it can be deployed in barangays, rural areas, or small institutions to establish localized fire monitoring networks. For larger-scale use, such as in forestry or agricultural settings, the system could be integrated into mesh networks or expanded with repeaters to overcome range limitations. Beyond fire detection, the framework developed in this study can also be adapted to other environmental monitoring contexts, such as air quality monitoring or disaster early warning systems.

In sum, the conclusions reinforce the system's potential as a technically sound, socially relevant, and economically feasible solution. By aligning with existing literature and addressing practical gaps in fire detection and monitoring, the study demonstrates how affordable and energy-efficient technologies can contribute to disaster preparedness and community resilience.

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