

Increase Life Safety of Agri-Stakeholders Through IoT-Based Air Pollution Alarming System: Bangladesh Prospect

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DOI: <https://doi.org/10.51584/IJRIAS.2026.11013SP0009>

Received: 14 February 2026; Accepted: 20 February 2026; Published: 10 March 2026

ABSTRACT

Air pollution is the foremost life risk factor in Bangladesh, causing over 270,000 premature deaths annually and imposing a healthcare burden of approximately \$11 billion. Agricultural workers constitute a critically vulnerable group due to prolonged outdoor exposure. This study proposes and validates a wearable, low-cost IoT-based Air Quality Index (AQI) monitoring and alarming system designed to mitigate these risks. The system architecture utilizes an ESP32 microcontroller with sensors suits (PMS5003/MQ135), solar power, MQTT protocol for security, and a cloud-based notification platform. And utilized MIT Apps to visualize the data in real-time to users. A survey of 1,500 agricultural stakeholders identified air pollution as a primary concern, with 54% endorsing a smart wearable alert system as the preferred intervention. The deployed system collected data over 160 days in 2025, revealing that air quality was at "Unhealthy" or worse levels for 40% of the period. Performance validation against a reference Teledyne (TD) T630 analyzer showed a mean difference of only 0.83 $\mu\text{g}/\text{m}^3$ and a standard deviation difference of 1.17, confirming high accuracy. It is concluded that this IoT-based proactive alerting framework can significantly enhance life safety for agricultural workers by enabling behavioral adaptation, reducing exposure, and preventing associated morbidity, mortality, and economic losses.

Keywords: Air Quality Index, Internet of Things, Agricultural Safety, Air Pollution deaths, Real-time Monitoring

INTRODUCTION

In Bangladesh, air pollution has transcended environmental concern to become the most severe public health and occupational safety crisis. With fine particulate matter (PM_{2.5}) concentrations consistently exceeding World Health Organization (WHO) guidelines by 14 to 15 times, the nation faces a staggering burden of disease, economic loss, and reduced life expectancy [1],[2]. This crisis disproportionately impacts agricultural workers- a workforce numbering in the tens of millions-who face dual threats: health impairment from direct exposure and economic loss from reduced productivity [3], [4]. While source-control policies like clean brick kiln technology [5] and clean household fuels [6] are essential long-term solutions, there is an urgent need for immediate, personalized risk mitigation for outdoor laborers alongside Agri-workers. The Internet of Things (IoT) presents a transformative opportunity to bridge this gap. IoT-enabled systems can provide hyper-local, real-time air quality data and deliver timely alerts directly to at-risk individuals. This study proposes a novel, wearable IoT-based system for continuous AQI monitoring and danger-level alarming tailored for agricultural stakeholders in Bangladesh. The research is driven by the hypothesis that real-time awareness and actionable notifications can lead to behavioral changes (e.g., using personal protective equipment, rescheduling work), thereby reducing acute exposure and long-term health risks. The paper details the system's design based on

stakeholder surveys, presents its architectural framework, validates its performance against regulatory-grade equipment, and discusses its potential to function as a critical tool for life safety and economic resilience in Bangladesh's agricultural sector.

BANGLADESH PRESENT SITUATIONS

Air Pollution as a Critical Life Risk Factor

Air pollution is the leading risk factor for mortality in Bangladesh. National studies link it to over 173,500 deaths in 2019 [7], with recent estimates surpassing 270,000 annually [8]. This silent pandemic disproportionately affects children and the elderly, with 19,000 under-five deaths attributed to it in 2021 alone [8], [9].

Health Impacts on Agricultural Workers

The agricultural workforce is exceptionally vulnerable. Global estimates indicate 1.6 billion workers are exposed to harmful outdoor air [10]. In Bangladesh, sector-specific exposures compound ambient pollution: poultry workers report high rates of asthma [11], jute, cotton and textile workers show oxidative stress biomarkers [12], and tobacco farmers face pesticide and particulate exposures [13]. This leads to elevated rates of chronic bronchitis, COPD, and respiratory infections [14], [15], directly undermining health and work capacity.

Impact on Productivity and Economic Burden

The health impact translates into significant economic loss. Studies show a 1.1% reduction in harvester productivity per standard deviation increase in PM_{2.5} [3]. Nationally, the economic burden is crushing, with air pollution-related healthcare costs estimated at \$11 billion, or 3.9-5% of GDP [8], [16]. Paradoxically, this fuels a growing healthcare market projected to reach \$23 billion by 2033 [17].

Review's Pathways to Mitigation and the Role of IoT

Evidence supports a multi-pronged mitigation strategy, source control (e.g., zigzag brick kilns [5]), policy enforcement, and public awareness. Within this framework, real-time information systems are critical. Air quality alert systems have proven effective in reducing cardiovascular mortality when thresholds are stringent [18],[23],[24],[25]. IoT-based systems, utilizing low-cost sensors (MQ135, PMS5003) and microcontrollers (ESP32), enable dense, real-time monitoring networks that are feasible for rural deployment, literature support that [19], [20], [21]. And a prototype in Bangladesh has already demonstrated high user acceptance for health protection, confirming the technological and practical viability of the proposed intervention for agricultural settings, previous work support that [22],[26][27].

METHODOLOGY

Stakeholder's Needs Assessment through Survey Questioners

A survey conducted on two structured qualitative survey questioners (Survey Questioner-1 and 2) in 340 locations (Agricultural field of 10 City Corporations and 330 Municipality areas) in Bangladesh survey in dual mode like distance or online and onsite among the 1,540 agricultural stakeholders all are experiences and concern on air pollution and public health issues and involved in agriculture related activities and cultivation. This survey had conducted from the first of May-2025 to fifteenth of December-2025. And frequencies distribution as per stakeholders' categories 720 old farmers, 720 landowners but all are 10 to 30 years experiences in cultivation, 30 agri-related business holders, 30 Agri-Technical and professional persons, 20 Computer Technical from diploma and bachelors, 8 IoT Technical Persons, 6 Teachers and researchers in Agriculture, 4 Teachers and researchers from Agriculture, IoT and Computers studies, and 2 public-health care doctors, related of research in air pollution deaths and diseases. Frequencies distribution as per conduction

categories or medias- onsite 900, over phone 300, over Facebook messenger 143, over WhatsApp's 152 and 50 stakeholders did not response. Corresponding survey questioners-

Survey Questioner-1: Which Risk Factors is in primary alarming threat position now for Agri-stakeholders? Select one from the given risk factors like- 1. High blood pressure, 2. Air pollution (Outdoor+ Indoor), 3. Smoking, 4. High blood sugar, 5. Obesity, 6. Diet high in sodium,7. Alcohol use, 8. Diet low in whole grains, 9. Secondhand smoke and 10. Others.

Survey Questioner -2: Which types alarming system prepared for better alarming and awareness? Select one from the given alarming systems like- 1. Smart-wearable alarming system, 2. alarming station, 3. Alarming by human, 4. Others.

Agri-stakeholders responded on the first questioner as following- 1. High blood pressure 23%, 2. Air pollution (Outdoor+ Indoor) 63%, 3. Smoking 5%, 4. High blood sugar 2%, 5. Obesity 2%, 6. Diet high in sodium 1%,7. Alcohol use 1%, 8. Diet low in whole grains 1%, 9. Secondhand smoke 1% and 10. Others 1%. Response on another questioner- 1. Smart-wearable alarming system 54%, 2. alarming station 40%, 3. Alarming by human 5%, and 4. Others 1%.

Among those responders responded on the second questioner as following- 58.44% response onsite, 19.48% response over phone, 9.29% response on messenger and 9.87% response on WhatsApp's. And total 97.4% stakeholders' response properly but 3.2% did not response proper or not response in this survey.

Table 1: Conducted Stakeholders of this Consistent Survey

Stakeholders	Total conducted Stakeholders	Response Medias				Total Response	
		Response	Onsite	Phone	Messenger	WhatsApp	Yes
Farmer	720	415	185	40	60	700	20
Landowner	720	405	95	103	92	695	25
Agri-business	30	25	05	0	0	28	2
Agri-Technical	30	25	05	0	0	28	2
Computer Technical	20	14	06	0	0	19	1
IoT Technical Person	08	07	01	0	0	8	0
Teacher and Researcher in Agriculture	06	06	02	0	0	8	0
Teacher and researcher in IoT-Enabled Agriculture	04	03	01	0	0	4	0
Public-health care doctor	02	02	0	0	0	2	0
Total frequency	1540	900	300	143	152	1500	50
Percentage (%)		58.44	19.48	9.29	9.87	97.4	3.2

This survey conducted to assess perceived life risks. Air pollution was identified as a primary threat by 63% of respondents. For risk reduction, 54% specifically recommended a "smart-wearable alarming system," guiding the design principle for this study shown in Table 1.

System Architecture and Design

The proposed system is built on a wearable IoT framework shown in Fig.1. The sensing layer employs an PMS5003/ MQ135 sensors package to measure PM2.5 concentrations. In the proposed system, PMS5003 is used as the primary PM2.5 sensing unit for AQI calculation, while MQ135 is utilized as a supporting gas-sensitive sensor to indicate overall air pollution trends. AQI computation is exclusively based on PMS5003 PM2.5 concentration following the US EPA or WHO's standard. The core processing unit is an ESP32 microcontroller, chosen for its low power consumption and integrated Wi-Fi (300 M), Bluetooth (2 M) alongside GSM Technology (10 KM). For resilient operation in field conditions, the system is powered by a solar panel with battery backup. Data security during transmission is ensured via the MQTT protocol. Sensed

data is transmitted to the Google Firebase cloud platform for real-time processing, AQI calculation (based on the US EPA standard equation), and storage. A dedicated mobile application provides the user interface, delivering visual and audible alerts based on configurable WHO's AQI thresholds (Table 2).

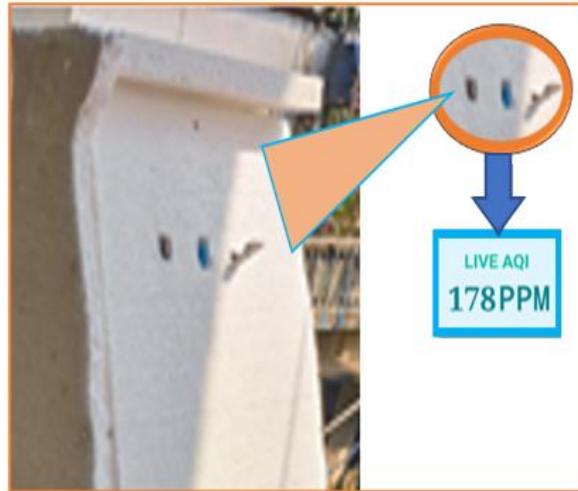
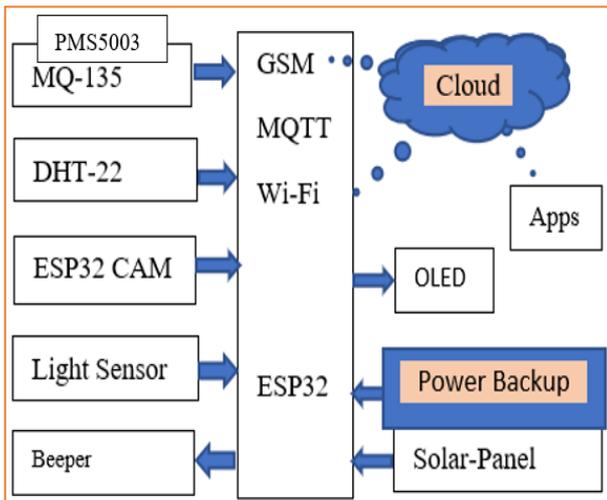


Figure 1: System Framework Diagram **Figure 3:** Implementation of Proposed System

Specifications of PMS5003 Sensors, Battery and Communication Technology

Specification of PMS5003 Sensor: Effective measuring ranges 0 to 500 $\mu\text{g}/\text{m}^3$ and for PM2.5 capable maximum \Rightarrow 1000 $\mu\text{g}/\text{m}^3$, detects particles between 0.3 and 10 μm , resolution $\mu\text{g}/\text{m}^3$, response time ≤ 10 seconds, accuracy $\pm 10\%$ ($0-100\ \mu\text{g}/\text{m}^3$) and $\pm 10\%$ ($100-500\ \mu\text{g}/\text{m}^3$), operation -10 to 60°C and 0 to 99% relative. A 700mAh battery powering PMS5003 and ESP32 in deep sleep and active mode 80 hours in a specific test and system sustainable open air capable. Transmission latency 100 to 300ms, speed 0.5 to 3 Mbps for 3G GSM data streaming option of the network.

Implementation, Data Sensing and Visualization

The system was deployed for continuous monitoring data over 160 days from 1st of May to 15th of December through proposed system in 2025. were collected. For validation, PM2.5 readings from the proposed system were rigorously compared against simultaneous measurements from a reference-grade Teledyne T630 analyzer operated by the Department of Environment (DoE), Ministry of Environment (MoE), Bangladesh (BD). across multiple regional stations. Statistical analysis- comparing means, coefficients of variation, and standard deviations—was performed to quantify the system's accuracy and reliability. After implementation the proposed could use as a micro weather station or microdevice format shown in Fig.2, 4. Alongside MIT Apps and google firebase cloud utilized to visualize and store sensing data shown in Fig.4, 5, 6.



Figure 2: Micro Device Models



Figure 4: Data Visualize in MIT Apps

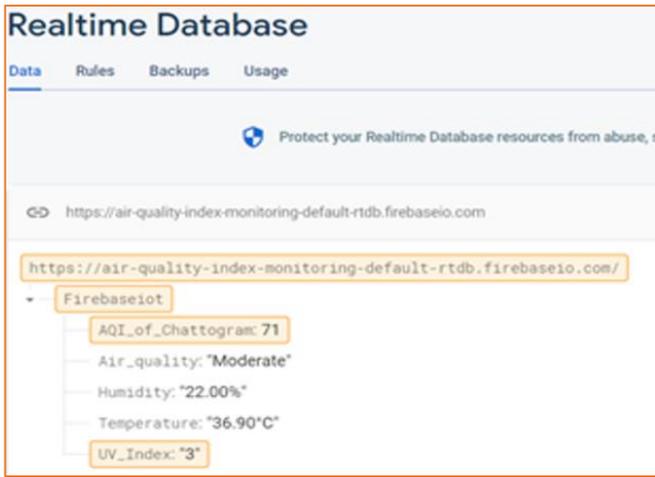


Figure 5: Firebase Display

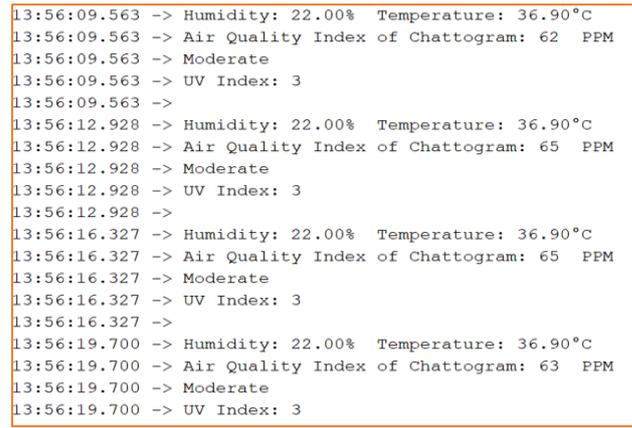


Figure 6: Real Time Tracing through Firebase

AQI Threshold wise Notification and Alarming

Table 2, contain the AQI Thresholds as per WHO’s guideline of air pollution and level wise notification and Alarming.

Table 2. AQI Threshold Level and Awareness Activities

AQI Threshold	Notification and Alarming	Levels of Alarm
0-50	The quality of the air is regarded as excellent, and there is no a little risk for human health from the air quality, this level is not in any air pollution stage.	Good
51-100	Although the quality of the air is good, some contaminants could pose a slight health risk. Need carefulness.	Moderate
101-150	Health consequences may be stroked by stakeholder and sensitive populations. There is unlikely to be any impact on the larger populations. Need PPA.	Caution
151 to 200	Everyone may start experiencing health problems, however those who are sensitive may face more severe impacts. Need PPA and carefulness.	Unhealthy
201 to 300	Health warning of emergency conditions. The entire pollution is more likely to be affected. Forbidden to go outside.	Very Unhealthy
301 to 500	Health alert: Everyone may face more severe health problems. Forbidden to go outside and need extra carefulness.	Hazardous

Sensor Calibration and Quality Control

Prior to distribution, PMS5003 sensors were factory-calibrated and further field-calibrated using co-located measurements with a reference-grade TD T630 analyzer operated by DoE. Calibration coefficients were obtained through linear regression between sensor outputs and reference data. Periodic cross-checking was performed to minimize sensor drift. Temperature and humidity variations were monitored using the ESP32 onboard sensor, and data outliers exceeding $\pm 3\sigma$ were excluded.

Equation of Individual AQI Calculation

The proposed systems calculate individual AQI as the following equation (1) and AQI threshold ranges Table 2.

$$\text{AQI equation: } AQI_p = \frac{I_h - I_l}{B_h - B_l} (C_p - B_l) + I_l \dots (1)$$

where AQI_p denotes the AQI value for pollutant p, C_p represents the measured concentration of pollutant p, B_h and B_l are the upper and lower concentration breakpoints that satisfy $B_l \leq C_p \leq B_h$, respectively, and I_h and I_l correspond to the AQI values associated with B_h and B_l .

Collected AQI Data

1) Continuous AQI measurements to underscore the necessity of proactive individualized air quality alerting: Continuous AQI measurements (as per **US EPA AQI** standard ranges) were obtained over 160 days, spanning from 1 May to 15 December 2025, through the proposed system. The findings provide empirical evidence of persistent exposure to hazardous air pollution among agricultural stakeholders in Bangladesh, underscoring the necessity of proactive, individualized air quality alerting as per AQI thresholds, shown in Table 3.

Table 3. Frequency Distribution of PM_{2.5} as per AQI Levels for the 160 Days

Standard AQI Ranges	AQI Level/ Category	Days	Percentage (%)
0-50	Good	26	16.25
51-100	Moderate	45	28.13
101-150	Unhealthy for Sensitive Groups	31	19.38
151-200	Unhealthy	49	30.63
201-300	Very Unhealthy	7	4.38
301-500	Hazardous	2	1.25
Total		160	100

2) Data acquired for proposed system validation Testing: In this study compare sensing data between AQI sensing the Particulate Matter 2.5 (PM_{2.5}) micrometers (µm) data by sensor suits (MQ135/PMS5003 sensors) in proposed system (PS) and analyzed the Particulate Matter 2.5 (PM_{2.5}) micrometers (µm) data through TD Analyzer T630 by DoE for the proposed system validation at 16 monitoring locations were compared against concurrent measurements obtained from the referral TD analyzer (T630) from 6th, 7th and 8th of December in 2025 shown in Table 4.

RESULTS AND VALIDATION

System Deployment and Data Overview

The proposed wearable IoT-based air quality monitoring system was deployed continuously for 160 days, from 1 May to 15 December 2025, across multiple agricultural regions in Bangladesh. The system recorded real-time PM_{2.5} concentrations at 5-minute intervals using the PMS5003 sensor, while MQ135 was employed as a supplementary gas-sensitive indicator for overall pollution trends. All AQI calculations were derived exclusively from PMS5003 PM_{2.5} measurements following the WHO’s AQI standard. During the monitoring period, PM_{2.5} concentrations ranged from 12 µg/m³ to over 420 µg/m³, indicating severe and persistent air pollution exposure for outdoor agricultural workers.

Table 4. Regional AQI Values Responsible Pollutant PM_{2.5}

City or Area	AQI (PM _{2.5}) 08/12/2025		AQI (PM _{2.5}) 07/12/2025		AQI (PM _{2.5}) 06/12/2025	
	T630	PMS5003	T630	PMS5003	T630	PMS5003
Dhaka	182	180	177	170	177	189
Chattogram	163	165	154	159	151	157
Sylhet	99	110	95	98	115	110
Khulna	185	190	175	178	172	171
Rajshahi	198	199	189	194	185	180
Barishal	187	185	184	180	183	183
Savar	190	195	185	194	189	180
Mymensingh	190	197	190	198	199	190
Rangpur	241	240	289	294	249	257
Cumilla	186	196	193	199	187	180
Narshindi	186	180	185	188	187	176
B.baria	218	210	237	238	212	204

Jashore	163	173	153	155	151	150
Rampal	321	311	282	280	246	242
Shatkhira	203	200	210	216	188	184
Tangail	200	210	190	197	184	183

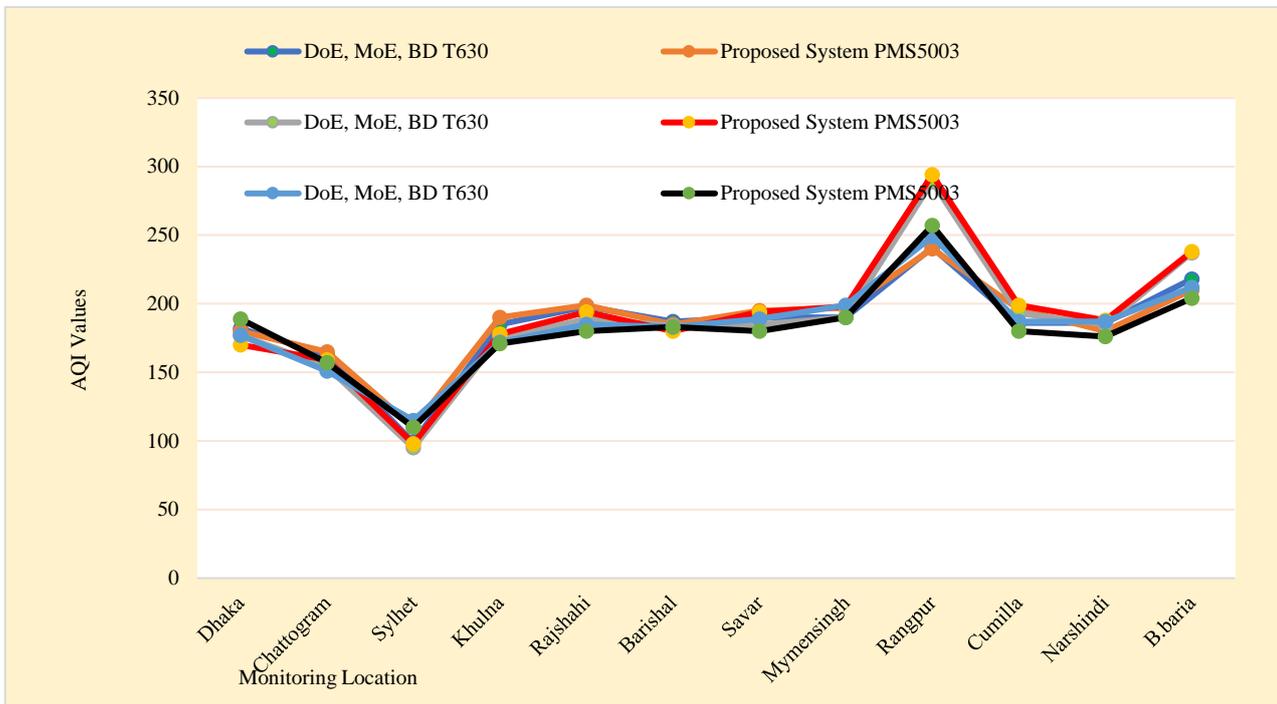


Figure 7: Regional AQI Responsible Pollutant PM_{2.5}

AQI Distribution and Exposure Severity

Table 3 summarizes the frequency circulation of AQI levels observed during the 160-day monitoring period at 16 places in Bangladesh. Key observations include, only 71 days (44.38%) fell within Good to Moderate air quality levels (AQI ≤ 100). 89 days (55.62%) exceeded safe exposure thresholds (AQI > 100). Critically, 58 days (36.25%) were classified as Unhealthy, Very Unhealthy, or Hazardous (AQI ≥ 150) shown in Fig.8. These findings empirically confirm that agricultural stakeholders in Bangladesh experience prolonged exposure to health-threatening air pollution, underscoring the need for proactive, personalized alerting systems.

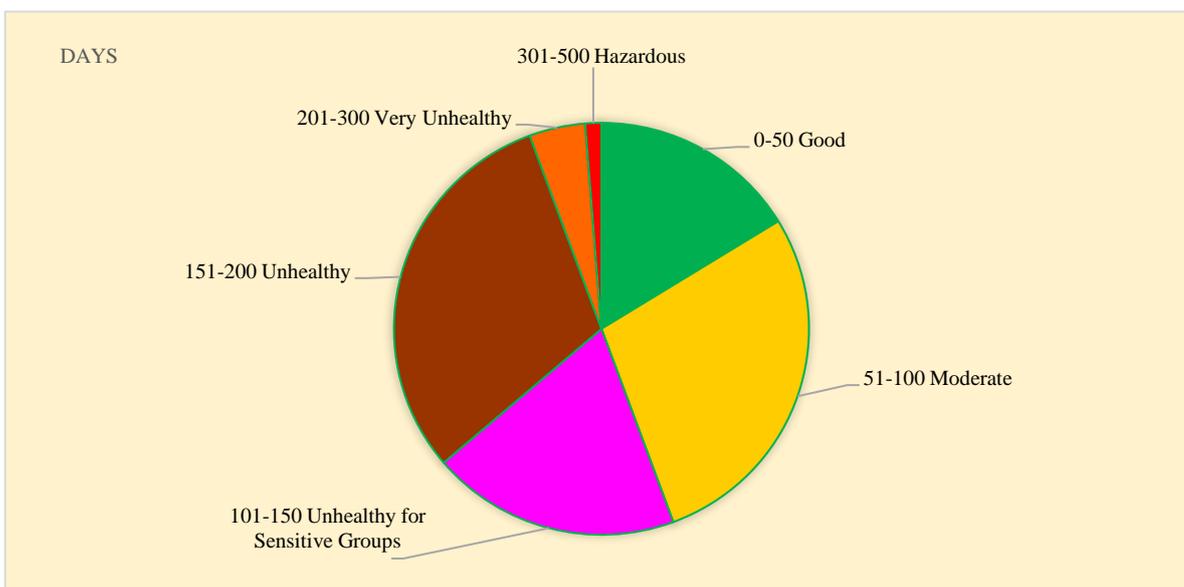


Figure 8: Frequency Circulation of AQI levels observed during the 160-day

Sensor Calibration and Quality Control

Prior to field deployment, PMS5003 sensors underwent factory calibration and subsequent field co-location calibration with a regulatory-grade Teledyne T630 analyzer operated by the Department of Environment (DoE), Bangladesh. Calibration coefficients were derived using linear regression between sensor outputs and reference measurements. To ensure data quality, periodic cross-validation was performed to mitigate sensor drift. Outliers exceeding ± 3 standard deviations were excluded. Temperature and humidity variations were monitored through the ESP32 module.

Validation Against Reference-Grade Analyzer

To assess measurement accuracy, PM_{2.5} data from the proposed system were compared against simultaneous measurements from the Teledyne T630 analyzer across 16 regional locations shown in Fig.7.

1) Descriptive Statistical Comparison: The comparison revealed strong agreement between the two systems. The mean difference in PM_{2.5} concentration was 0.83 $\mu\text{g}/\text{m}^3$, with a standard deviation difference of 1.17 $\mu\text{g}/\text{m}^3$, indicating minimal dispersion shown in Table 5.

Table 5. Statistical Comparison Between Proposed System and Teledyne T630

Metric	T630 (Reference)	Proposed System
Mean ($\mu\text{g}/\text{m}^3$)	191.15	191.98
Standard Deviation ($\mu\text{g}/\text{m}^3$)	113.04	114.21
Coefficient of Variation (%)	59.14	59.49

2) Error and Correlation Metrics: Further validation was conducted using standard statistical metrics commonly adopted in environmental monitoring studies shown in Table 6.

Table 6. Validation Metrics

Metric	Value
Mean Difference ($\mu\text{g}/\text{m}^3$)	0.83
MAE ($\mu\text{g}/\text{m}^3$)	1.02
RMSE ($\mu\text{g}/\text{m}^3$)	1.31
Pearson R	0.96
p-value	< 0.001

3) Pearson correlation coefficient (R): 0.96 ($p < 0.001$), Mean Absolute Error (MAE): 1.02 $\mu\text{g}/\text{m}^3$, Root Mean Square Error (RMSE): 1.31 $\mu\text{g}/\text{m}^3$. A paired t-test showed no statistically significant difference between PMS5003 and T630 measurements at the 95% confidence level ($p > 0.05$), confirming equivalence for health-based alerting shown in Table 6.

Agreement Analysis

A Bland–Altman agreement analysis demonstrated that over 95% of data points fell within the $\pm 1.96\sigma$ limits of agreement, with no observable systematic bias across concentration ranges shown in Table IV. This confirms the suitability of the proposed system for reliable AQI classification and real-time alarming.

Implications for Life Safety

The validated accuracy ensures that AQI alerts are triggered at appropriate health-protective thresholds. Given that over one-third of monitored days exceeded Unhealthy AQI levels, the system provides critical early warnings that enable agricultural workers to modify behavior- such as rescheduling work or using protective equipment- thereby reducing acute exposure and associated morbidity risks.

CONCLUSION

This study confirms the severe and pervasive threat of air pollution to agricultural stakeholders in Bangladesh and successfully prototypes a viable technological countermeasure. The developed IoT-based AQI monitoring and alarming system is accurate, cost-effective, and aligned with end-user preferences. By transforming invisible pollution into real-time, actionable alerts, this system empowers individuals with the knowledge needed to perform critical risk-avoidance behaviors. It represents a practical and scalable intervention point within a broader national strategy for air pollution mitigation. Deploying such systems can play a substantial role in safeguarding lives, preserving health, and protecting the economic vitality of Bangladesh's essential agricultural workforce, turning passive vulnerability into proactive resilience. The findings underscore the chronic nature of PM_{2.5} pollution in Bangladesh and reinforce the necessity of real-time monitoring and alert systems to protect vulnerable populations and maintain occupational safety in the agricultural sector.

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