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From Wildfire Detection to Community Health Preparedness: An Edge-Enabled IOT Monitoring Framework

Satyam Mishra[1]*, Shaili Singhal[2], Abha Kiran Rajpoot[2], Himika Verma[3], Pramod Shetty[4]

[1]Department of Electrical and Electronics Engineering, Galgotias University, Greater Noida, Uttar Pradesh, India.
[2]SCSE, Galgotias University, Greater Noida, Uttar Pradesh, India.
[3]School of Engineering and Technology, VIPS, Delhi, India.
[4]Department of Computer Science and Artificial Intelligence (CSAI), KIET (Deemed to be University), Ghaziabad, Uttar Pradesh, India.
Corresponding author: Satyam Mishra | mishra.satyam@galgotiasuniversity.edu.in | Department of Electrical and Electronics Engineering, Galgotias University, Greater Noida, Uttar Pradesh, India.
Author emails: Shaili Singhal — shaili.singhal@galgotiasuniversity.edu.in; Abha Kiran Rajpoot — akrajpoot@gmail.com; Himika Verma — himika.verma@vips.edu; Pramod Shetty — pramod.sethy@kiet.edu.
ORCID iDs (author-provided): Satyam Mishra 0000-0001-8286-7027 | Shaili Singhal 0009-0006-8336-3465 | Abha Kiran Rajpoot 0000-0002-0643-3646 | Himika Verma 0009-0006-8723-6834 | Pramod Shetty 0009-0006-9012-2467

ABSTRACT: Wildfire ignition can threaten forest resources and create smoke hazards for nearby communities. However, rapid detection of fire-like conditions is not equivalent to measurement of inhaled pollutants or clinical risk. This methodological case study critically reinterprets an author-supplied ESP32 NodeMCU prototype and develops an explicit pathway from environmental event detection to accountable health preparedness. The previously described prototype combines DHT11 temperature/humidity, an MQ-2 smoke-responsive channel, infrared flame sensing, an edge-hosted dashboard, a local buzzer and ThingSpeak logging. Its two-out-of-three rule uses heat, dryness and a smoke indicator. The precursor manuscript reports approximately 96% estimated decision accuracy in controlled tests, 2–4 s end-to-end detection, local alert activation within 1 s after crossing a threshold, and over 95% cloud-delivery consistency. Raw trial records, calibrated particulate measurements and health outcomes were unavailable for reanalysis. We derive the rule's behaviour under independent and dependent sensor responses and identify critical differences between ignition alerts and exposure advisories. A proposed two-tier verification design integrates reference-calibrated PM2.5 monitoring, meteorology, spatial context and authorized public-health communication. The work provides an evidence-audited technical framework and prospective evaluation protocol, without claiming real-world exposure reduction or clinical benefit.

1. INTRODUCTION

Forests protect biodiversity, soil, catchments and environmental conditions on which communities rely. Wildfires can remove vegetation, damage infrastructure and release smoke that travels beyond the ignition zone. The World Health Organization

emphasizes the need for early warning, coordinated risk communication and preparedness in responding to wildfire-related health hazards (WHO, 2026). In parallel, evidence on smoke-associated cardiovascular and respiratory harms is growing, although the strength of evidence varies by endpoint and exposure definition (Chen et al., 2021; Gould et al., 2024; Li et al., 2025). A low-cost fire sensor can contribute to a response system only if its signals are accurately described and followed by appropriate verification; it is not itself a medical diagnostic or exposure monitor.

The central question of this manuscript is whether a low-cost, locally responsive wildfire-monitoring architecture can provide a defensible first stage for a future community health warning system, while remaining explicit about what it has and has not measured.

2. SCIENTIFIC CONTEXT AND RATIONALE

Wildfire smoke is a heterogeneous mixture whose composition varies with vegetation, combustion stage, meteorology and burning of manufactured materials. Of particular relevance to public health are fine particulate matter (PM2.5), carbon monoxide and other combustion products. Ambient concentrations, indoor infiltration, duration and individual vulnerability all influence exposure. Respiratory outcomes have comparatively consistent support in the literature; cardiovascular associations have been reported but differ across studies, regions and outcomes (Chen et al., 2021; Gould et al., 2024; Li et al., 2025). A recent multidisciplinary review also highlights the difficulties of attribution and causal inference (Chen et al., 2026). The present system does not measure individual dose, diagnose disease or quantify prevented health events.

Satellite active-fire products and remote-imaging methods provide wide-area information, albeit with constraints associated with observation interval, cloud conditions and pixel size (Justice et al., 2002). Aircraft-based thermal mapping offers another valuable but resource-intensive observation modality (Merino et al., 2012). Wireless ground sensors can contribute persistent, site-specific observations but inherit deployment, communications and energy limitations (Akyildiz et al., 2002). The relevant design question is not whether one modality replaces the other, but how local sensing can trigger rapid field investigation while satellite imagery, meteorology and calibrated air-quality observations inform subsequent geographic assessment. This distinction matters when translating engineering indicators into trustworthy public advice.

This journal has published related satellite-based forest-fire resource-and-health assessments and smoke mapping (More et al., 2026a, 2026b). Unlike those remote-sensing analyses, the supplied precursor describes a physically implemented, ground-level ESP32 system. The distinct contribution of this article is an evidence audit of its ignition measurements, an exact clarification of the fusion-rule assumptions, a proposed missing-data-safe escalation pathway and a predefined field/air-quality validation framework. None of the satellite, clinical or particulate measurements in other studies are attributed to the present device.

2.1. Research objectives and contribution boundaries

The objectives are: (i) document the precursor hardware, communications and decision mechanism without changing its recorded specifications; (ii) distinguish observed controlled-test statements from values that cannot be independently verified; (iii) analyze how dependence between indicators changes the mathematical interpretation of majority fusion; and (iv) define staged validation before communities could rely on subsequent exposure messages. The source package includes a six-page technical article, not the raw traces, event labels, calibration files or code needed for a new empirical analysis. Accordingly, the present work is framed as a case-based methodological perspective rather than a newly conducted field or clinical study.

3. MATERIALS AND METHODS

3.1. Provenance of the technical case study

This case study is derived from the six-page author-supplied article, "A Scalable and Real-Time IoT-Based Forest Fire Monitoring System Using NodeMCU Sensor Nodes and Cloud Analytics" (Mishra et al., author-supplied manuscript). The supplied article documents a working hardware prototype, representative simulated-condition ranges and summary performance claims. It does not identify the number of independent tests, supply individual sensor traces or disclose complete calibration and classification procedures. The publication and submission history of the precursor is not established by the provided file. Editorial evaluation of any distinct manuscript must therefore be preceded by disclosure of the prior work and its status; a change of journal or wording alone is not a new experiment.

3.2. Hardware and layered architecture

The edge platform comprises a perception layer (DHT11, MQ-2/smoke input, infrared flame input), processing and network functions on an ESP32 NodeMCU board, and visualization through a local web page and a ThingSpeak cloud channel. The on-node buzzer provides an immediate audible indicator. Node identifiers are intended to associate readings with installation zones. The original design describes independent, replicated Wi-Fi nodes rather than a demonstrated large-area mesh or satellite-connected deployment. The ESP32 provides integrated Wi-Fi and a 12-bit analog-to-digital converter, although ADC count alone cannot establish a pollutant mass concentration (Espressif Systems, 2026).

Table 1. Prototype components and evidence-appropriate interpretation

Component	Recorded role	Important interpretation
ESP32 NodeMCU	Acquisition, Wi-Fi, rule, local interface	Edge alert can continue without cloud access.
DHT11	Temperature and relative humidity	Rated near 0–50 °C; values above range need replacement sensor.
MQ-2 / smoke channel	Combustible-gas / smoke-responsive analogue signal	Not a validated PM2.5 monitor; ppm requires analyte-specific calibration.
IR flame detector	Flame-presence digital indicator	Logged by prototype; not in the precursor 2-of-3 rule.
Buzzer and web dashboard	Local audible and visual alert	Indicates possible fire conditions, not health-risk severity.
ThingSpeak channel	Remote logging and plots	Historical visibility; constrained by platform update rate.

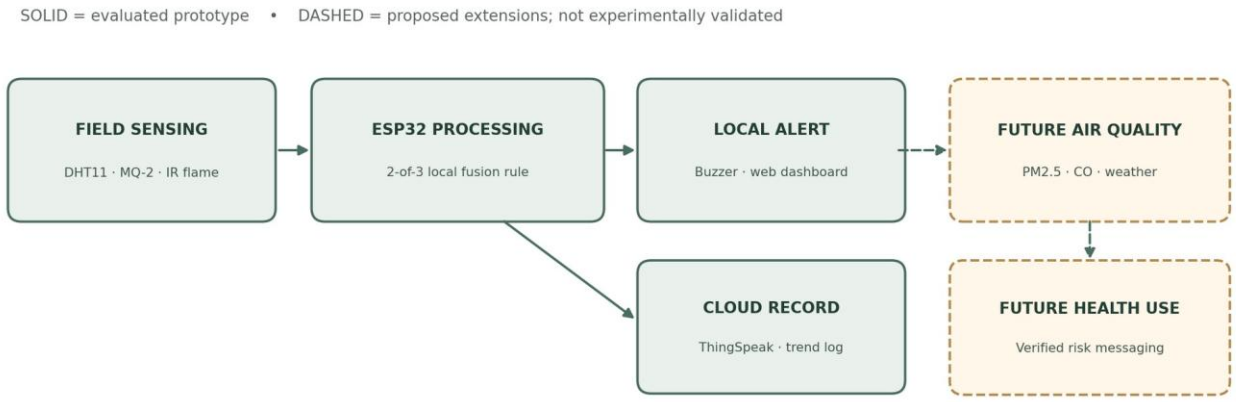


Figure 1. Implemented local-monitoring chain (solid) and proposed, unevaluated health-surveillance extensions (dashed). Diagram newly drawn from the precursor description.

3.3. Acquisition, local display and remote transmission

Firmware developed in the Arduino IDE configures sensing channels and runs an acquisition/decision loop. The DHT11 supplies temperature and relative humidity; the MQ-2 and smoke channels enter through analog readings; and the flame detector is digitally polled. The ESP32 provides a soft-access-point interface at 192.168.4.1, with approximately 1–2 s local dashboard refresh reported in the source. Separately, an available upstream network allows HTTP uploads to ThingSpeak. Under the current free-service terms, ThingSpeak has a 15 s minimum update interval (ThingSpeak, 2026), so remote logging

cannot be assumed to have the latency of the local alarm. The cloud and edge pathways must be evaluated as distinct subsystems.

The precursor reports raw ESP32 ADC values and smoke estimates in parts per million. A 12-bit ADC reading ranges from 0 to 4095 counts, but conversion to analyte-specific concentration requires an explicit response model and calibration. In addition, the MQ-2 is a combustible-gas-responsive sensor; its analog signal should not be interpreted as particulate mass concentration (PM2.5) or as a validated smoke toxicity measure. Without documented heater conditioning, span calibration, co-exposure tests and environmental corrections, the reported "330 ppm" threshold is a prototype-specific decision setting rather than a health-protective standard. No new conversion is attempted here.

3.4. Fire-indicator fusion and decision logic

The original algorithm takes temperature T (°C), relative humidity H (%) and a smoke-related signal S, applying thresholds $T > 45$, $H < 35$ and $S > 330$ (as labeled in the source). Let $X_T = 1(T > 45)$, $X_H = 1(H < 35)$ and $X_S = 1(S > 330)$, with $1(\cdot)$ the indicator function. The local alarm equals $A = 1(X_T + X_H + X_S \geq 2)$. The infrared flame sensor is collected or displayed but is not part of this majority-rule expression. Because calibration evidence for S is absent, the threshold must not be interpreted as a standardized gas, ambient PM2.5 or clinical alert value.

Let p be the probability that any one of the three inputs triggers falsely in a non-fire interval, and q the probability that it triggers in a fire interval. If and only if the inputs are independent and identically distributed under each respective condition, the majority rule yields $P(\text{false alarm}) = 3p^2 - 2p^3$ and $P(\text{detection}) = 3q^2 - 2q^3$. For illustration, $p = 0.05$ gives 0.00725 (0.725%); $q = 0.90$ gives 0.972 (97.2%). These are mathematical consequences of hypothetical input probabilities, not sensitivity, specificity, or confidence intervals estimated from the prototype. The independence requirement is especially restrictive because elevated temperature and low relative humidity are typically related.

Without an independence assumption, the exact probability of two or more simultaneous triggers is $P(X_T X_H) + P(X_T X_S) + P(X_H X_S) - 2P(X_T X_H X_S)$, where each product denotes a joint event. This identity shows why marginal single-sensor rates are insufficient: joint statistics are needed. At the extreme of perfectly coupled identical sensors, the majority-rule probability equals that of one sensor (p for false triggering and q for true triggering), so its theoretical noise-reduction advantage disappears. These limiting cases, plotted in Figure 2, are an analytical sensitivity exercise rather than a fitted dependence model.

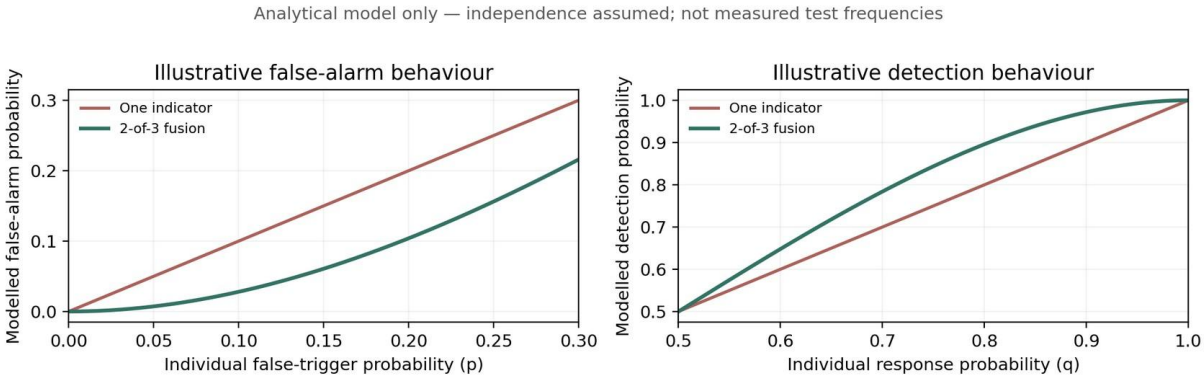


Figure 2. Illustrative majority-fusion probabilities calculated from the stated model; curves are mathematical examples, not experimental performance estimates.

3.5. Test conditions and reported endpoints

The source describes controlled normal, moderate and fire-like settings with representative measurements rather than a publicly accessible trial dataset. Its "accuracy" is described as the proportion of trials for which binary status agreed with the assigned condition. Because event counts, labeling rules, uncertainty estimates, independent repetitions, and raw data were not supplied, no confusion matrix, confidence interval or receiver-operating curve can be computed. Tests were not documented as naturally occurring forest fires and do not include population exposures or biological measurements.

Table 2. Representative ranges and configured thresholds in the supplied tests

Scenario	Temperature	Relative humidity	Smoke indicator*
Normal	28–32 °C	55–65%	80–120
Moderate increase	35–40 °C	40–50%	150–250
Fire-like condition	45–60 °C	20–35%	300–600
Trigger setting	>45 °C	<35%	>330

*The precursor labels the smoke values ppm after calibration but does not supply the calibration record. Readings beyond the DHT11 50 °C rating are indicative only.

4. RESULTS AND DISCUSSION

4.1. Prototype observations already reported

The source reports approximately 96% estimated classification agreement during controlled demonstrations. It also reports 2–4 s end-to-end detection, activation within 1 s once the threshold condition is met, refreshing of the local dashboard about every 1–2 s, and cloud transmission consistency above 95%. Several concurrent node streams were said to operate without noticeable delay, but the number of nodes, traffic load and loss denominators are not reported. These figures are retained strictly as source-reported performance summaries and do not establish independent real-world detection performance or operational coverage.

Table 3 deliberately distinguishes the source-reported percentage from independently estimable validation statistics. For example, the nominal 96% does not specify whether the positive (fire-like) and negative trials were balanced; the same overall accuracy could conceal very different sensitivities, false-positive rates and predictive values. The operational consequences depend on event prevalence, deployment context and delayed/missing measurements. A complete labeled trial register is therefore necessary before the metric can inform threshold selection.

Table 3. Performance findings and interpretive limits

Outcome	Value in supplied source	What can be inferred
Alert-decision accuracy	Approximately 96% (estimated)	Controlled-case agreement only; denominators unavailable.
End-to-end detection delay	Approximately 2–4 s	For the described local test conditions.
Post-threshold local alarm	At most 1 s	Local action after the rule is satisfied.
Dashboard refresh	Approximately 1–2 s	Applies to the embedded local interface.
Cloud-delivery consistency	Greater than 95%	The original logging setup; packet counts unavailable.
Multi-node operation	Parallel streams supported	No documented stress-load or forest-scale test.

4.2. Why rapid ignition alerts are relevant but insufficient for health claims

A rapid local ignition notification can be useful as a trigger for human verification, fire-service action and investigation of downwind smoke. It cannot by itself identify who is exposed, predict duration of pollutant transport or determine the appropriate health message. An operational evidence chain needs: verified event location and timing; meteorological context; quality-controlled pollution measurements; identification of potentially exposed populations; and approval by the relevant emergency-management and health authorities. Only the first element is partly represented in the existing apparatus.

The potential need for rapid communication is heightened for people with pre-existing heart or lung disease, older adults, children and workers who spend extended periods outdoors (US EPA, 2026; WHO, 2026). Chen et al. (2021) detail

cardiovascular biological pathways and gaps, while Li et al. (2025) provide an epidemiological example linking wildfire-related PM2.5 exposure with cardiovascular emergency visits. These external studies do not demonstrate that the source prototype measures PM2.5, improves warning uptake or prevents any cardiovascular event. Such claims would require prospective exposure evaluation and separate health-effect research.

4.3. The importance of calibrated air-quality measurements

The core measurement boundary is between a signal correlated with combustion and a traceable assessment of polluted air. Low-cost environmental sensors can support screening if the research question and data quality requirements are clearly defined. US EPA guidance recommends planned collocation, documented siting, environmental-interference assessment and transparent communication of uncertainty (US EPA, 2022). A suitable extension would include a particle sensor evaluated against a reference-grade PM2.5 monitor; the existing MQ-2 voltage cannot substitute for that work. Carbon-monoxide assessment would require a sensor validated for its specified range and interfering gases.

4.4. Failure modes and decision-quality safeguards

Several failures may produce apparently plausible but misleading outputs: the MQ-2 requires warm-up and is cross-sensitive; the DHT11 has a limited rated operating range; sunlight or reflection may disturb flame sensing; correlated temperature and humidity shifts may spur two simultaneous alerts; and Wi-Fi interruption may suppress logging while the node continues operating. Future firmware should distinguish SAFE, SUSPECTED EVENT and INSUFFICIENT DATA states, using explicit sensor-validity flags rather than treating missing channels as normal. Time stamps, calibration version, uptime and local-versus-cloud event timing should accompany each record. Debouncing and on-site verification are necessary before messages are escalated beyond the responsible response team.

4.5. Translation-ready claims and withheld claims

The evidence hierarchy is intentionally conservative. The source supports the presence of an ESP32 prototype and reports summary performance under controlled demonstrations. The analytical addition supports statements about a defined Boolean fusion rule under explicit distributional assumptions. The environmental-health literature supports concern about wildfire smoke, including susceptible cardiovascular populations. None of these sources establishes that this particular device predicts human exposure, that a warning reached residents, or that morbidity was reduced. The proposed architecture should be evaluated using a prospective protocol in which field truth, exposure truth and public communication are independently documented.

5. PROPOSED VALIDATION FOR ENVIRONMENTAL-HEALTH DEPLOYMENT

5.1. Separate the engineering and exposure claims

Two questions should be preregistered for follow-up. First, does the system detect independently established early fire events with useful sensitivity and acceptable false alerts across weather, sites and sensor ageing? Second, once a fire is confirmed, can calibrated particulate and meteorological data support geographically timely and understandable public-health messages? These questions demand different reference standards. Device agreement in a laboratory-like trial is an engineering endpoint, while usefulness of population advice is a separate public-health implementation endpoint.

Two falsifiable expectations arise from this design. H1 (engineering): a site-calibrated, quality-gated combination of signals will reduce false alerts per node-day relative to each component rule without unacceptable loss of sensitivity, evaluated with paired, site-held-out observations. H2 (information delivery): when reference environmental data are available, an agency-reviewed tiered workflow will produce fewer unsupported population warnings than direct publication of raw prototype alarms, assessed in blinded tabletop exercises. Both hypotheses remain untested; no effect sizes, power results or significance claims are asserted.

5.2. Sampling, controls and reference measurements

Engineering validation should use repeated, supervised, permitted fire-like tests alongside representative negative controls (hot dry periods, dust, non-fire smoke or emissions, varying sunlight, and power/network interruptions). An independently documented event onset and adjudicated labels should define the reference condition. Each sensor node should be evaluated before and after environmental conditioning and across available deployment locations. Sample size should be planned from

desired precision for sensitivity and false-alarm rates; individual intervals, not artificially multiplied correlated samples, should be treated as the unit of analysis. Fire safety permits and operational supervision must precede any combustion test.

Environmental-health validation requires a separate exposure measurement chain. Proposed instrumentation includes a calibrated PM2.5 monitor, appropriately selected CO equipment, local wind and humidity measurements, mapped sensor coordinates and traceable timestamps. ESP32 fine-time measurement offers an additional location-research option whose precision would need separate testing (Barral Vales et al., 2022). Lower-cost particle measurements should be collocated against a reference and validated across smoke concentrations, seasons and sites (US EPA, 2022). The analysis should report spatial and temporal cross-validation, transport uncertainty and calibration drift; meteorological or satellite context can improve plume interpretation. No human participants are needed for the preliminary instrument-validation phase. Any later linkage to admissions or patient characteristics requires independent ethics and data-governance review.

5.3. Pre-specified reporting metrics

The primary engineering report should include a case-by-case confusion matrix, sensitivity, specificity, precision, false positives per node-day, event-onset-to-local-alarm delay, sensor availability, energy autonomy, packet delivery fraction and performance stratified by weather and site. Calibrated exposure work should report reference bias, mean absolute error, residual distributions, drift and missingness. A practical health-warning exercise should separately measure authority verification time, message delivery, interpretation and false escalation. A simulation of stakeholder responses is not evidence of reduced admissions, mortality or individual exposure.

Table 4. Proposed evaluation matrix (not conducted)

Study stage	Reference / design	Primary outcome
Ignition recognition	Independent event record; blinded case labels	Sensitivity, specificity, false alerts/node-day
Node robustness	Environmental strata and network interruptions	Uptime, missingness, local latency
Air quality	PM2.5 reference collocation, meteorology	Bias, precision, drift, uncertainty
Spatial transport	Geolocation plus satellite/wind models	Spatial validation and lead-time errors

5.4. A proposed two-tier operational protocol

An accountable workflow can use two tiers. Tier 1 is a locally generated suspected-fire status for trained responders, subject to data-quality checks and independent on-site or remote verification. Tier 2 is a distinct, authority-controlled environmental-health communication based on confirmed source information, meteorology, validated PM2.5 or other relevant monitoring and locally approved public-health protocols. Both tiers should record timestamps, evidence quality, decision responsibility and the reason for escalation. Only Tier 1 is implemented in the supplied prototype; Figure 3 and the validation matrix describe a prospective design, not evaluated software or verified health benefit. Mock warning exercises should evaluate message delivery, clarity and escalation timelines without being described as patient outcomes.



Figure 3. Evidence-separated escalation from the existing ESP32 alert to proposed, untested fire confirmation and public-health communication. Blue boxes are described by the supplied prototype; orange boxes are prospective design requirements.

6. REPRODUCIBILITY, ETHICS AND LIMITATIONS

Reported hardware type, threshold logic, board-level connectivity, dashboards and representative reading ranges can be reconstructed at a high level from the author-supplied six-page paper. Full technical replication still requires original Arduino source, sampling intervals, pin assignments, ADC attenuation and calibration method, board and sensor versions, raw time series, trial identifiers, site metadata and network logs. No such materials were supplied for this editorial revision, and no claim of a new dataset or data repository is made. The mathematical graphs in Figure 2 are newly plotted from equations and contain no measured samples.

Limitations include controlled rather than in-situ validation; missing sample counts and confidence intervals; uncertain calibration of the smoke variable; partial sensor-range exceedance; correlated triggers; limited Wi-Fi coverage; cloud rate constraints; and no direct particulate, exposure or clinical measures. The device therefore must not be advertised as showing "96% accuracy" for real fires or for cardiovascular protection without qualifier. Separately, this methodological paper may overlap with the precursor in hardware and results. Originality requires a substantive new question or analysis and transparent prior-work disclosure, not merely rewriting the source text.

7. CONCLUSIONS

The supplied ESP32 system illustrates how inexpensive environmental nodes can raise local alarms and create accessible remote records. Its controlled-condition performance summaries are encouraging but insufficient to infer environmental exposure or medical benefit. The present methodological contribution is an explicit separation between suspected fire events and population health advisories, including a dependence-aware reading of the fusion rule and a staged validation framework. Progress toward responsible deployment requires independent field adjudication, reproducible code and labeled observations, traceable PM2.5 evaluation, meteorological integration, and authorization procedures with local health agencies. Until completed, the prototype is a preliminary forest-fire monitoring tool, not a calibrated exposure network or clinical decision-support system.

Declarations

Authorship and contributions

The five-author byline and institutional details on this manuscript were provided by the submitting team for this revision. The cited precursor manuscript has a different author list. All named authors must independently confirm substantial contributions, authorship eligibility, final manuscript approval and responsibility for the content. Permission, attribution and prior-publication considerations relating to the precursor work must be resolved before journal submission. The ORCID iDs for all five authors have been provided for this manuscript, but identity matching has not been independently verified. Individual CRediT contribution roles still require confirmation.

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Ethics, data availability and conflicts of interest

Ethics: this manuscript analyzes a device-based environmental monitoring prototype and proposes future validation; the provided materials describe no human or animal studies. Investigators must confirm any local fire-testing permits or safety approvals. Data availability: only aggregate results and representative ranges were supplied with the precursor; raw trials, code and calibration files were not supplied and are not deposited by this draft. Conflicts of interest: each author must provide a verified disclosure before submission.

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