Design and implementation of a solar-powered IoT-based real-time air quality monitoring system

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ABSTRACT

Air pollution has become a global issue due to rapid urbanization and industrialization. Air quality monitoring is essential for mitigating the adverse effects of air pollution on public health and the environment. This study presents a solar-powered internet of thing (IoT)-based air quality monitoring system designed for autonomous operation in outdoor settings. The prototype integrates an ESP32 microcontroller with low-cost sensors for PM2.5, PM10, temperature, humidity, and heat index. Powered by a solar panel and battery, the system ensures off-grid functionality, while Wi-Fi transmission to the Blynk platform, enables real-time visualization, historical record storage, and instant user access through mobile dashboards. The system was calibrated against reference instruments and deployed for 14 consecutive days. Results confirmed stable data transmission and reliable performance that suitability for outdoor use without reliance on grid power under real-world conditions. Furthermore, correlation analysis showed a strong relationship between PM2.5 and PM10, and moderate associations with humidity. Regression analysis further identified humidity and heat index as the most significant predictors, while temperature exhibited only minor influence. These findings demonstrate the feasibility of a low-cost, portable, and energy-autonomous IoT monitoring system, providing accurate real-time insights to support evidence-based air quality management.

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1. INTRODUCTION

The global climate system is undergoing a critical transformation driven by escalating levels of air pollution, which exceed the World Health Organization's recommended safety thresholds by more than double. This trend signals a deepening ecological crisis, with major contributors including congested transportation networks, industrial emissions, open waste burning, and rapid urbanization [1]. Fine particulate matter (PM2.5), nitrogen oxides (NOx), and carbon dioxide (CO_2) are among the most hazardous pollutants released into the atmosphere, posing severe threats to public health [2], [3]. Due to their microscopic size, PM2.5 particles can penetrate deeply into the respiratory and circulatory systems, increasing the risk of chronic diseases such as lung cancer, cardiovascular disorders, and stroke. Moreover, global warming exacerbates these impacts by elevating the heat index, thereby intensifying skin and eye irritation risks [4].

These developments underscore the urgent need for accurate, continuous, and real-time monitoring systems capable of providing dependable air quality data to support informed decision-making and sustainable urban management.

The internet of things (IoT) has emerged as a transformative paradigm for real-time monitoring due to its ability to connect distributed sensors and enable seamless data acquisition, processing, and communication [5]–[8]. IoT technologies have been widely applied across domains, including smart homes [9], smart agriculture [5], [10], indoor and outdoor environmental monitoring [11]–[13], energy management [14], [15], healthcare [16], and micro-climate monitoring [17]. Leveraging IoT-enabled sensors for air quality monitoring allows for responsive, autonomous, and scalable systems. For instance, García *et al*. [18] developed an IoT platform integrating a web portal and mobile application with LTE-based data transmission, while Shah and Mishra [3] introduced a low-power IoT framework for PM2.5 prediction. Similarly, Mumtaz *et al*. [19] designed an IoT monitoring solution incorporating multiple gas sensors with cloud-based analytics for health-related applications. Other initiatives have demonstrated the integration of Firebase-powered platforms and a range of IoT sensors such as PMSA003, MQ-131, and MICS-6814 to monitor pollutants including PM2.5, PM10, CO_2, CO, and ozone [20]. Collectively, these studies highlight the growing role of IoT technologies in advancing real-time environmental monitoring.

Despite these advancements, IoT-based monitoring systems continue to face limitations, particularly high operational costs, dependence on grid electricity, and restricted geographic coverage in underserved areas [21], [22]. Recent research has emphasized renewable energy integration, especially solar power, as a cost-effective and sustainable solution [23]–[25]. However, many systems still fall short in terms of affordability, portability, and user-oriented real-time visualization dashboards, thereby limiting their suitability for wide-scale deployment. Beyond hardware design, statistical analyses have been increasingly incorporated into air quality studies to better interpret pollutant dynamics. Regression models, in particular, have proven effective in quantifying associations between particulate matter and meteorological parameters. For example, Vaishali *et al.* [26] applied correlation and regression analyses to evaluate PM2.5 variations in Delhi, while Parasin and Amnuaylojaroen [27] developed a multivariate regression framework combining PM2.5, NOx, and CO with temperature and humidity, achieving strong explanatory power. Similarly, Chu *et al*. [28] employed spatial regression to calibrate low-cost PM2.5 sensors, improving accuracy by reducing systematic bias. These studies reinforce the value of integrating regression-based methods into IoT monitoring frameworks to strengthen interpretability and policy relevance.

In response, the present work develops a solar-powered IoT-based monitoring system designed for both energy autonomy and analytical rigor. The system integrates an ESP32 microcontroller with low-cost sensors for PM2.5, PM10, temperature, humidity, and heat index, powered by solar photovoltaics and battery backup. Real-time visualization is supported via the Blynk cloud platform, while statistical analysis including correlation and regression is applied to explore the relationships between pollutant concentrations and meteorological factors. This combined approach provides a cost-effective, portable, and data-driven solution for advancing sustainable air quality management in both urban and rural settings. The paper is structured as follows: section 1 discusses the background and motivation; section 2 outlines the proposed system design and methodology; section 3 presents calibration results, field performance, and comparative analysis; and section 4 concludes the study with insights and recommendations for future development.

2. PROPOSED SYSTEM ARCHITECTURE AND METHOD

The methodological framework adopted in this study is summarized in Figure 1, which outlines the sequential stages of system development and validation. The workflow progresses through four primary stages, including system design and development, system simulation and calibration, field deployment and testing, and data analysis and interpretation.

2.1. System design and development

The proposed solar-powered air quality monitoring system is designed to operate for real-time environmental monitoring and transmission to a cloud server responsible for data storage in Blynk application. A general block diagram illustrating the overall system architecture is presented in Figure 2. It is composed of low-power air quality sensors, the microcontroller used to process operations, IoT-enabled communication network and cloud server as well as renewable solar energy sources used for power supply. This section describes the key components and their roles in achieving a reliable and efficient monitoring solution.

The first important part of the proposed system is the microcontroller which is the brain of IoT-based air pollution monitoring systems. In this work, the system's operations are orchestrated by the ESP32 microcontroller, which acts as the central processing unit. This microcontroller efficiently manages data collection from sensors, performs preliminary data processing, and enables wireless communication through its integrated Wi-Fi module. Its energy-efficient design is critical to maintaining the system's self-sustaining functionality. The ESP32 handles wireless communication by transmitting the processed data to a cloud-based platform via Wi-Fi. The system employs the Blynk IoT application, offering users a streamlined interface for real-time visualization of air quality metrics. This platform enables remote monitoring and delivers timely alerts, empowering users to respond proactively to changes in air quality. This seamless integration ensures stakeholders have reliable access to actionable insights.

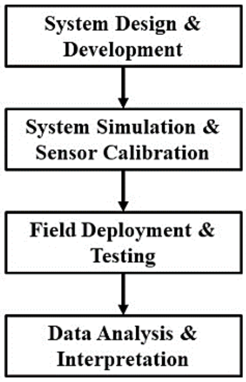


Figure 1. Methodological framework of the proposed solar-powered IoT-based air quality monitoring system

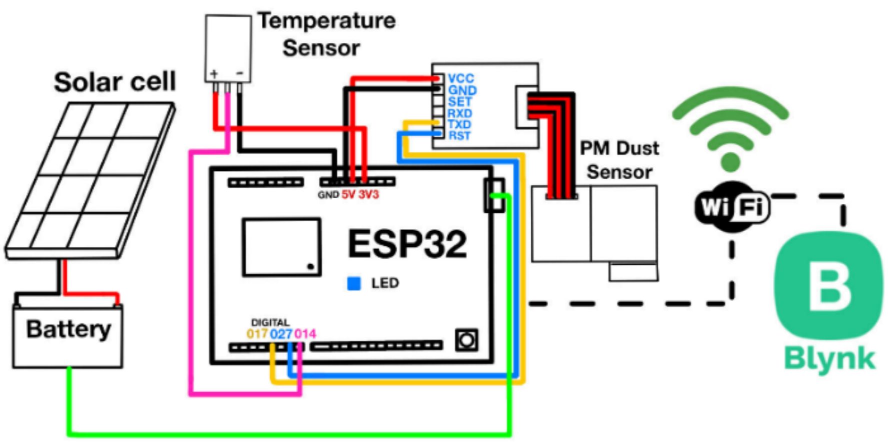


Figure 2. Hardware schematic showing solar power unit, ESP32 controller, sensors, and cloud connectivity

The second part is sensor which is used to measure various air quality parameters such as particulate matter, temperature, humidity and heat index. In this work, environmental monitoring is facilitated through two primary sensors. A temperature sensor is used to capture ambient temperature and heat index data, providing valuable context for interpreting air quality measurements. Additionally, a PM dust sensor is used to detect particulate matter concentrations, such as PM2.5 and PM10, which are vital indicators of air pollution.

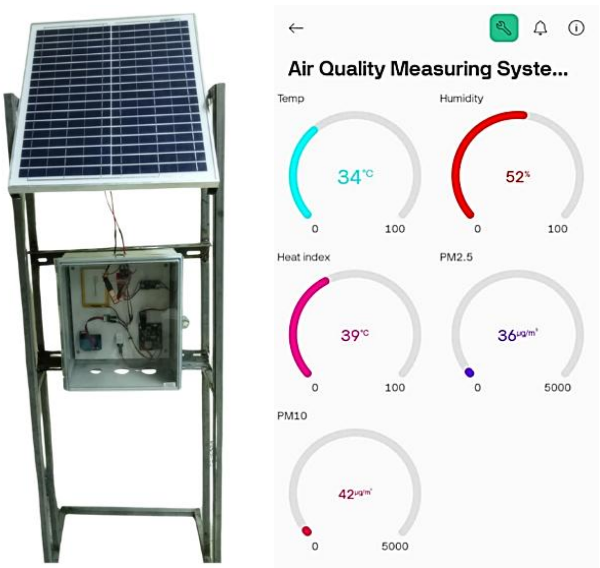
In order to measure temperature and humidity, the DHT22 digital sensor is employed for measuring both temperature and humidity. This high-precision sensor utilizes a capacitive humidity sensing element alongside a thermistor to detect the surrounding air conditions. The measured data is then converted into a digital signal and transmitted directly to a microcontroller, providing real-time values of relative humidity and ambient temperature with high reliability and stability.

Laser dust sensor PMS3003 is used to measure the dust concentration in the air. The working principle is based on the laser scattering theory. When laser light is emitted by detecting the position of particles, it produces a faint light. The scattering in a specific direction of the waveform is related to the diameter of the particle scattering light, the classification of the waveform according to different size systems. Consider that the conversion formula may have different sizes according to the concentration of the real-time particle number, according to the calibration method.

The power supply is a critical component of the system, ensuring reliable and efficient operation under varying environmental conditions. In this design, energy is primarily harvested using a 20-watt solar panel, which provides power to both the sensors and the microcontroller. To maintain uninterrupted functionality during periods of low solar irradiance, a 3.7 V, 3000 mAh lithium polymer (Li-Po) battery is integrated as a backup energy source. This battery type is chosen for its high energy density, low self-discharge rate, and long cycle life. Additionally, it is equipped with a built-in protection circuit, enhancing safety by preventing overcharging, deep discharge, and short circuits. The gel-based electrolyte inside the battery is non-flammable, reducing the risk of thermal incidents and contributing to the overall safety of the system.

Moreover, to ensure compatibility with the ESP32 board, which requires a stable 5 V input, a step-up voltage regulator module is employed to boost the battery's 3.7 V output to the necessary operating voltage. This configuration not only maximizes energy efficiency but also supports continuous system performance, even in variable lighting conditions. By combining solar energy harvesting with intelligent power management and a reliable energy storage solution, the system achieves high operational stability and sustainability.

As illustrated in Figure 3 and Figure 3(a), demonstrated the developed prototype integrates the ESP32 controller, particulate matter and environmental sensors, and a solar power unit within a compact housing. This configuration enables autonomous, portable operation and ensures suitability for deployment in outdoor environments. The ESP32 was programmed to manage data acquisition, preprocessing, and Wi-Fi transmission to the Blynk platform. As shown in Figure 3(b), the platform provides a mobile dashboard that displays temperature, humidity, heat index, PM2.5, and PM10 in real time, while also storing historical records. This combination of hardware and software supports both reliable field monitoring and user accessibility.



(a) (b)

Figure 3. Prototype implementation of the solar-powered IoT-based air quality monitoring system and its real-time user interface; (a) physical prototype of the developed monitoring unit and (b) real-time air quality dashboard displayed on the Blynk application

2.2. System simulation and sensor calibration

Following design and assembly, the system is subjected to simulation and debugging in order to verify data transmission reliability, cloud synchronization, and energy management stability. To provide a functional overview, the proposed system architecture can be conceptualized as a three-layer structure, as illustrated in Figure 4. The first layer, data acquisition, comprises the PMS3003 and DHT22 sensors. The second layer, data processing and communication, is handled by the ESP32 microcontroller. The final layer, data visualization, is implemented through the Blynk cloud platform, which enables user interaction via real-time dashboards.

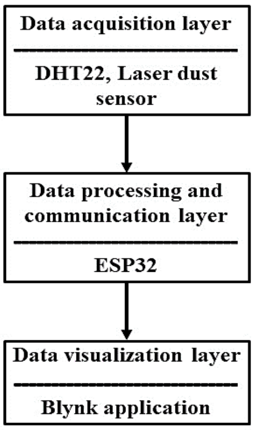


Figure 4. Layered block diagram of the system architecture, representing data acquisition, data processing and communication, and visualization through the Blynk application

Sensor calibration was subsequently conducted by benchmarking the PMS3003 against a TSI DustTrak II aerosol monitor and the DHT22 against a Testo 635-2 thermo-hygrometer. Each parameter was measured ten times, and the average values were used to calculate the percentage error and standard deviation (SD) as summarized in Table 1. The PM2.5 sensor exhibited a minor positive deviation of 0.50 μg/m³, corresponding to a percentage error of 1.67%, with a SD of 0.35, indicating stable repeatability. Similarly, the PM10 sensor showed a negative deviation of –1.30 μg/m³ (2.85% error) with an SD of 0.75, which, although slightly higher, still remains within acceptable limits for low-cost monitoring devices.

Table 1. The calibration of sensors in the proposed system

Measurement data	Standard value	Proposed system	Error	%Error	SD
PM2.5	30.00	30.50	0.50	1.67%	0.35
PM10	45.50	43.80	-1.30	2.85%	0.75
Temperature	34.80	34.00	0.80	2.30%	0.50
Heat index	45.00	46.50	1.50	3.26%	0.85
Humidity	66.00	67.00	1.00	1.52%	0.60

For meteorological parameters, the temperature sensor reported an underestimation of 0.80 °C (2.30% error, SD=0.50), while the heat index was slightly overestimated by 1.50 °C (3.26% error, SD=0.85). Humidity measurements revealed a marginal positive bias of 1.00% RH, corresponding to an error of 1.52% with a low SD of 0.60, suggesting reliable performance in varying conditions. Overall, the results confirm that the proposed system achieves a high degree of consistency and accuracy when compared with standard instruments. The percentage errors for all parameters remain below 3.5%, demonstrating the suitability of the system for field deployment. The relatively small SD values further highlight the stability of sensor outputs across repeated measurements, reinforcing the reliability of the system in long-term monitoring applications.

2.3. Field deployment and testing

Following calibration, the prototype system was deployed in an outdoor environment for a continuous 14-day monitoring period. The unit was powered exclusively by a solar panel and rechargeable battery, ensuring uninterrupted off-grid operation. The device was mounted on a stable platform to optimize air exposure while minimizing potential obstructions or ground-level disturbances. Throughout the deployment, the system was configured to log measurements of PM2.5, PM10, temperature, humidity, and heat index at hourly intervals. Data were transmitted via Wi-Fi to the Blynk cloud platform, where they were archived for subsequent analysis.

2.4. Data analysis and interpretation

The collected dataset was systematically processed to prepare for statistical evaluation. Hourly averages were computed to assess temporal variations, while diurnal patterns were extracted to capture daily pollutant cycles. Meteorological parameters were incorporated to examine their influence on particulate matter dynamics. Statistical techniques, including correlation analysis and multiple linear regression, were applied to quantify associations between PM concentrations and environmental factors. These procedures provided the methodological foundation for evaluating pollutant variability and meteorological interactions without drawing on results at this stage.

3. RESULTS AND DISCUSSION

To evaluate the system's performance under real-world conditions, a field test was conducted over a period of 14 consecutive days. During this time, the device continuously collected data outdoors for 24 hours each day. Figure 5 shows the collected data for PM2.5 and PM10. It can be observed that the 24-hour concentration patterns of PM2.5 and PM10 particulate matter. Throughout the day, PM10 levels consistently exceed those of PM2.5. Both pollutants exhibit a noticeable upward trend during the evening and nighttime hours, with peak concentrations observed between 8:00 and 9:00 PM. This increase is likely associated with elevated human activity during these hours, such as vehicular traffic or from the burning of farmers. Conversely, the lowest pollutant levels occur around 1:00 PM, suggesting that air quality fluctuates in relation to daily human activities and environmental conditions.

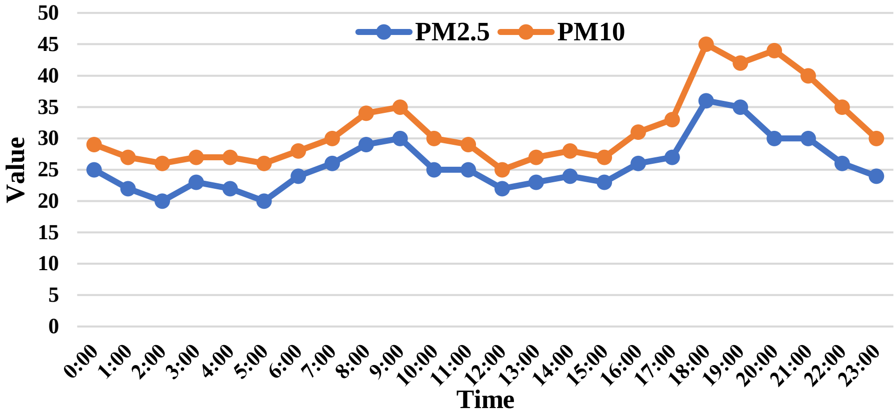


Figure 5. Hourly average concentrations of PM2.5 and PM10 over a 24-hour cycle

Figure 6 shows the result for the hourly variations of temperature, heat index, and relative humidity over a period of 24 hours. It can be observed that, both temperature and heat index begin to rise in the morning, reaching their peak between approximately 1:00 PM and 3:00 PM, corresponding to the warmest part of the day. As evening approaches, both values gradually decline. Notably, the heat index remains consistently higher than the actual temperature throughout the day, highlighting the influence of humidity in making the ambient conditions feel warmer. Relative humidity exhibits only modest fluctuations, with higher levels recorded during the night and early morning, and a slight decline during daytime hours, inversely correlating with the temperature rise.

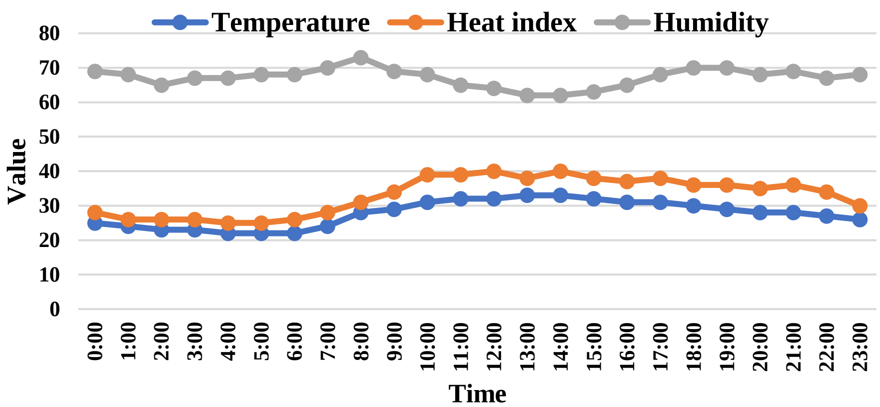


Figure 6. Hourly variations in temperature, heat index, and relative humidity

The field test revealed clear diurnal trends in air quality and environmental parameters. Particulate matter concentrations (PM2.5 and PM10) consistently peaked during the late afternoon and early evening hours, likely reflecting increased human activities such as traffic congestion and biomass burning. This pattern is in line with existing literature, which links such fluctuations to urban activity cycles and meteorological conditions. PM10 levels were consistently higher than PM2.5, suggesting the presence of larger airborne particles, potentially from construction or road dust.

The environmental conditions monitored, specifically temperature, heat index, and humidity, exhibited expected daily cycles. The heat index remained higher than ambient temperature throughout the day, underscoring the effect of humidity in intensifying perceived heat. Relative humidity peaked during night and early morning, decreasing during the warmest part of the day, which inversely mirrored temperature trends.

One of the key advantages of the system is the use of the Blynk platform for data visualization. Its real-time dashboard not only provided intuitive access to environmental metrics but also supported remote monitoring and alert capabilities, features that are essential for both individual users and government agencies managing public health and pollution control. Despite its strong performance, there are opportunities for future improvement. Expanding the range of pollutants measured (e.g., CO, NO_2, and O_3), incorporating GPS for geotagged data, and extending the deployment period across different seasons would enhance the system's robustness and analytical power. Additionally, implementing machine learning models could enable predictive analytics and anomaly detection for smarter environmental decision-making.

The system's continuous performance over 14 days, powered exclusively by solar energy, highlights the success of the energy management design. The integration of a 20 W solar panel and 3.7 V Li-Po battery, coupled with a step-up voltage regulator, ensured reliable power supply even under variable sunlight conditions. This demonstrates the viability of deploying the system in remote or off-grid areas, enhancing the accessibility of environmental monitoring solutions. Over 14 days of continuous outdoor operation, the device demonstrated 98.5% uptime, a 1.2% data loss rate, and an average cloud latency of 2.3 seconds. These metrics validate the robustness of the solar-powered IoT system. Furthermore, it indicated that PM2.5 exceeded the WHO 24-hour guideline of 25 µg/m³ [29] during 36% of the observation period, underscoring significant public health risks. Such findings demonstrate the system's potential utility for informing policy decisions and enabling community-level alerts.

Table 2 compares this system with recent IoT-based monitoring studies in terms of measured pollutants, power source, portability, and cost. The results have been shown that prior studies in air quality monitoring have primarily depended on grid-based power sources [17], [18], [21], which restrict their deployment in remote or off-grid settings. Even though some of these systems included multiple sensors, their applicability was limited by cost, lack of renewable energy integration, or industrial-oriented designs that were not suitable for community-level environmental monitoring. A more recent work [25] adopted a solar and battery supply, improving portability. However, it still did not provide real-time cloud-based visualization or decision-making tools for stakeholders.

Table 2. Comparison of nutrient control methods for hydroponic farming

Ref. no.	Pollutants measured	Power source	Communication	Portability	Novelty/limitations
[17]	PM2.5	Grid electricity	GSM/LTE	Limited	Low-power IoT design, but dependent on grid
[18]	CO_2, CO, and PM	Grid electricity	Wi-Fi	Limited	Industrial focus, not suitable for rural/off-grid
[21]	O_3, PM, NO_2, and CO	Grid electricity	Wi-Fi	Medium	Rich sensor set, but high cost and no renewable integration
[25]	PM2.5 and CO	Solar+battery	GSM	Portable	Solar-powered, but no real-time user interface
This work	PM2.5, PM10, temp, RH, and heat index	Solar (20 W)+Li-Po battery	Wi-Fi (ESP32 → Blynk)	High (compact, off-grid)	Low-cost, portable, renewable-powered with real-time cloud visualization and stakeholder decision support

The proposed system distinguishes itself by addressing these limitations through a compact, off-grid, and renewable-powered design that leverages solar energy with Li-Po battery backup. In addition, the system supports real-time data communication via Wi-Fi (ESP32 to Blynk platform), enabling cloud-based visualization and interactive monitoring. Unlike earlier works that focused narrowly on PM2.5 or CO, this system measures a broader set of parameters (PM2.5, PM10, temperature, humidity, and heat index), thereby offering more comprehensive environmental insights. Most importantly, the integration of real-time visualization with stakeholder decision support represents a novel contribution, ensuring that the collected data is not only technically robust but also directly actionable for environmental management and public health decision-making. Thus, compared to previous systems, this work provides a low-cost, portable, and sustainable IoT-based solution that advances both the technical functionality and the practical usability of real-time air quality monitoring.

Beyond technical performance, the statistical evaluation provides further insights into pollutant dynamics. Figure 7 presents the correlation matrix summarizing the relationships between particulate matter (PM2.5 and PM10) and meteorological parameters (temperature, heat index, and humidity). A strong positive correlation was observed between PM2.5 and PM10 (r=0.72), suggesting that fine and coarse particles are largely influenced by similar emission sources and atmospheric processes. Both fractions responded positively to relative humidity, with PM2.5 showing a stronger correlation (r=0.42) compared to PM10 (r=0.38), reflecting the greater sensitivity of fine particles to hygroscopic growth and secondary aerosol formation. Conversely, temperature exhibited only weak positive correlations with PM2.5 (r=0.22) and PM10 (r=0.17), indicating that thermal effects alone cannot fully account for particulate variability. The heat index was highly correlated with temperature (r=0.90), emphasizing that meteorological drivers are strongly interdependent.

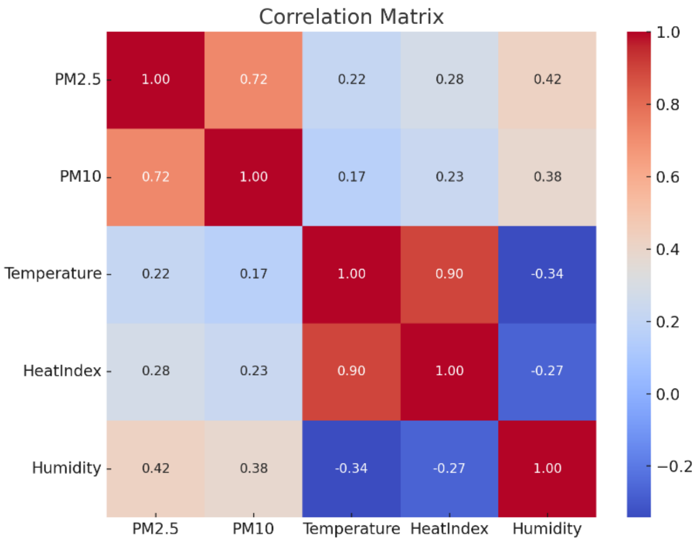


Figure 7. Correlation matrix of PM2.5, PM10, temperature, heat index, and humidity

To further examine these relationships, multiple linear regression analysis was performed, with PM2.5 and PM10 as dependent variables and temperature, heat index, and humidity as predictors. The regression coefficients are summarized in Table 3. The results reveal several important patterns. First, humidity emerged as the dominant predictor of particulate levels, particularly for PM10 (β=0.91), reflecting the role of moisture in particle growth and aggregation. For PM2.5, humidity also had a strong positive effect (β=0.71), in line with studies showing the enhanced sensitivity of fine particles to ambient relative humidity [30]. Second, the heat index provided stronger explanatory power than temperature alone, with coefficients of β=0.27 (PM2.5) and β=0.40 (PM10). This suggests that thermo-hygrometric stress is a more accurate indicator of particulate behavior than isolated thermal conditions, consistent with findings in Yuan *et al.* [30] which emphasized the importance of composite meteorological indices in air pollution studies. Finally, the relatively small coefficients for temperature (β=0.12 for PM2.5, and β=0.04 for PM10) indicate that direct thermal effects were secondary in this dataset. Temperature may contribute indirectly through enhanced photochemical reactions, but its impact was overshadowed by humidity-driven mechanisms.

Table 3. Regression coefficient for PM 2.5 and PM 10 models

Variable	PM 2.5 coefficient	PM 10 coefficient
Constant	-34.80	-44.51
Temperature	+0.12	+0.04
Heat index	+0.27	+0.40
Humidity	+0.71	+0.91

Regression modeling reinforced these observations, confirming that humidity significantly influences PM variations, while temperature exhibits an inverse but less pronounced effect. These results align with prior studies: Vaishali [26] reported similar regression-based findings linking PM2.5 levels with meteorological variables in Delhi, while Parasin and Amnuaylojaroen [27] demonstrated that incorporating multiple factors into regression models improves explanatory power (R^2>0.8). Chu *et al*. [28] further highlighted the role of regression in calibrating low-cost PM sensors, underscoring its utility for enhancing system reliability.

Taken together, the correlation and regression analyses demonstrate that humidity and the heat index are the principal meteorological drivers of particulate concentrations, while temperature alone plays a limited role. These findings have direct implications for air quality forecasting: incorporating thermo-hygrometric indices such as the heat index can improve predictive accuracy, particularly in hot and humid climates. Moreover, the stronger humidity–PM2.5 association underscores the need for targeted fine-particle management strategies, while PM10 control may require attention to mechanical and resuspension sources in addition to meteorological influences.

4. CONCLUSION

This study developed and validated a solar-powered IoT-based system for real-time air quality monitoring. The integration of an ESP32 microcontroller, low-cost sensors, and renewable energy supply enabled autonomous and portable operation, with data continuously transmitted to the Blynk platform for visualization and storage. A 14-day field deployment confirmed stable performance and suitability for outdoor use without reliance on grid power. Statistical analysis revealed a strong correlation between PM2.5 and PM10 (r=0.72), while humidity showed the strongest influence on PM2.5. Regression results further identified humidity (β=0.71, β=0.91) and heat index (β=0.27, β=0.40) as dominant predictors of particulate levels, with temperature contributing only marginally. These findings underscore the importance of thermo-hygrometric conditions in shaping air pollutant variability. Overall, the proposed system offers a low-cost, energy-autonomous, and scalable solution for real-time monitoring. Importantly, the integration of correlation and regression analysis enhances the system's role in supporting evidence-based decisions for air quality management and policy planning. Future work will focus on extending deployment duration, incorporating additional pollutant sensors (e.g., CO_2 and NO_x), and integrating predictive models such as machine learning to further strengthen decision-support capabilities.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

The data that support the findings of this study are available on request from the corresponding author. The data, which contain information that could compromise the privacy of research participants, are not publicly available due to certain restrictions.

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