IoT-BASED MONITORING AND AUTOMATED AIR PURIFICATION SYSTEM FOR INDUSTRIAL POLLUTION CONTROL

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A Final Year Design Project (FYDP) submitted to the Department of Electrical & Electronic Engineering in partial fulfillment of the requirements for the degree of Bachelor of Science in Electrical & Electronic Engineering (BSEEE)

Department of Electrical & Electronic Engineering
BRAC University
January, 2026

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Declaration

It is hereby declared that

1. The Final Year Design Project (FYDP) submitted is my/our own original work while completing the degree at BRAC University.
2. The Final Year Design Project (FYDP) does not contain material previously published or written by a third party, except where this is appropriately cited through full and accurate referencing.
3. The Final Year Design Project (FYDP) does not contain material that has been accepted, or submitted, for any other degree or diploma at a university or other institution.
4. I/We have acknowledged all main sources of help.

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Ethics Statement

This Final Year Design Project (FYDP) has been conducted and prepared in full compliance with accepted academic and research ethical standards. All data collection, analysis, system design, and validation activities were performed responsibly, transparently, and without fabrication, falsification, or misrepresentation of results. Proper acknowledgment and citation have been provided for all referenced literature, tools, datasets, and methodologies used in the study, ensuring due credit to the original authors and sources.

Furthermore, this report represents original work, and the similarity index has been verified to be well below 30%, in accordance with institutional and academic integrity requirements. No part of this report has been plagiarized, nor has it been submitted previously for any academic degree or qualification. The authors take full responsibility for the content of this report and affirm their commitment to honesty, integrity, and ethical responsibility throughout the entire research and documentation process.

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Abstract

Industrial air pollution poses a critical public health challenge in Bangladesh, causing 102,000 premature deaths annually and reducing life expectancy by 5.5 years, yet existing monitoring and purification systems remain prohibitively expensive and ineffective for small and medium enterprises. This project developed an integrated IoT-based monitoring and automated air purification system to address this gap through real-time multi-pollutant sensing, fog-based distributed architecture, and adaptive two-stage filtration. The system was validated through controlled laboratory testing and industrial deployment at Allied Solar Energy Ltd., demonstrating 96.59% PM2.5 and 91.27% PM10 removal efficiency within 93 minutes of operation. Economic analysis revealed exceptional financial viability with 40% first-year ROI, 8.6-month payback period, and 5.31 benefit-cost ratio over five years. The low capital cost of 46,434 BDT makes the technology accessible to resource-constrained industries, potentially benefiting thousands of workers and surrounding communities while supporting regulatory compliance with Bangladesh Air Pollution Control Rules 2022.

Keywords: Industrial air pollution; IoT monitoring; Automated purification; HEPA Filtration; Mesh connection; Occupational health

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Table of Contents

Chapter 1: Introduction 1

1.1 Background and Motivation 1

1.1.1 Problem Statement 1

1.1.2 Background Study 2

1.1.3 Literature Gap 5

1.1.4 Relevance to Current and Future Industry 7

1.2 Objectives, Requirements, Specifications, and Constraints 8

1.2.1. Objectives 8

1.2.2 Functional and Nonfunctional Requirements 9

1.2.3 Specifications 10

1.2.4 Technical and Non-technical Considerations 10

1.2.5 Constraints in the Design Process 11

1.2.6 Applicable Compliance, Standards, and Codes 12

1.3 Systematic Overview of the Proposed Project 13

1.4 Conclusion 14

Chapter 2: Project Design Approach 15

2.1 Introduction 15

2.2 Identify Multiple Design Approaches 15

2.3 Description and Analysis of Multiple Design Approaches 17

2.3.1 Design Approach 1: Mesh-based Wireless Sensor Network (WSN) with a Centralized Control System 17

2.3.2 Design Approach 2: Fog-Based Distributed Sensor Node with Central Purifier Control 20

2.3.3 Design Approach 3: SmartChain Modular Edge-Based Purification 24

2.4 Functional Verification of Multiple Designs 27

2.4.1 Verification of Approach 1 27

2.4.2 Verification of Approach 2 29
2.4.3 Verification of Approach 3 30
2.5 Conclusion 32
Chapter 3: Use of Modern Engineering and IT Tools 33
3.1 Introduction 33
3.2 Selection of Appropriate Engineering and IT Tools 33
3.3 Use of Modern Engineering and IT Tools 34
3.3.1 Proteus 8 Professional: Virtual Prototyping and Circuit Simulation 34
3.3.2 Visual Studio Code & Python: IoT Communication Pipeline Emulation 34
3.3.3 MATLAB R2025a: Data Analysis and Performance Visualization 35
3.3.4 Arduino IDE: Embedded Firmware Development and Deployment 35
3.3.5 Blynk IoT Platform: Cloud Dashboard and Remote Monitoring 35
3.3.6 Altium Designer: Professional PCB Design and Layout 36
3.4 Conclusion 36
Chapter 4: Optimization of Multiple Designs and Finding the Optimal Solution 37
4.1 Introduction 37
4.2 Optimization of Multiple Design Approach 37
4.3 Performance Evaluation of Developed Solution 38
4.4 Identify Optimal Design Approach 40
4.5 Extraction Best Features for Hardware Implementation 43
4.6 Conclusion 44
Chapter 5: Completion of Final Design and Validation 45
5.1 Introduction 45
5.2 Completion of the Final Design 45
5.2.1 Sensor Node Implementation 47
5.2.2 Sensor Calibration 50
5.2.3 Data Aggregation Gateway (DAG) Implementation 52
5.2.4 IoT-Based Custom-Built Monitoring Unit Implementation 53

5.2.5 Central Control & Purification Unit Implementation 58
5.3 Evaluation of the Solution to Meet the Desired Needs...60
5.3.1 Testing in Controlled Environment 60
5.3.2 Industrial Testing and Validation..62
5.3.3 Validation and Analysis of the Components Used 70
5.3.4 Objectives Met 75
5.4 Conclusion 76
Chapter 6: Impact Analysis and Project Sustainability...77
6.1 Introduction...77
6.2 Impact Analysis 77
6.2.1 Technical Impact..77
6.2.2 Societal and Occupational Impact 78
6.2.3 Environmental Impact..78
6.2.4 Legal and Regulatory Impact..79
6.2.5 Economic and Industrial Impact 79
6.3 Sustainability Analysis and Alignment with SDGs 80
6.3.1 SDG 3: Good Health and Well-being 80
6.3.2 SDG 9: Industry, Innovation, and Infrastructure 80
6.3.3 SDG 11: Sustainable Cities and Communities 80
6.4 Long-Term Sustainability of the Project...81
6.5 Conclusion 83
Chapter 7: Engineering Project Management...84
7.1 Introduction...84
7.2 Define, Plan, and Manage Engineering Project 84
7.2.1 Project Timeline and Phase Structure 84
7.2.2 Team Organization and Responsibility Distribution 85
7.2.3 Effort Distribution and Workload Balance 87
7.3 Evaluate Project Progress 87

7.3.1 Progress Tracking Methodology ... 87
7.3.2 Performance Metrics and Key Performance Indicators ... 88
7.3.3 Milestone Achievement and Deliverable Quality ... 88
7.4 Risk Management and Analysis ... 88
7.4.1 Risk Identification and Assessment Framework ... 88
7.4.2 Material-Related Risks ... 89
7.4.3 Methodological Risks ... 89
7.4.4 Risk Analysis Methodologies ... 90
7.4.5 Risk Reduction Strategies and Contingency Planning ... 91
7.4.6 Ethical Compliance in Risk Management ... 92
7.5 Conclusion ... 92
Chapter 8: Economic Analysis ... 94
8.1 Introduction ... 94
8.2 Budget Analysis ... 94
8.2.1 Complete Budget Breakdown ... 94
8.2.2 Budget Utilization Metrics ... 97
8.3 Cost-Benefit Analysis ... 101
8.3.1 Benefit Estimation Framework ... 101
8.3.2 Annual Benefits Calculation ... 101
8.3.3 Return on Investment (ROI) Calculations ... 103
8.4 Evaluate Economic and Financial Aspects ... 106
8.4.1 Net Present Value (NPV) Analysis ... 106
8.4.2 Benefit-Cost Ratio (BCR) ... 107
8.4.3 Cost-Benefit Summary ... 108
8.4.4 Sensitivity Analysis ... 109
8.4.5 Risk-Adjusted Returns ... 111
8.4.6 Performance Benchmarking ... 113

8.5 Conclusion 114

Chapter 9: Ethics and Professional Responsibilities 116

9.1 Introduction 116

9.2 Identification of Ethical Issues and Professional Responsibilities 117

9.2.1 Public Health and Safety Obligations 117

9.2.2 Environmental Stewardship and Sustainability 118

9.2.3 Data Privacy and Information Security 119

9.2.4 Informed Consent and Stakeholder Engagement 119

9.2.5 Professional Competence and Honesty 120

9.2.6 Social Justice and Equitable Access 121

9.3 Application of Ethical Issues and Professional Responsibility 122

9.3.1 Ethics-Driven Design Decisions 122

9.3.2 Implementation of Safety and Privacy Safeguards 123

9.3.3 Stakeholder Communication and Transparency 124

9.3.4 Addressing Conflicting Ethical Demands 125

9.3.5 Reflection on Limitations and Future Responsibilities 126

9.4 Conclusion 127

Chapter 10: Conclusion and Future Work 129

10.1 Project Summary 129

10.2 Future Works 130

Chapter 11: Identification of Complex Engineering Problems and Activities 133

11.1 Identifying the Attribute of Complex Engineering Problem (EP) 133

11.2 How the Project Addresses Selected Attribute (EP) 133

11.3 Identifying the Attribute of Complex Engineering Activities (EA) 139

11.4 How the Project Addresses Selected Attribute (EA) 140

References 147

Appendix 151

Chapter 1: Introduction

1.1 Background and Motivation

Air pollution remains one of the most pressing environmental and public health challenges globally, particularly in rapidly industrializing regions like Bangladesh. Industrial emissions, including particulate matter (PM2.5 and PM10), volatile organic compounds (VOCs), carbon monoxide (CO), and nitrogen oxides (NOx), contribute significantly to degraded air quality, leading to respiratory diseases, cardiovascular issues, and premature deaths. In Bangladesh, industrial zones such as those in Gazipur and Narayanganj face acute pollution levels, exacerbating the burden on local communities and workers. This project addresses these challenges through the development of an IoT-based monitoring and automated air purification system tailored for industrial pollution control.

The system integrates real-time environmental sensing, wireless mesh networking for robust data transmission, and automated HEPA filtration units to achieve efficient removal of pollutants. By leveraging edge computing and cloud integration, it enables predictive analytics and remote oversight, ensuring compliance with environmental standards while minimizing operational costs. This introduction outlines the problem statement, background, literature gaps, industrial relevance, project objectives, requirements, specifications, constraints, and a systematic overview of the proposed solution.

1.1.1 Problem Statement

Industrial air pollution is a critical and escalating threat to public health, environmental sustainability, and economic productivity in Bangladesh. The country faces severe air quality challenges, with industrial emissions being a primary contributor. Studies indicate that air pollution is responsible for approximately 102,000 premature deaths annually in Bangladesh and reduces average life expectancy by about 5.5 years [1]–[3]. This crisis is exacerbated in industrial zones where traditional pollution control is inadequate.

Despite the gravity of the situation, existing purification systems in many sectors suffer from fundamental deficiencies:

- **Passive and Non-Adaptive Operation:** Conventional purifiers run on fixed schedules or manual control, unable to respond dynamically to real-time fluctuations in pollutant concentration. This leads to energy wastage during clean periods and insufficient cleaning during pollution spikes.
- **Lack of Integrated Monitoring:** There is a disconnect between sensing and purification. Most facilities lack comprehensive, real-time monitoring of key industrial pollutants (PM2.5, PM10, CO, NO_2, VOCs), preventing data-driven decision-making.
- **High Cost and Inflexibility:** Advanced, effective systems like those used in pharmaceutical industries are often prohibitively expensive and complex for widespread

adoption, particularly by Small and Medium Enterprises (SMEs) that dominate sectors like brick kilns and textiles.

- **Dependence on Unreliable Infrastructure:** Cloud-reliant IoT solutions assume stable internet, a challenge in many Bangladeshi industrial areas, risking system failure during connectivity loss.

Consequently, there is an urgent need for an intelligent, automated, and cost-effective air purification system that integrates real-time monitoring with adaptive control, functions reliably in local conditions, and is accessible to the industries that need it most. This project is designed to address this multifaceted problem directly.

1.1.2 Background Study

1.1.2.1 Literature Review

A substantial body of research has addressed air pollution control from industrial sources, with particular emphasis on public health impacts and emission mitigation technologies. Lelieveld et al. demonstrated that outdoor air pollution is a major contributor to global premature mortality, identifying industrial emissions as a dominant source of this burden [4]. Building on this concern, Chakrabartty and Gupta provided a comprehensive review of industrial air pollution control technologies, highlighting that conventional systems such as baghouse filters and basic scrubbers are energy intensive and lack real-time adaptability to fluctuating emission conditions [5].

Advancements in sensing and communication technologies have enabled real-time air quality monitoring within industrial environments. Kumar et al. demonstrated that IoT-based sensor networks can effectively monitor $PM_{2.5}$, PM_{10}, and gaseous pollutants, improving data availability for compliance and early warning purposes [6]. However, these monitoring-centric systems do not incorporate active purification or automated control mechanisms, limiting their direct impact on emission reduction.

Filtration-based purification techniques remain widely adopted due to their proven effectiveness. Activated carbon and HEPA filter systems have demonstrated strong performance in removing particulate matter and gaseous pollutants, with activated carbon achieving adsorption efficiencies exceeding 85% for SO_2 and VOCs [7]. Alternative industrial-scale approaches such as electrostatic precipitators and wet scrubbers have also been extensively studied. ESPs are capable of achieving $PM_{2.5}$ removal efficiencies greater than 99%, but they require high power input and may generate ozone as a secondary pollutant [8]. Wet scrubbers and selective catalytic reduction systems are effective for acid gas removal, though they introduce operational challenges related to wastewater management and disposal [9].

Field-scale and experimental investigations have further demonstrated the effectiveness of multi-stage filtration systems in industrial settings. High particulate reduction efficiencies have been reported in brick kiln applications and diesel exhaust treatment using hybrid filtration and scrubbing configurations [10], [11]. In parallel, detailed analyses of activated carbon adsorption mechanisms have improved understanding of gas–solid interactions relevant to industrial purification [12].

TABLE I. BACKGROUND RESEARCH AND LITERATURE REVIEW

No.	Reference	Technology/Focus	Key Insights
[4]	J. Lelieveld et al., 2015	Global Air Pollution Burden	Stresses the role of industrial emissions in global premature mortality.
[5]	R. K. Chakrabartty et al., 2020	Review on Industrial Pollution Control	Reviews current technologies and their limitations, highlighting energy consumption and lack of real-time adjustment.
[6]	P. Kumar et al., 2020	IoT Monitoring for Air Pollution	Describes the role of IoT sensors in real-time pollution tracking and early warning systems.
[10]	S. Kumar et al., 2022	PM2.5 Removal in Brick Kilns	Field study showing 93% PM2.5 reduction using multi-stage filters in India.
[11]	A. A. Abdulwahid et al., 2020	Wet Scrubber Performance	Investigated bubble dynamics inside a diesel exhaust wet scrubber for particulate removal.
[12]	M. Ahmed, 2020	Activated Carbon for Air Purification	Detailed activated carbon adsorption behavior for industrial gases.
[13]	M. P. Kaushik et al., 2021	Air Pollution Monitoring Using Smart Sensors	Proposed multi-sensor IoT system for urban and industrial air quality tracking.
[14]	S. S. Kale et al., 2021	Analysis of Electrostatic Precipitators	Studied efficiency and ozone side-effects of ESP systems in industries.
[15]	R. Thilagamani et al., 2021	Hybrid IoT Model for Pollution	Presented hybrid IoT architecture for real-time pollution monitoring and prediction.
[16]	J. Zhang et al., 2020	Industrial Air Cleaning Techniques	Review of air purification and filtration technologies for industrial sources.
[17]	A. Gupta et al., 2020	Smart Air Quality Monitoring Using AI	Developed AI-based air quality prediction integrated with IoT devices.
[18]	S. M. M. Rahman et al., 2022	Low-cost Air Quality Sensors	Evaluated performance of low-cost PM and gas sensors for industrial deployment.
[19]	C. D. Tran et al., 2021	Modular Pollution Control Systems	Proposed modular air purifier units for industrial zones.
[20]	S. F. Mohamed et al., 2021	IoT-Based Pollution Control	Designed an automated pollution control system for factories.
[21]	G. Prabha et al., 2022	Energy Efficient ESP Systems	Improved electrostatic precipitator design reducing energy use.
[22]	R. Verma et al., 2020	Filtration and Air Pollution Control	Comprehensive study on filtration tech in air pollution control.
[23]	F. Alhamid et al., 2021	Advanced Wet Scrubbers	Introduced smart wet scrubber system with IoT-enabled feedback.
[24]	A. J. Chawla et al., 2022	Real-Time Air Quality Networks	Proposed WSN-based air quality networks for industrial zones.
[25]	L. Zhang et al., 2021	VOC Gas Detection Techniques	Evaluated VOC gas sensors for factory-level applications.
[26]	P. Sivakumar et al., 2022	Energy Efficient Air Filtration	Optimized air filtration devices for industrial energy savings.
[27]	A. Patel et al., 2021	Industrial Air Purification Challenges	Discussed challenges in adapting purification systems to different industries.

Recent studies increasingly focus on smart sensing, system integration, and intelligent control. Multi-sensor IoT platforms have been proposed for urban and industrial air quality tracking, emphasizing data fusion and spatial coverage [13]. Performance analyses of ESP systems have further examined efficiency gains alongside ozone-related side effects [14]. Hybrid IoT architectures and predictive models have been introduced to enhance real-time pollution monitoring and forecasting capabilities [15]. Comprehensive reviews of industrial air cleaning technologies continue to highlight the trade-offs between efficiency, energy consumption, and operational complexity [16].

The integration of artificial intelligence with IoT-based air quality systems has enabled predictive analytics and adaptive response strategies [17]. Concurrently, the validation of low-cost sensors has supported scalable industrial deployment without significant loss of accuracy [18]. Modular air purification units have been proposed to improve flexibility and scalability across diverse industrial zones [19]. Automated IoT-based pollution control systems have further demonstrated the feasibility of closed-loop monitoring and mitigation [20].

Energy efficiency has emerged as a critical design objective in recent research. Improved ESP designs and optimized filtration architectures have shown reduced power consumption while maintaining high removal efficiencies [21], [22]. Advanced wet scrubber systems incorporating IoT-enabled feedback mechanisms have been introduced to enhance operational control [23]. Wireless sensor network–based air quality monitoring frameworks have further strengthened distributed industrial surveillance capabilities [24].

Additional studies have evaluated VOC detection techniques suitable for factory-level monitoring and control [25], while optimized filtration devices have demonstrated measurable energy savings in continuous industrial operation [26]. Despite these advancements, persistent challenges remain in adapting purification systems across heterogeneous industrial environments, particularly in achieving seamless integration between sensing, intelligence, and actuation layers [27]. The literature summarized in Table I reflects a clear progression from conventional, standalone pollution control technologies toward intelligent, energy-aware, and modular systems.

1.1.2.2 Survey Report

A field survey was conducted from June 21 to August 1, 2025, to assess air pollution and purification effectiveness across six industrial sites. The goal was to identify pollution sources, their impact on workers, and existing control measures to inform the design of an automated air purification and IoT monitoring system.

Interviews were held with 100 workers and three chief engineers from:

- Mark Designers LTD (Garments)
- ASR Bricks (Brick Kiln)
- AR Cement (Cement)
- Square Pharmaceuticals, Square Toiletries, and Square Consumers LTD

Responses on pollutants, health symptoms, and purification methods were analyzed thematically. A severity scale (1-5) was applied based on self-reported data and benchmarked against WHO, OSHA, and other industrial standards.

The survey revealed significant disparities in pollution control. Traditional industries like brick kilns and cement face severe challenges, while modern facilities like pharmaceuticals employ effective mitigation. Key findings are summarized below:

TABLE II. CROSS-INDUSTRY COMPARISON

Industry	Primary Pollutants	Key Purification	Worker Health Impact	Severity (1-5)
Garments (Mark Designers LTD)	Dust, fibers, chemical dyes	Exhaust fans, limited masks	Eye irritation, coughing, headaches	**3**
Brick Kiln (ASR Bricks)	PM2.5/PM10, smoke, SO_2, CO	Cloth masks only	Severe chronic respiratory issues	**5**
Cement (AR Cement)	Cement dust (silica), NOx, SOx	Bag filters, PPE (use inconsistent)	Silicosis risk, eye/skin issues	**4**
Pharma (Square Group)	VOCs, API aerosols	HEPA filters, fume hoods, activated carbon	Mild dizziness, no severe issues	**1**
Toiletries (Square Group)	VOCs, fragrances	Air scrubbers, activated carbon, HEPA filters	Occasional sneezing, nausea	**2**
Consumer (Square Group)	Powder dust, minor VOCs	Bag filters, ventilation, air purifiers	Coughing, throat irritation	**2**

The findings provide critical requirements for the proposed project:

1. **Targeted Pollutant Detection:** The system must be equipped to monitor the specific pollutants identified: particulate matter (PM2.5/PM10) for brick and cement, VOCs for pharmaceuticals and toiletries, and gases like SO_2, CO, and NOx.

2. **Adaptive Purification Response:** Effective integration of purification technologies is required based on the industry:

   - HEPA/Bag Filters & Electrostatic Precipitators for particulate matter.
   - Activated Carbon Filters & Scrubbers for VOCs and chemical fumes.

3. **Compliance and Automation:** The IoT system must enable real-time monitoring and automated control to maintain air quality within regulatory limits (WHO, OSHA, local standards like "Clean Air 2025"), ensuring both worker safety and regulatory compliance.

The survey confirms that enhanced, automated air quality management is urgently needed, particularly in traditional manufacturing sectors. The proposed system will leverage successful strategies from advanced industries to create a scalable, real-time solution for reducing health risks and improving productivity across the industrial spectrum.

1.1.3 Literature Gap

The existing landscape of industrial air pollution control reveals several critical and interconnected gaps that the proposed integrated system aims to address. While numerous solutions exist, they are often fragmented, leading to inefficiencies and barriers to widespread adoption, especially for small and medium enterprises (SMEs).

Current systems predominantly exhibit a functional dichotomy; they are either monitoring-oriented or purification-focused, with few synergistically bridging the two. These approaches are rarely enhanced by the automation, intelligence, and connectivity afforded by the Internet of Things (IoT) and Machine Learning (ML). This separation results in reactive, rather than proactive, pollution management. Furthermore, there is a notable scarcity of tailored decision-support systems designed for the stringent budget and infrastructure constraints typical of SMEs, such as brick kilns. The envisioned system responds directly to this unmet need by integrating real-time IoT monitoring with a modular, automated purification system, engineered for rapid deployment, cost and energy efficiency, and adaptability across diverse industrial settings.

The specific research and practical gaps can be detailed as follows:

First, conventional systems are largely inflexible. They operate on fixed schedules or static thresholds, unable to dynamically modulate their purification intensity in response to real-time fluctuations in pollutant concentration [28]. This “always-on” or manually triggered approach leads to significant energy waste during low-pollution periods and inadequate response during sudden spikes, failing to optimize both resource use and air quality protection.

Second, prevalent high-efficacy purification technologies suffer from low energy efficiency and high operational cost. Solutions like Electrostatic Precipitators (ESPs) and Wet Scrubbers, while effective at capturing particulates and gases, are often prohibitive for cost-sensitive operations due to their substantial power consumption and ancillary requirements (e.g., water, chemical agents) [8], [29]. This economic barrier prevents their adoption in the very industries where pollution is often most severe.

Third, these systems demand high and consistent maintenance. Technologies such as ESPs require regular cleaning of plates and components, while filter-based systems need frequent manual checking and replacement to prevent clogging and maintain efficiency [8], [30]. This reliance on skilled labor and downtime for upkeep adds to the total cost of ownership and can lead to system neglect or failure in settings with limited technical support.

Fourth, there is a prevalent shortfall in generating effective, actionable data insights. Many monitoring setups lack real-time data processing, advanced analytics, and intuitive reporting capabilities [6], [28]. Data is often logged for retrospective compliance checking rather than being used for predictive analytics, trend forecasting, or providing immediate, actionable alerts to floor managers, resulting in missed opportunities for preventative intervention.

Fifth, existing solutions demonstrate poor scalability. It is challenging to adapt a single system design cost-effectively for the vastly different spatial scales, pollutant loads, and financial capacities of small, medium, and large industries [31]. Solutions are often either oversized and economically unviable for SMEs or undersized and ineffective for larger facilities, lacking a modular architecture that can grow with operational needs.

Finally, the increasing connectivity of industrial systems introduces significant cybersecurity vulnerabilities. IoT-enabled air quality systems, if not designed with security as a core principle, can become entry points for cyberattacks. Many lack adherence to critical industrial control system (ICS) security standards, such as the NIST SP 800-82 guide, leaving them vulnerable to data breaches, manipulation of sensor readings, or even takeover of control functions, posing risks to both operational integrity and safety [32].

In summary, the research gap is defined not by a lack of individual technologies but by the absence of a holistic, intelligent, and economically accessible integration of monitoring, purification, and data analytics. The proposed system is conceived to fill this gap by delivering an adaptive, efficient, and secure solution that is viable for the broad spectrum of industrial players, from large pharmaceuticals to small-scale brick kilns.

1.1.4 Relevance to Current and Future Industry

The proposed system is a direct and practical intervention designed to meet the urgent demands of modern industry. Its relevance is driven by a powerful convergence of regulatory, economic, and strategic imperatives that define both current operational survival and future market leadership.

The push for adoption originates from clear and mounting pressures. Regulatory compliance has evolved from a static checklist into a dynamic, data-intensive requirement. With frameworks like the Bangladesh Air Pollution (Control) Rules 2022 and stringent international supply chain standards, industries are compelled to provide verifiable, real-time proof of emission control. This system transforms compliance from a manual, retrospective burden into an automated, transparent process, significantly mitigating legal liabilities and safeguarding market access.

Economically, the system addresses two critical fronts: human capital and operational overhead. A healthier work environment, free from acute pollution, directly reduces absenteeism, lowers long-term healthcare costs, and sustains higher levels of worker focus and productivity. Concurrently, the system's intelligent, adaptive operation—activating purification only when and where needed—targets one of industry's largest variable costs: energy consumption. This dual focus on human and energy efficiency translates into a compelling return on investment.

Beyond compliance and cost, the system serves as a powerful tool for strategic differentiation and market positioning. In an era where corporate social responsibility (CSR) is scrutinized by consumers and investors alike, demonstrable investment in worker safety and environmental stewardship enhances brand reputation. For export-oriented industries, particularly in Bangladesh, this is often a non-negotiable prerequisite for engaging with ethically conscious global buyers and securing a competitive edge.

Finally, the system is inherently forward-looking, embedding the core principles of Industry 4.0. By integrating IoT connectivity, real-time analytics, and automated control, it does not merely solve a pollution problem; it lays the digital foundation for smarter, more responsive, and sustainable manufacturing. Its deployment is a decisive step toward the data-driven, transparent, and agile operations that define the future of the industrial sector.

In conclusion, the project’s relevance is unequivocal. It provides a critical bridge between an immediate, severe health and environmental challenge and the technological pathway to industrial resilience and growth. The system is not an optional upgrade but a necessary tool for industries navigating the intertwined demands of worker welfare, regulatory scrutiny, economic efficiency, and global competitiveness.

1.2 Objectives, Requirements, Specifications, and Constraints

1.2.1. Objectives

The project's goals are formulated to be Specific, Measurable, Achievable, Relevant, and Time-bound (SMART), directly addressing the identified problem and gaps.

Six core objectives guide the design, development, and validation of the system, ensuring a comprehensive solution.

1. **Real-Time Monitoring:** To design and implement a robust IoT-based system for the continuous, real-time measurement and analysis of key industrial air pollutants, including particulate matter (PM2.5, PM10) and gaseous pollutants (CO, CO_2, NO_2, TVOCs).
2. **High-Efficiency Purification:** To engineer a multi-layer filtration unit, utilizing HEPA and activated carbon technologies, capable of achieving a minimum pollutant reduction efficiency of 90% for PM2.5 in an industrial setting.
3. **Adaptive & Efficient Control:** To develop an intelligent control algorithm that dynamically adjusts purification fan speed (via PWM) based on real-time air quality data, optimizing for energy efficiency while maintaining air quality standards.
4. **Economic Viability:** To create a solution with a total budget under ৳50,000, demonstrating a compelling return on investment (ROI) and payback period to ensure accessibility and adoption by SMEs.
5. **Standards Compliance:** To rigorously validate the system's performance against international air quality benchmarks, specifically the World Health Organization (WHO) Air Quality Guidelines [10].
6. **Data Visualization & Security:** To develop a secure, locally-hosted web application dashboard for real-time data visualization, historical trend analysis, and system control, with data integrity maintained in a personal database.

These objectives collectively ensure the project delivers a technically sound, economically feasible, and user-accessible system that meets the defined need for intelligent industrial air pollution control.

1.2.2 Functional and Nonfunctional Requirements

The system's requirements are categorized into what it must *do* (functional) and *how well* it must perform under various conditions (non-functional).

The requirements are derived directly from the problem statement, objectives, and stakeholder needs identified in the background study.

Functional Requirements:

1. **Real-time Sensing & Display:** The system shall continuously measure specified pollutants and display their concentrations on a local interface (e.g., OLED) and remote dashboard.
2. **Automated Actuation:** The purification unit shall activate automatically within 10 seconds of any monitored pollutant exceeding a WHO-based threshold and shall deactivate when levels return to a safe range.
3. **Data Management:** The system shall log timestamped sensor data with a minimum 1-minute resolution to a local database, retaining data for at least 30 days.
4. **Alerting:** The system shall trigger a visual (OLED) alarm locally, and a notification on the remote dashboard, when pollutant levels enter a "hazardous" range.
5. **Remote Access & Control:** Authorized users shall be able to view real-time data, historical charts, and manually override system states (ON/OFF) via a web-based interface from any network-connected device.

Non-Functional Requirements:

1. **Environmental Robustness:** Sensor nodes and the control unit shall be housed in IP54-rated enclosures to operate reliably in dusty, high-humidity environments with ambient temperatures of 0–50°C.
2. **Energy Efficiency:** The total operational power draw of the central purification unit and three sensor nodes shall not exceed 25 Watts under typical load.
3. **System Reliability:** The core monitoring and purification control shall maintain >99% uptime, with fail-safe logic to default to continuous purification if the control system fails.
4. **Maintainability:** Critical consumables (HEPA and carbon filters) shall be replaceable by facility personnel within 15 minutes without specialized tools.
5. **Security:** All data transmission between nodes, the gateway, and the dashboard shall be encrypted using AES-256. The system shall require user authentication for controlled access.

This set of functional and non-functional requirements provides a clear blueprint for the system's capabilities and quality attributes, ensuring it is fit for purpose in the challenging industrial environment.

1.2.3 Specifications

The system's technical specifications translate functional requirements into measurable engineering targets, derived from component datasheets, international standards, and calculated performance criteria.

Sensor Array Performance: The integrated multi-sensor suite provides comprehensive air quality monitoring. The PMS5003 sensor measures particulate matter (PM) from 0–500 µg/m³ with ±10% accuracy in the 100–500 µg/m³ range. For gaseous pollutants, the SPEC SGPC3 detects NO_2 (0–50 ppm, ±5 ppm accuracy). The Fermion MEMS gas sensor, interfaced via a 16-bit ADS1115 ADC, monitors CO levels. Volatile Organic Compounds (VOCs) and indoor air quality are measured by the CCS811 sensor and the more advanced ENS160 MOX sensor, the latter paired with an AHT21 for temperature and humidity compensation to ensure measurement accuracy.

Filtration and Purification Performance: The purification module employs a two-stage filtration system. The primary particulate stage uses an H13-grade HEPA filter with a minimum efficiency of 99.95% on 0.3 µm particles. The secondary stage uses four car filters with a minimum 85% adsorption efficiency for Total VOCs (TVOCs). System performance is driven by dual Arctic P12 Max fans, delivering a combined airflow of ≥275 m³/h. This enables a Clean Air Delivery Rate (CADR) sufficient for 6 Air Changes per Hour (ACH) in a standard 40.5 m³ industrial space, translating to a full air purification cycle within 13–15 minutes.

System Power and Communication: Designed for energy efficiency, the system operates on low-voltage DC power (12V and 5V rails) with a maximum total power consumption of ≤20W, typically drawing ~17.11W. The IoT and control backbone is built around an ESP32-WROOM-32 microcontroller, providing integrated Wi-Fi (IEEE 802.11 b/g/n) and Bluetooth connectivity. Nodes are configured in a star network topology with an effective indoor range of approximately 30 meters per node.

Data Architecture: Data handling ensures reliability and responsiveness. A SQLite database on the central gateway provides resilient local storage. The monitoring dashboard receives updates with a latency of less than 5 seconds, enabling near real-time oversight and decision-making.

1.2.4 Technical and Non-technical Considerations

A successful design must navigate a series of limiting factors and broader considerations. The development process is bounded by practical realities that shape the final solution.

Technical Constraints:

These are the active engineering and performance factors that positively guide the system's design and capabilities.

- **Modularity & Scalability:** The architecture must allow for the system to be scaled up or down, enabling deployment in settings ranging from a small workshop to a large factory floor.

- **Sensor Fusion & Data Accuracy:** Integrating data from multiple, lower-cost sensors (e.g., PM, VOC, gas) and applying calibration algorithms to improve overall measurement reliability and accuracy.
- **Edge Computing for Autonomy:** Implementing local processing on the microcontroller (ESP32) to run core automation logic, ensuring the purification system responds immediately to sensor thresholds without cloud dependency.
- **Energy-Efficient Operation:** Designing the system circuitry and software (e.g., sleep modes, fan speed control) to minimize power draw, extending battery life during outages and reducing operational costs.
- **Real-Time System Responsiveness:** Ensuring the closed-loop control system—from sensor reading to fan/filter activation—has minimal latency to effectively respond to sudden pollution spikes.

Non-Technical Considerations:

These are the human, strategic, and ethical factors that define the project's broader purpose and ensure its successful adoption.

- **Societal Health Benefit:** The core mission is to reduce the disease burden and improve the quality of life for industrial workers and surrounding communities.
- **Cultural Usability & Acceptance:** Designing intuitive interfaces and providing training to overcome potential resistance to new technology and ensure smooth integration into existing workplace routines.
- **Legal Compliance Facilitation:** The system must actively help industries meet national (e.g., Bangladesh Air Pollution Rules) and international environmental and workplace safety regulations.
- **Ethical Data Stewardship:** Upholding strong principles of data privacy, ensuring worker monitoring data is anonymized, secured, and used transparently and responsibly.
- **Environmental Sustainability:** Evaluating and minimizing the solution's own lifecycle impact, including energy consumption, material selection, and end-of-life plans for filters and electronics.

1.2.5 Constraints in the Design Process

There were both technical and non-technical constraints in the design process. The constraints are explained below separately.

Technical Constraints: These are the fixed, external technical limitations that the design must work within.

- **Internet Reliability:** The design cannot assume continuous, high-quality internet connectivity for core functionality; it must be resilient to network outages.

- **Budget Limitation:** A total hardware budget of approximately ৳50,000 restricts component choices, excluding high-end, laboratory-grade analytical sensors.
- **Power Availability:** The system must account for unstable grid power in target areas and be designed to function with a low-power footprint and backup power capability.
- **Local Component Sourcing:** The bill of materials must primarily consist of electronic components and hardware that are readily available for purchase within Bangladesh to ensure maintainability and scalability.

Non-Technical Constraints: These are the external, non-engineering boundaries and challenges that shape the project's context and implementation.

- **Operator Skill Level:** The system must be operable and maintainable by personnel with varying levels of technical expertise, limiting design complexity in user-facing components.
- **Industrial Workspace Limitations:** The physical design must account for harsh environments (dust, humidity) and space constraints typical in SMEs like brick kilns or small factories.
- **Regulatory Ambiguity:** Navigating potentially unclear or evolving local environmental regulations, requiring the system to be adaptable to changing compliance reporting standards.
- **Timeframe for Deployment:** The development and pilot deployment schedule is limited, prioritizing a functional Minimum Viable Product (MVP) over a feature-complete system in the initial phase.

1.2.6 Applicable Compliance, Standards, and Codes

The project's development is firmly anchored in a comprehensive framework of international standards and Bangladesh-specific regulations. In areas where the novel integration of IoT, solar power, and automated filtration lacks explicit codification, custom criteria have been developed through good engineering practice, stakeholder consultation, and iterative validation [34]. This ensures the system meets operational, safety, and regulatory requirements from development through deployment.

International Standards: The system's technical foundation is built upon key international benchmarks. For sensor accuracy, ISO 21501-4:2018 governs the calibration and performance verification of the PMS5003 particulate matter sensors, ensuring reliable measurement of PM2.5 and PM10 levels critical for compliance [35]. The filtration system adheres to ISO 16890:2016, which defines the testing and classification of air filters; this informed the selection of H13-grade HEPA filters and activated carbon filters to achieve targeted removal efficiencies [36]. Hardware resilience in harsh industrial environments is guaranteed by IEC 60529:2013 (IP Code), mandating IP54-rated enclosures to protect against dust and moisture ingress [37].

The IoT architecture follows IEEE 802.11-2020 for robust, low-latency Wi-Fi communication, enabling real-time data transmission [38]. System design also incorporates ASHRAE Standard 62.1-2022 to ensure adequate ventilation and air change rates, guiding the specification of fan capacity [39]. Broader project management and sustainability are addressed through ISO 14001:2015 for environmental management, promoting the use of solar power and recyclable materials [40], and ISO 31000:2018 for structured risk management, ensuring project reliability and on-time delivery [41].

Bangladesh-Specific Codes and Standards: Compliance with national law is paramount. The Bangladesh National Ambient Air Quality Standards (BNAAQS) establish the mandatory concentration limits for pollutants such as PM2.5 (15 µg/m³ annual mean) and SO_2, which directly define the system's performance targets for emission reduction [42]. These are operationalized through the Air Pollution (Control) Rules 2022, which provide the regulatory framework for industrial emission control, monitoring, and reporting to the Department of Environment (DoE) [43]. The overarching Bangladesh Environment Conservation Act, 1995 (BECA) empowers this regulatory structure, making adherence to the aforementioned rules a legal necessity [44]. For electrical safety, the system aligns with BDS IEC 60335-1, the national adoption of the international safety standard for electrical appliances, ensuring safe operation in industrial settings [45].

Development of Custom Criteria: For novel aspects lacking specific standards, custom performance criteria were established. For IoT-driven automation, a target of <0.5-second latency for sensor-to-actuator response was set, based on IEEE communication principles and DoE monitoring needs, alongside a 99.5% system uptime goal derived from quality management principles [46]. The integration of solar power for off-grid resilience follows best practices in renewable energy system design, tailored to local conditions. These custom criteria were validated through iterative lab and field testing, with stakeholder feedback ensuring they meet practical and regulatory expectations, thereby filling the gaps where formal standards are still evolving [47].

1.3 Systematic Overview of the Proposed Project

The proposed solution is an integrated hardware-software system designed for automated industrial air quality management. Its core innovation lies in its **mesh-based architecture**, which balances responsiveness, reliability, and cost.

The system is decomposed into four interconnected subsystems, each with a distinct role, working in concert to achieve the project objectives.

1. **Distributed Sensor Network:** Multiple, strategically placed sensor nodes form the data acquisition layer. Each node, built around an ESP32 microcontroller, houses a suite of sensors (PM, CO, NO_2, VOC, etc.) to monitor the local air. It performs initial data averaging and transmits readings wirelessly to a central point.

2. **Data Aggregation & Fog Gateway:** This unit acts as the system's "local brain." An ESP32-based gateway receives data from all sensor nodes, aggregates it, and runs the control algorithm. It makes real-time decisions (e.g., turn purifier ON/OFF, adjust fan

speed) based on predefined logic and thresholds, independent of an internet connection. This fog layer ensures low latency and operational resilience.

3. **Central Purification Unit:** The primary actuation component. It consists of a custom-designed chamber containing a HEPA filter and an activated carbon filter. Airflow is generated by two high-static-pressure DC fans (Arctic P12 Max). The fans are controlled via Pulse Width Modulation (PWM) from the fog gateway, allowing adaptive speed adjustment for energy savings.

4. **User Interface & Data Management:** A custom web application, hosted locally on the gateway, provides a real-time dashboard displaying pollutant levels, system status, and historical trends. All data is stored in a local database (e.g., SQLite). This interface serves as the primary point for human oversight and control.

This systematic design ensures that pollutant monitoring, intelligent decision-making, and effective purification are tightly integrated into a cohesive, autonomous system. The fog-based approach specifically addresses the constraints of the operating environment, making it a robust and practical solution for industrial pollution control in Bangladesh.

1.4 Conclusion

Chapter 1 has systematically established the foundation for the project. It has articulated a critical problem—ineffective industrial air pollution control in Bangladesh—supported by direct field evidence and a review of existing literature that reveals a contextual gap. From this analysis, a set of clear, actionable objectives and detailed requirements has been derived. The proposed solution, a fog-based IoT monitoring and automated purification system, has been outlined, demonstrating its direct relevance to current and future industrial needs. The chapter also defined the technical specifications, acknowledged the design constraints, and confirmed alignment with necessary standards and ethical codes. This comprehensive introduction sets the stage for the subsequent chapters, which will delve into the detailed design, analysis, implementation, and validation of the proposed system.

Chapter 2: Project Design Approach

2.1 Introduction

The successful realization of a complex engineering system necessitates a structured and analytical approach to its design. Rather than converging on a single solution prematurely, a rigorous methodology was employed to conceive, model, and evaluate multiple distinct design architectures. This chapter details that process, fulfilling the requirements of Course Outcomes CO5 (Design multiple engineering solutions) and CO6 (Analyze alternative design solutions). It begins by identifying three fundamentally different architectural paradigms for an IoT-based air purification system. Each approach is then described in detail, covering its topology, decision-making logic, and data flow. Finally, a systematic analysis is conducted, comparing the designs across a defined set of ten performance matrices—including cost, scalability, response time, and power consumption—to substantiate the selection of the optimal design. The outcome of this chapter is a justified, evidence-based choice for the system architecture that will be implemented and validated in subsequent phases of the project.

Figure 1 shows a conceptual block diagram of the system that satisfies all the objectives of the project set in Chapter 1.

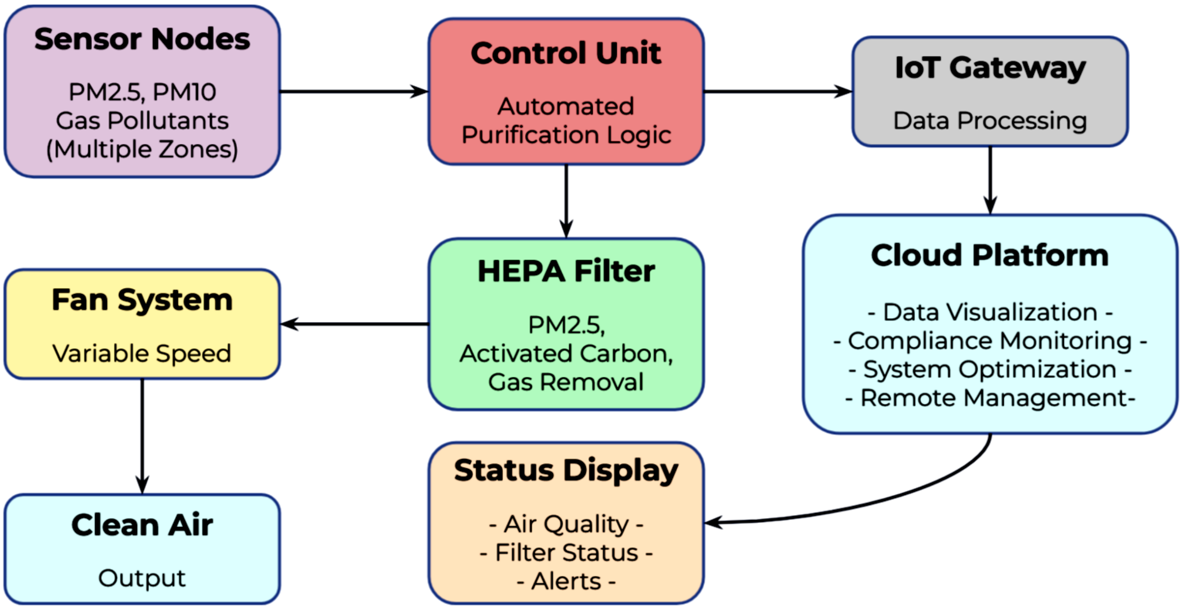

Figure 1: Block Diagram of a Design to Satisfy All the Objectives

2.2 Identify Multiple Design Approaches

The identification of viable design alternatives is a critical first step in engineering problem-solving. To ensure a comprehensive exploration of the solution space, the design process began not with components, but with architectural paradigms during the “Design Phase” of FYDP (FYDP-D). The core functional requirement—linking distributed sensing to centralized actuation via intelligence—can be realized through different distributions of computing resources and network structures. The goal was to explore the spectrum from highly centralized to fully decentralized control, each with distinct implications for cost, complexity, and robustness.

The project's specific context—industrial settings in Bangladesh with potential internet unreliability, budget constraints, and a need for rapid response—guided the identification of relevant architectures. Three canonical models from IoT and industrial automation were selected and adapted:

1. **The Centralized Cloud Model:** This is a prevalent model in commercial IoT where "things" (sensors/actuators) are dumb terminals connected to a powerful cloud brain. It offers extensive data analytics and remote access but depends entirely on network connectivity. This was adapted into Design Approach 1: Mesh-based Wireless Sensor Network (WSN) with a Centralized Cloud Control System. The addition of a mesh network was considered to enhance data collection reliability in large or obstructed spaces, a common industrial challenge.

2. **The Fog/Edge Computing Model:** To mitigate cloud dependency, this model processes data closer to the source. "Fog" computing introduces an intermediary layer (a gateway or local server) that can make decisions without cloud round-trips. This paradigm directly addresses the connectivity constraint and was instantiated as Design Approach 2: Fog-Based Distributed Sensor Node with Central Purifier Control. This approach deliberately separates the intelligence (fog gateway) from the actuation (central purifier) to optimize cost and efficiency.

3. **The Fully Distributed Edge Model:** Pushing intelligence to the extreme edge results in autonomous units that sense, decide, and act independently. This model maximizes responsiveness and fault tolerance, but at the cost of hardware duplication. It was conceptualized as Design Approach 3: SmartChain Modular Edge-Based Purification. This approach tests the hypothesis that maximum localization of control is worth the increased per-unit cost and complexity.

The three approaches were not chosen at random; they were systematically identified based on their ability to explore key engineering trade-offs relevant to the project's constraints:

- **Locus of Intelligence (Cloud vs. Fog vs. Edge):** This is the primary differentiator. How and where is the decision to purify made?
- **Network Topology (Mesh vs. Star):** How do the sensing nodes communicate? Does the network shape influence reliability and range?
- **Actuation Strategy (Centralized vs. Distributed):** Is there one large purifier or many small ones? This drives cost, power, and coverage strategy.
- **Dependency on External Infrastructure:** To what extent does the core function rely on stable internet or grid power?

By identifying these three distinct approaches—spanning the cloud-fog-edge continuum and exploring different network and actuation strategies—the project ensures a robust and unbiased design exploration. This methodological identification provides a solid foundation for the subsequent detailed description, simulation, and comparative analysis needed to arrive at an optimal, context-aware solution.

During the FYDP-D, the three design approaches were simulated via Proteus 8.21 Professional as a part of the course evaluation. One thing to be noted is that the simulations were done using the MQ-7 and MQ135 sensors instead of the PMS5003, CCS811, ENS160+AHT21, Fermion MEMS CO, and NO_2 sensors. This was done due to the unavailability of the sensor libraries in Proteus.

2.3 Description and Analysis of Multiple Design Approaches

During the FYDP-P, we proposed three design approaches that were structurally and topologically different from each other. We have successfully simulated all three approaches. In this chapter, we will explain each of the design approaches in great detail.

2.3.1 Design Approach 1: Mesh-based Wireless Sensor Network (WSN) with a Centralized Control System

This design outlines a Mesh-based Wireless Sensor Network (WSN) with a Centralized Control System. The core idea is to use multiple, interconnected sensor nodes to gather environmental data over an area and send it to a single, central unit that processes the data, controls local equipment, and forwards the information to a cloud platform for remote monitoring.

Figure 2 illustrates the block diagram depicting the entire system flow for Design Approach 1, and Figure 3 shows the implemented system within the Proteus 8.21 Professional environment.

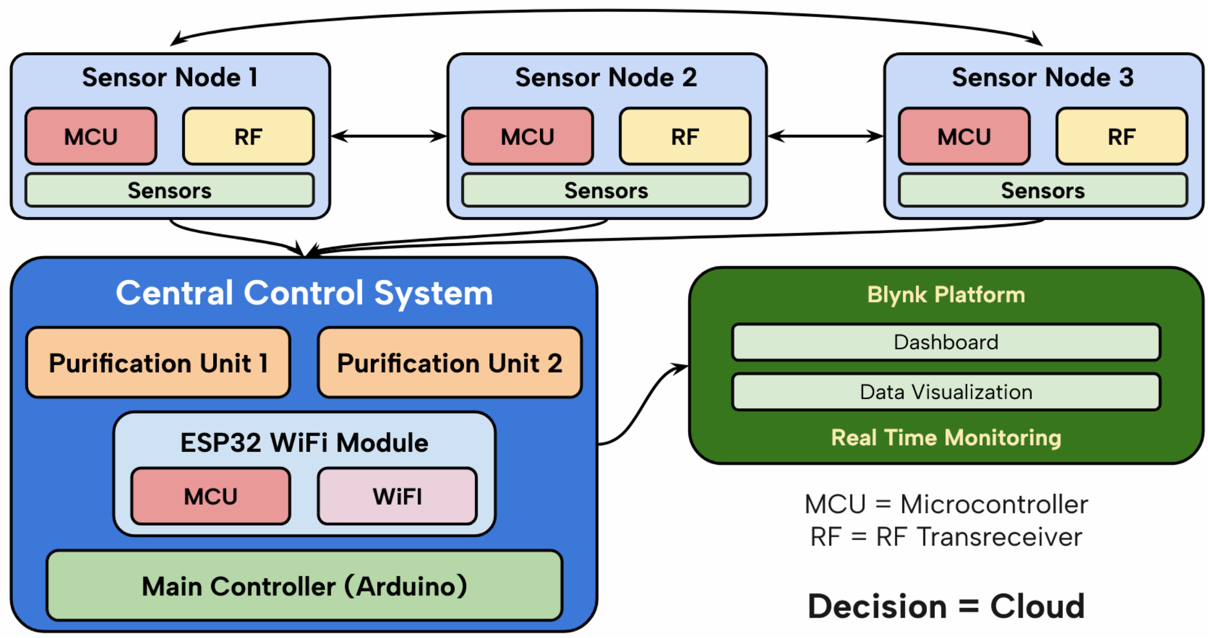

Figure 2: Block Diagram of Approach 1: Mesh-based Wireless Sensor Network (WSN) with a Centralized Control System

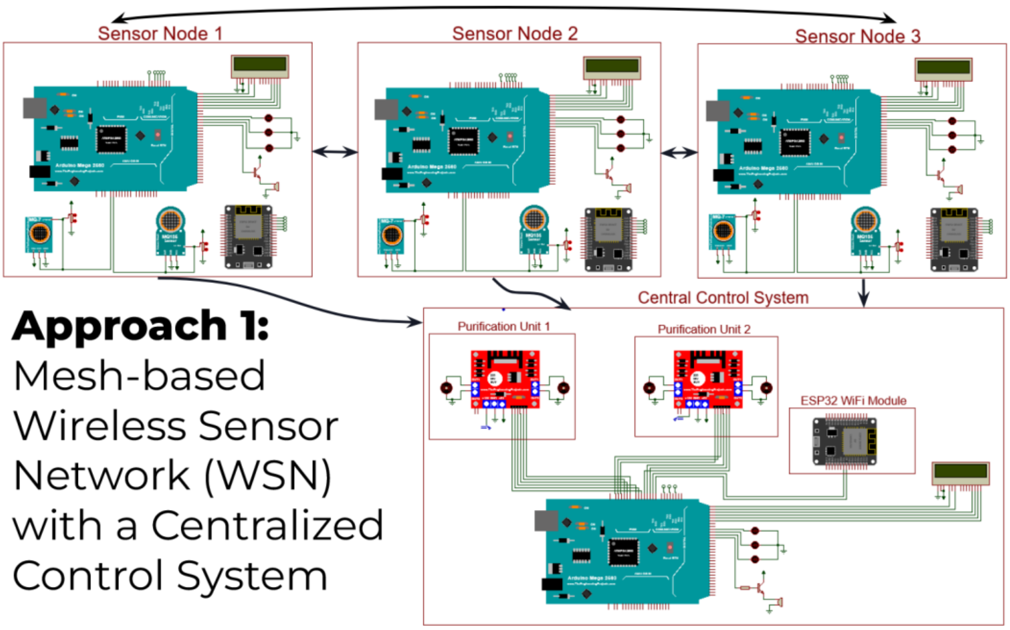

Figure 3: Circuit Implementation of Approach 1: Mesh-based Wireless Sensor Network (WSN) with a Centralized Control System

2.3.1.1 Sensor Nodes and Mesh Network

The system's foundation is a set of distributed Sensor Nodes. Each node is an independent unit equipped with a microcontroller (MCU), various sensors to measure environmental parameters (like air quality, temperature, etc.), and a radio frequency (RF) transceiver for wireless communication.

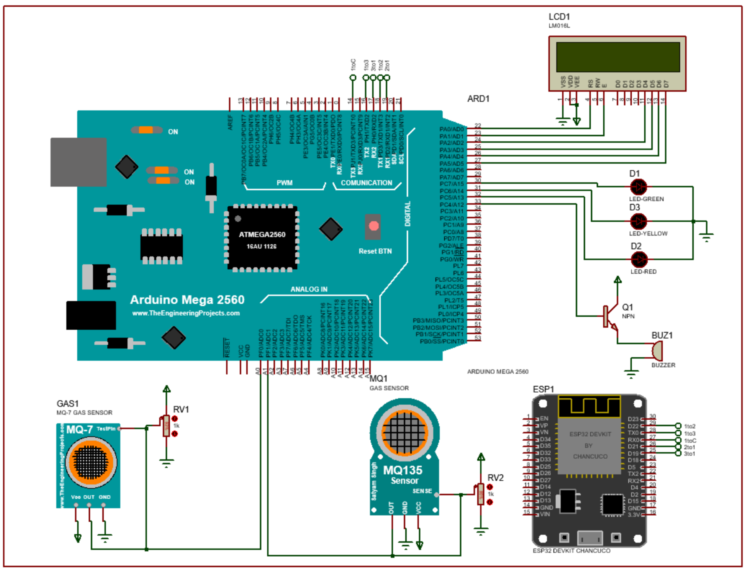

Figure 4: Schematics of Sensor Nodes of Approach 1

These nodes are organized into a mesh network. Unlike a simple star network, where every node must communicate directly with the center, a mesh topology allows nodes to communicate with each other. This creates a more robust and resilient network. If a node is too far from the central system, it can relay its data through a neighboring node, extending the network's overall range and creating redundant communication paths.

Figure 4 depicts the sensor node schematic for the design approach 1.

2.3.1.2 Central Control System (CCS)

All data collected by the sensor nodes is ultimately sent to a Central Control System. This unit acts as the system's brain and gateway. The schematic of the CCS for the Approach 1 is shown in Figure 5 It consists of several key components:

- **Main Controller (Arduino):** This is the primary processing unit that receives and aggregates data from all the sensor nodes in the WSN. It runs the main logic for the system.
- **Purification Units:** These are the actuator components of the system. Based on the sensor data it receives (e.g., if a pollutant level exceeds a certain threshold), the Main Controller can activate or deactivate these units to take corrective action, such as filtering the air.
- **ESP32 WiFi Module:** This module serves as the bridge to the internet. The Main Controller passes the processed data to the ESP32, which then uses its built-in WiFi capabilities to connect to a local network and send the data to a cloud service.

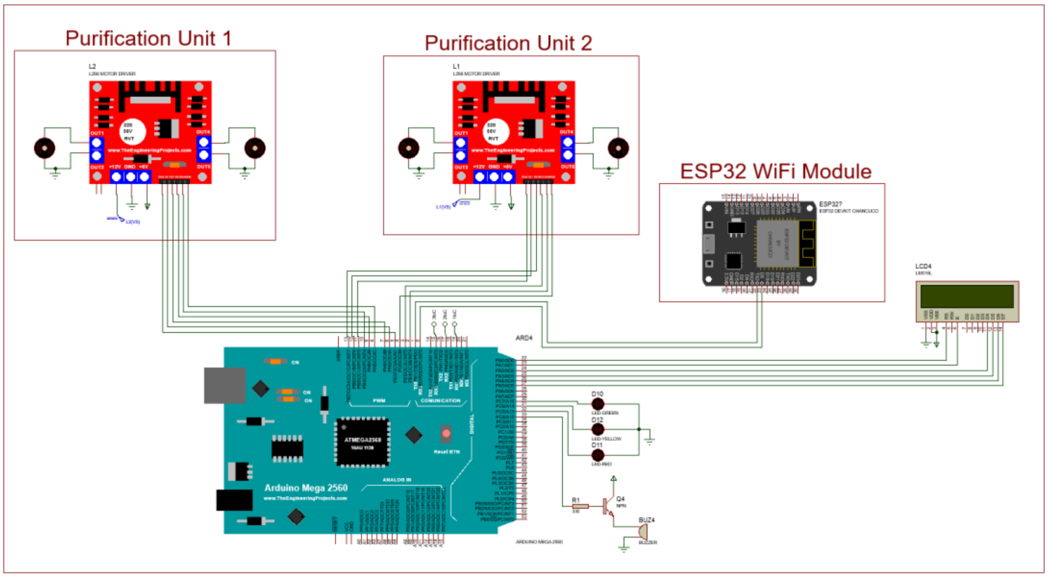

Figure 5: Schematics of the Central Control System (CCS) of Approach 1

2.3.1.3 Cloud Platform and Real-Time Monitoring

The final layer of the architecture is the cloud integration, handled by the Blynk Platform (or a similar IoT service). Once the ESP32 sends the data to the cloud, the platform provides several powerful features:

- **Dashboard & Data Visualization:** Users can access a custom dashboard through a web browser or mobile app to view the sensor data in an easy-to-understand format, using gauges, charts, and graphs.

- **Real-Time Monitoring:** The system allows for live monitoring of the conditions reported by the sensors from anywhere with an internet connection.
- **Cloud-Based Decisions:** The architecture supports making decisions in the cloud. This means rules and logic can be configured on the cloud platform itself, which can then send commands back to the Central Control System to operate the purification units, offering greater flexibility for remote management.

Figure 6 shows the overall Blynk Interface for the design approach 1, where it shows the readings of the two sensors for the three sensor nodes and also shows the purifier fan status for both the purification units.

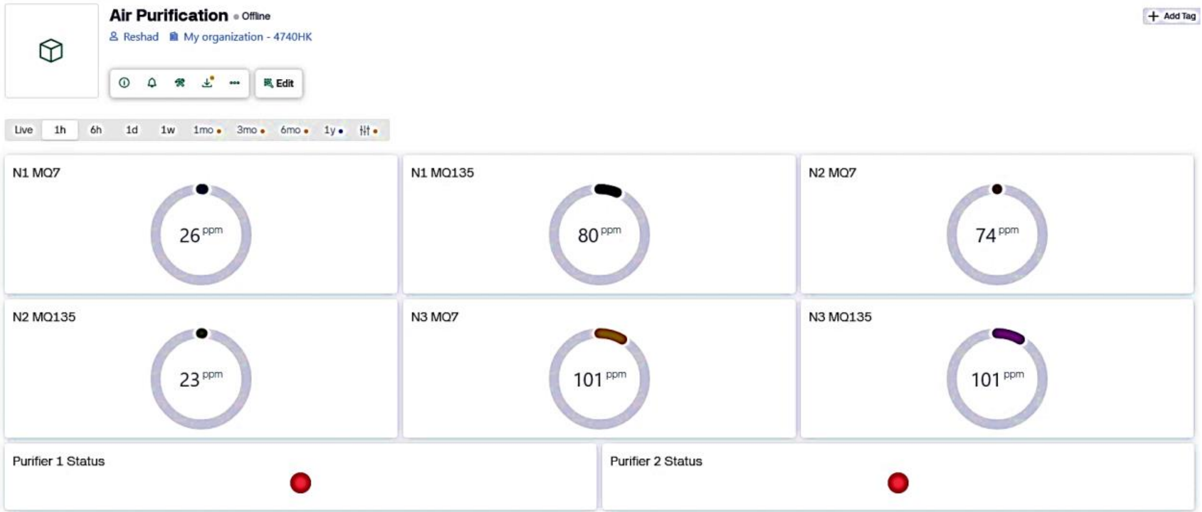

Figure 6: Blynk Interface for Design Approach 1

2.3.2 Design Approach 2: Fog-Based Distributed Sensor Node with Central Purifier Control

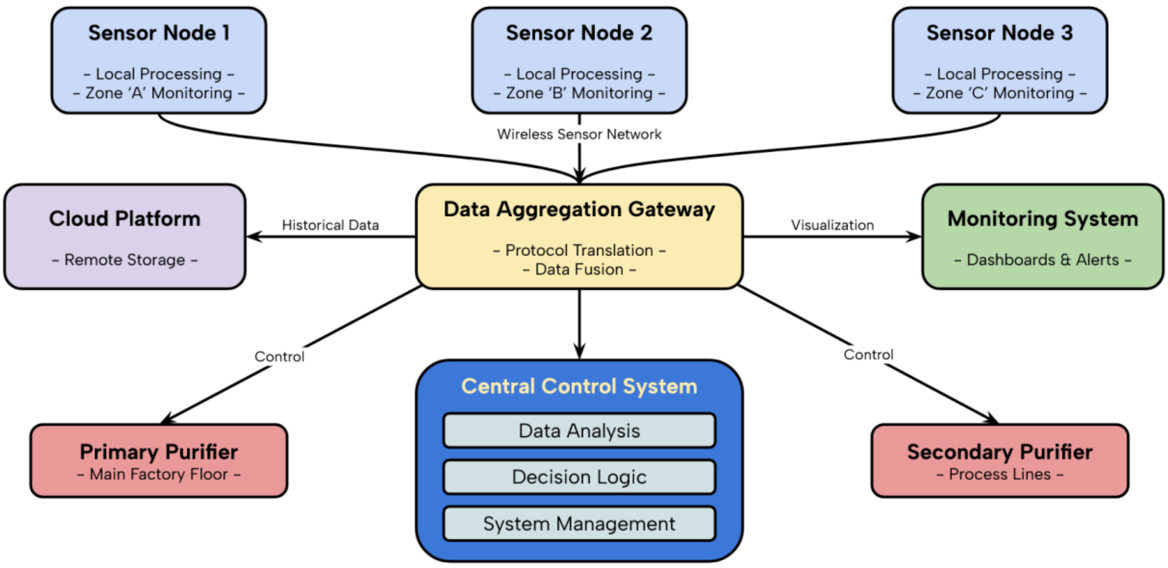

Figure 7: Block Diagram of Approach 2: Fog-Based Distributed Sensor Node with Central Purifier Control

This design uses a fog computing architecture to create a responsive and efficient environmental monitoring and control system. Instead of sending all raw sensor data directly to the cloud, it uses an intermediate “fog” layer—the Data Aggregation Gateway—to process data locally, enabling faster decision-making for time-sensitive control tasks.

Figure 7 illustrates the block diagram depicting the entire system flow for Design Approach 2, and Figure 8 shows the implemented system in the Proteus 8.21 Professional environment.

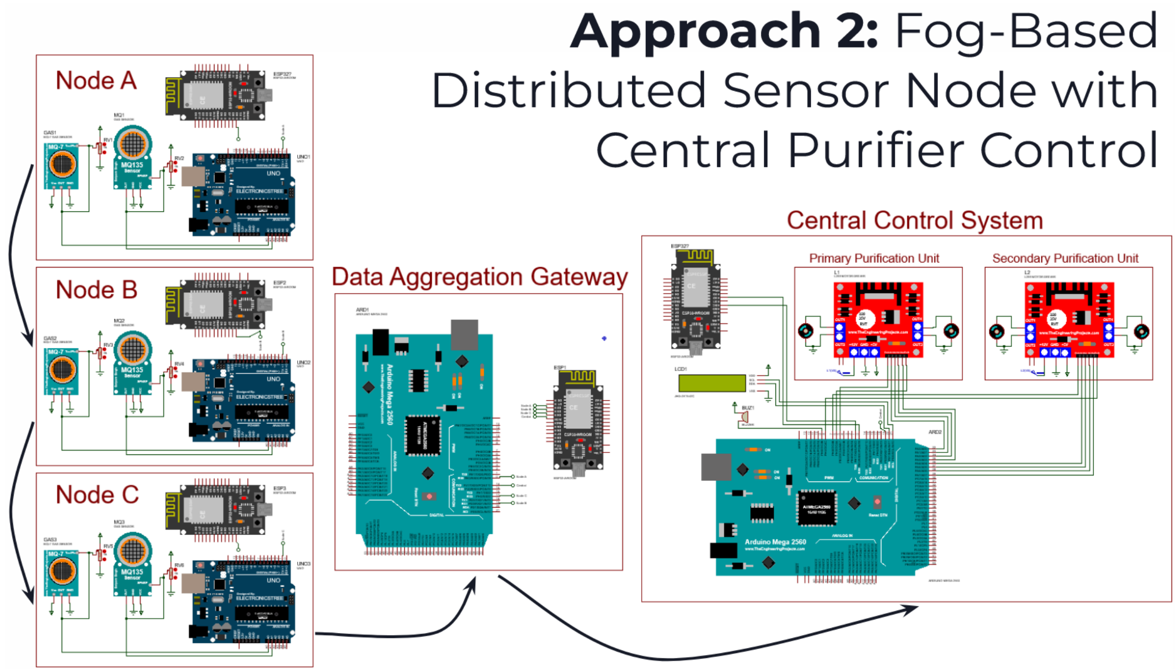

Figure 8: Circuit Implementation of Approach 2: Fog-Based Distributed Sensor Node with Central Purifier Control

2.3.2.1 Distributed Sensor Nodes

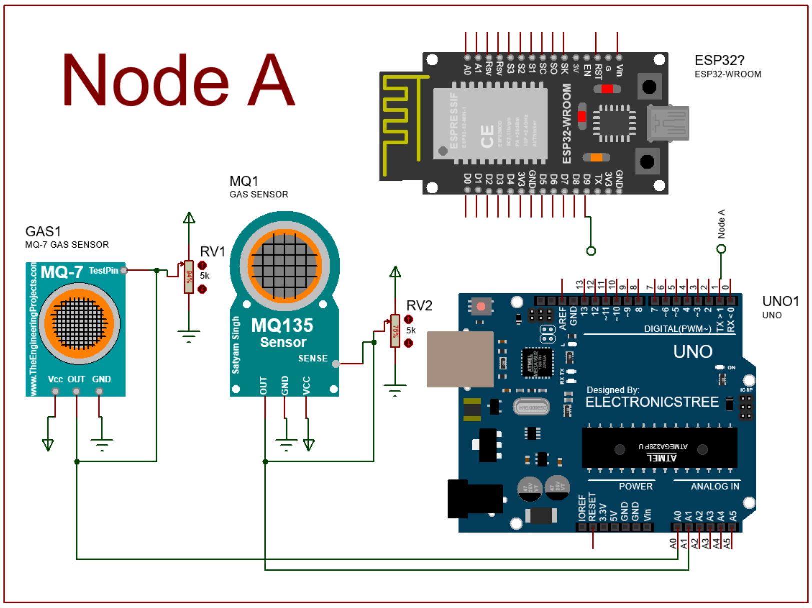

Figure 9: Schematics of Sensor Nodes of Approach 2

The system starts with multiple distributed sensor nodes (Node A, B, C), each responsible for monitoring a specific zone. Unlike the previous mesh approach, these nodes act more independently. Each node is a self-contained unit with its own microcontroller, a set of sensors (e.g., for different gases), and a WiFi module.

A key feature here is local processing. Each node can pre-process its sensor readings—for example, by averaging values or converting them into meaningful concentrations—before transmitting the data. This reduces network traffic and offloads some computational work from the central gateway. Figure 9 shows the schematics of one of the three sensor nodes for Design Approach 2 built via Proteus 8.21 Professional.

2.3.2.2 Data Aggregation Gateway (The Fog Layer)

This is the central nervous system of the design and represents the fog computing layer. It sits between the sensor nodes and the other parts of the system. The gateway's primary role is to act as an intelligent intermediary. Figure 10 shows the Data Aggregation Gateway for Design Approach 2.

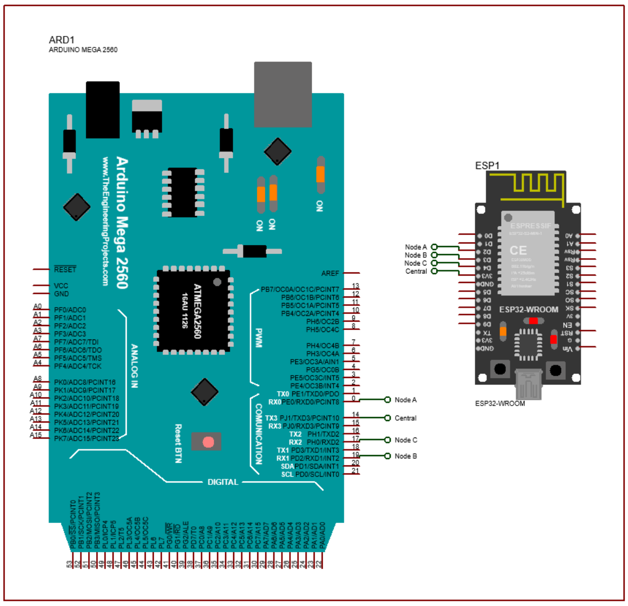

Figure 10: Schematics of the Data Aggregation Gateway (Fog) of Approach 2

It receives data from all the individual sensor nodes and performs several critical functions:

- **Data Fusion:** It combines information from different zones to build a complete picture of the overall environment. For instance, it can determine if a problem is localized to one area or is widespread.
- **Protocol Translation:** It can standardize the data format before sending it to various destinations, such as the cloud, a local dashboard, or the control system.
- **Immediate Analysis:** It analyzes the aggregated data in near real-time. This allows it to make quick decisions, like sending an immediate alert to a local monitoring system without the delay of a round-trip to the cloud.

2.3.2.3 Central Control System & Purifiers

Based on the analysis performed at the gateway, control commands are sent to a dedicated Central Control System (CCS). This system's sole focus is on managing the physical hardware. It contains the decision logic to interpret the commands from the gateway and operate the Primary and Secondary Purification Units. Figure 11 depicts the schematic of the CCS for the Design Approach 2.

This separation is efficient: the gateway handles complex data management and aggregation, while the control system focuses purely on the time-critical task of actuation.

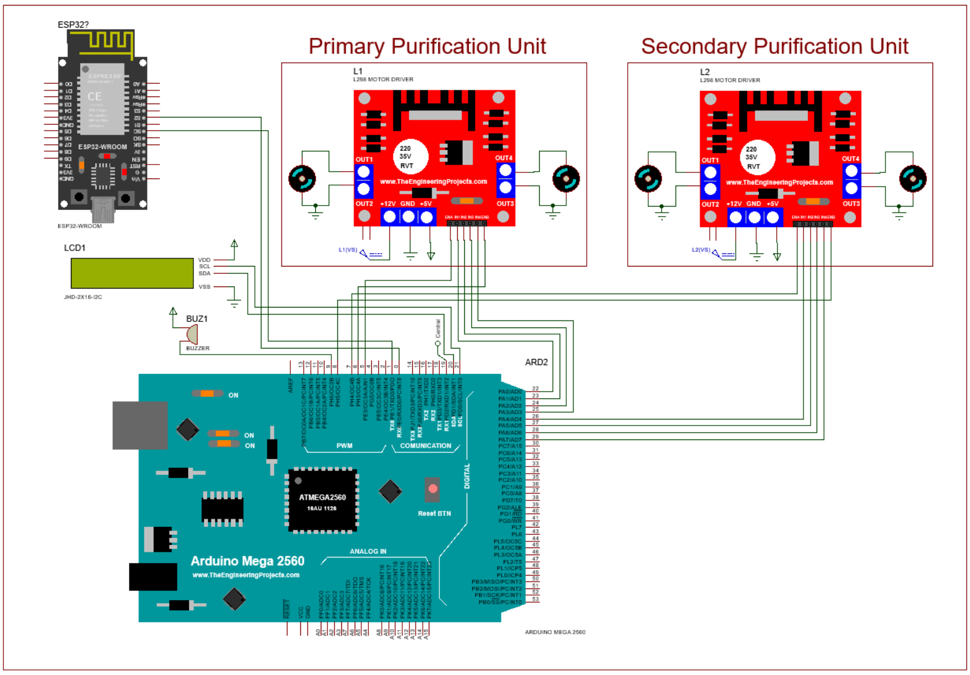

Figure 11: Schematics of the Central Control System (CCS) of Approach 2

2.3.2.4 Monitoring & Cloud Platforms

Figure 12: Blynk Interface for Design Approach 2

The Data Aggregation Gateway also routes information to two other key destinations:

- **Monitoring System:** This system receives data for real-time visualization on dashboards. It's the primary interface for human operators to observe the facility's status and receive immediate alerts generated by the gateway.

- **Cloud Platform:** This is used for long-term data storage. The gateway sends historical data to the cloud for later analysis, pattern recognition, and record-keeping. Importantly, in this fog model, the cloud is not directly involved in the immediate control loop, which improves the system's speed and reliability.

Figure 12 shows the IoT monitoring dashboard of Design Approach 2 projected via Blynk.

2.3.3 Design Approach 3: SmartChain Modular Edge-Based Purification

This design approach uses a modular, edge-based architecture where each sensor node is a fully autonomous "smart" unit. It moves the decision-making and control actions away from a central hub directly to the edge of the network, creating a highly responsive and decentralized system.

Figure 13 shows the implemented system within the Proteus 8.21 Professional environment, and Figure 14 illustrates the block diagram depicting the entire system flow for Design Approach 2.

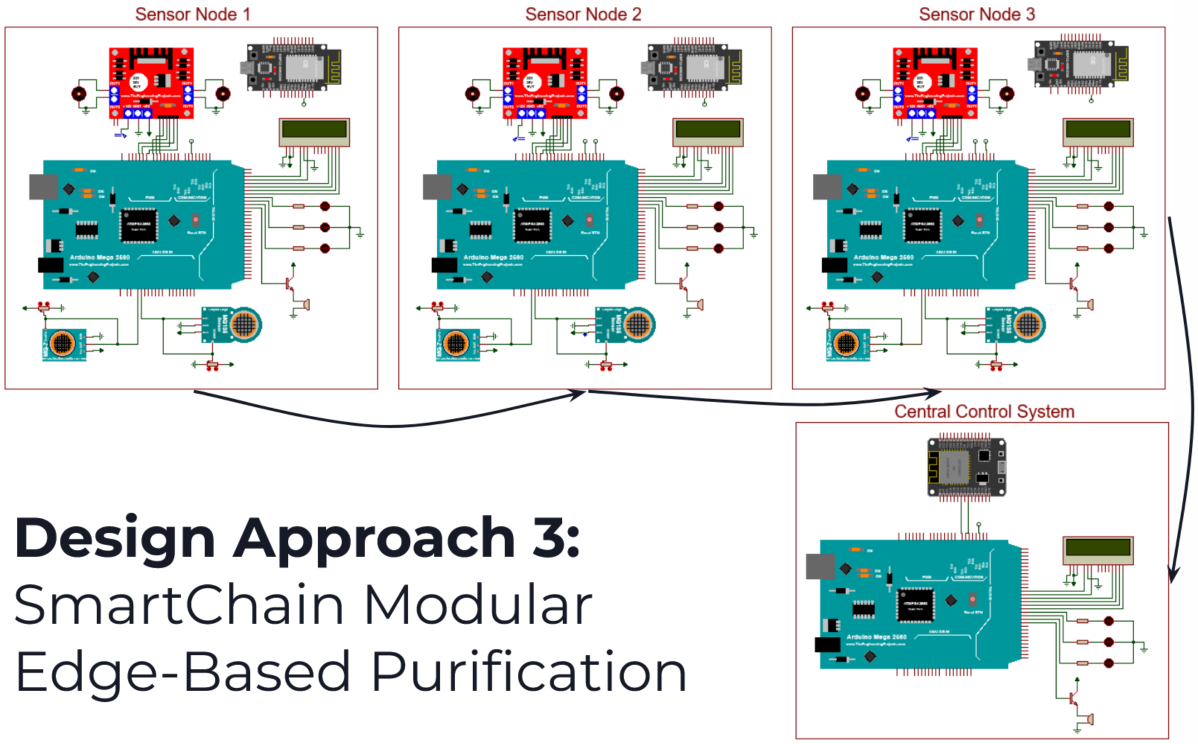

Figure 13: Circuit Implementation of Approach 3: SmartChain Modular Edge-Based Purification

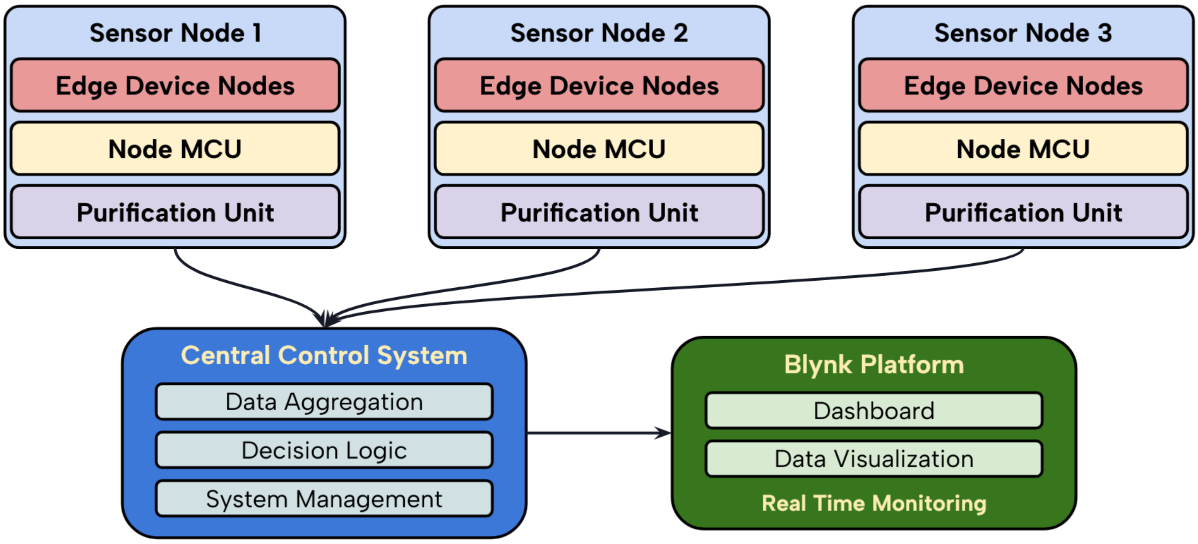

Figure 14: Block Diagram of Approach 3: SmartChain Modular Edge-Based Purification

2.3.3.1 Autonomous Edge Nodes

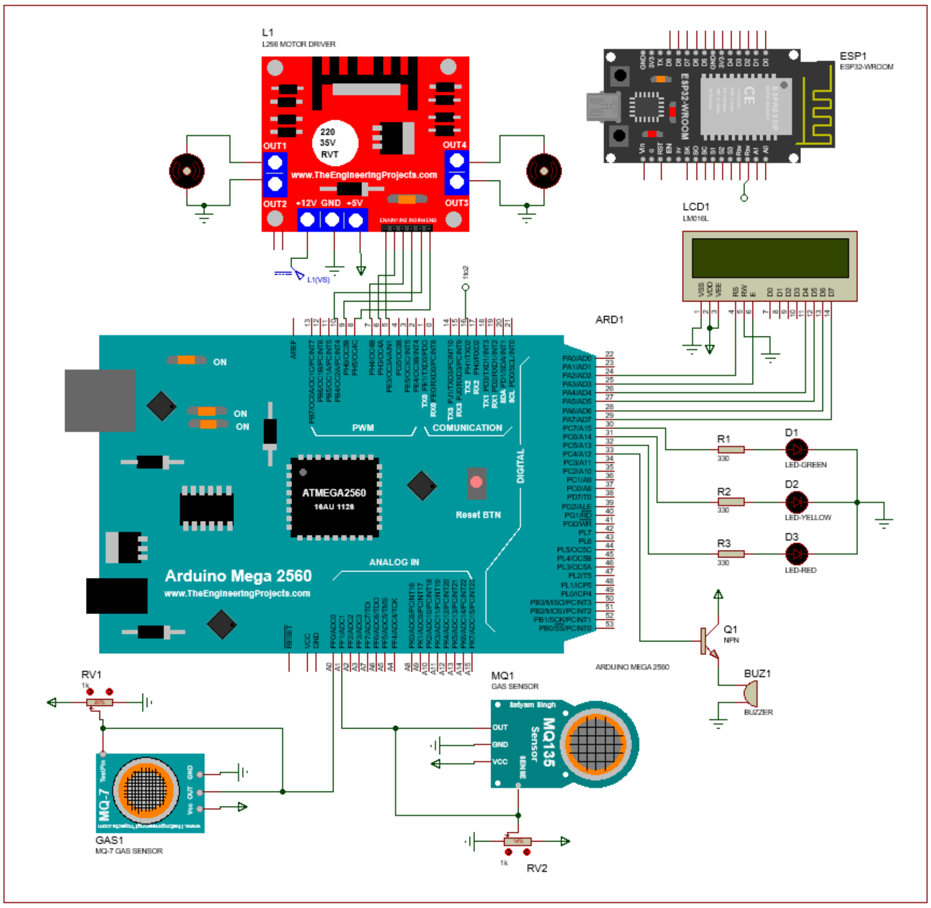

Figure 15: Schematics of Sensor Nodes (Edge) of Approach 3

The core of this design is the set of autonomous edge nodes. Figure 15 depicts the schematics of this concept. Unlike previous approaches, where nodes were just for sensing, these are complete, self-sufficient systems. Each modular node contains:

- A microcontroller (MCU) for processing.
- A suite of sensors to monitor the local environment.
- An integrated purification unit for direct, local action.
- A communication module to report its status.

The key concept here is edge computing. Each node independently analyzes its own sensor data and, using its own internal logic, decides when to activate its purification unit. This means there's virtually zero delay between detecting an issue and taking action, as the node doesn't need to ask a central system for permission. This makes the system extremely fast and reliable; even if the central system goes offline, each node can continue to perform its primary function.

2.3.3.2 Central Control System (Supervisory Role)

In this architecture, the Central Control System evolves from a commander into a manager, the architecture of which is presented in Figure 16. It doesn't issue moment-to-moment commands to the purifiers. Instead, its role is supervisory:

- **Data Aggregation:** It listens for status updates and performance data from all the independent edge nodes.

- **System Management:** It provides a single point of oversight to monitor the health and operational status of the entire distributed network.

- **High-Level Decision Logic:** It can execute overarching strategies, such as adjusting the sensitivity thresholds on all nodes or coordinating a system-wide response if multiple nodes report issues simultaneously.

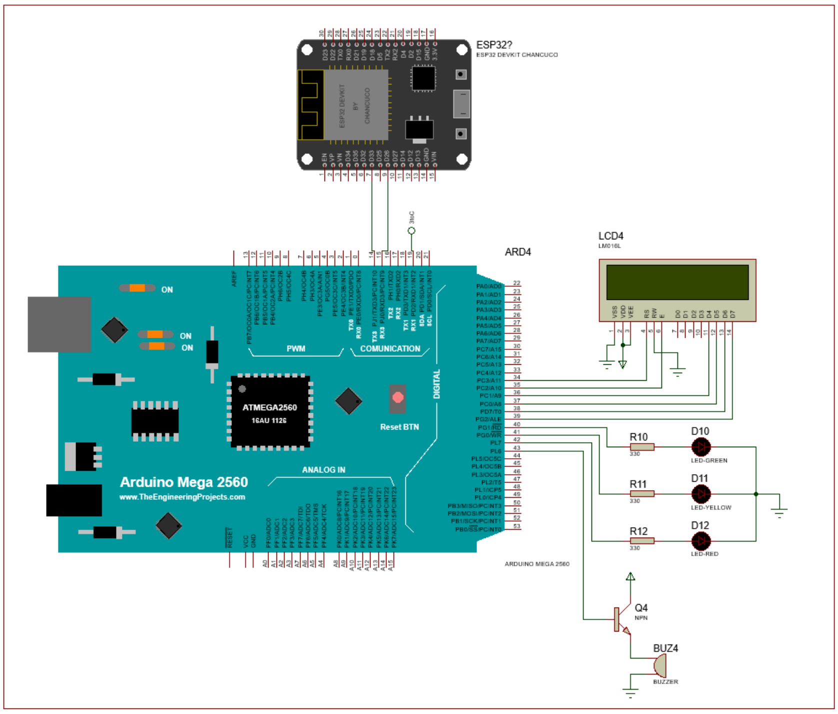

Figure 16: Schematics of the Central Control System (CCS) of Approach 3

2.3.3.3 Cloud Platform for Monitoring

The supervisory Central Control System forwards the aggregated data it collects to the Blynk Platform. This allows users to get a high-level overview of the entire system from a remote location. The cloud dashboard can display the status of each individual node, visualize historical data trends, and provide a comprehensive real-time view of the environment being managed. The critical control actions, however, remain at the edge, ensuring the system's core functionality is not dependent on internet connectivity. The Blynk-based IoT interface for the Design Approach 3 is shown in Figure 17.

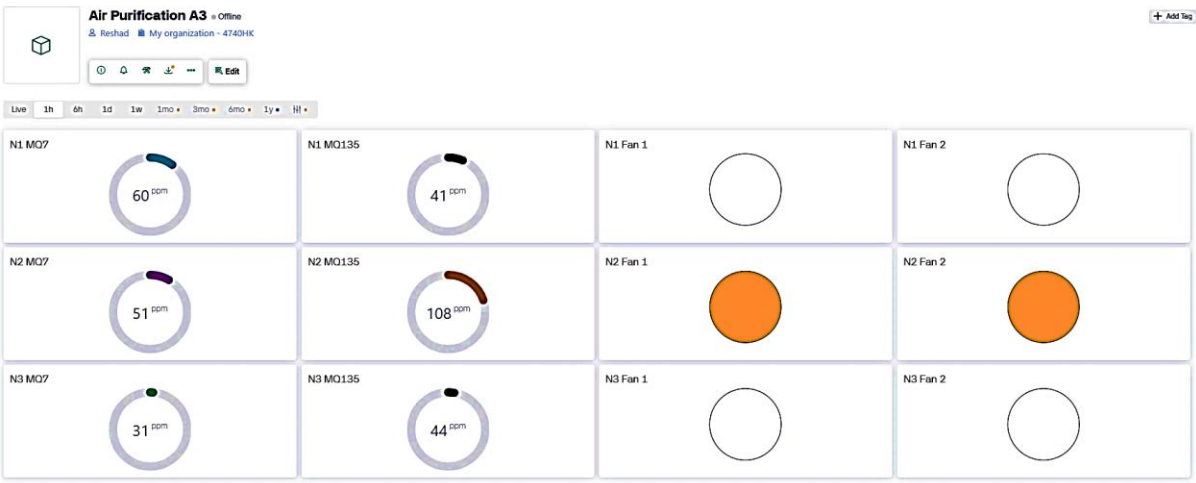

Figure 17: Blynk Interface for Design Approach 3

2.4 Functional Verification of Multiple Designs

In this chapter, we will verify if all the functionalities of our design approaches are working as intended. We'll try to represent the entire working principle of our designs. The MQ-7 and MQ-135 sensors measure the amount of Carbon Monoxide (CO) and Methane (NH_3) content in the air. The acceptable ranges for these two gases are:

- MQ-7 (CO) < 45 ppm
- MQ-135 (NH_3) < 50 ppm

All three design approaches follow these two thresholds.

2.4.1 Verification of Approach 1

For Design Approach 1: Mesh-based Wireless Sensor Network (WSN) with a Centralized Control System, both purification units will be activated if even one sensor node detects a value exceeding the acceptable range for any of the gases. The Red/Yellow LEDs in the central control system will be ON based on the pollution levels. The Green LED will light up if the level of the gases is in an acceptable range. Here are the pollution levels and the condition of the LEDs, Buzzer, and LCD.

- **Red LED ON:** $CO/NH_3 > 100$ ppm; Buzzer: ON (LCD: Pollution: High)
- **Yellow LED ON:** 100 ppm > CO > 45 ppm; 100 ppm > NH_3 > 50 ppm; Buzzer: ON (LCD: Pollution: Moderate)
- **Green LED ON:** CO < 45 ppm; NH_3 < 50 ppm; Buzzer: ON (LCD: Fresh Air :))

Figures 18 – 20 show these stages in the simulated environment, and Figures 21 – 22 show the Blynk interface update during the various stages.

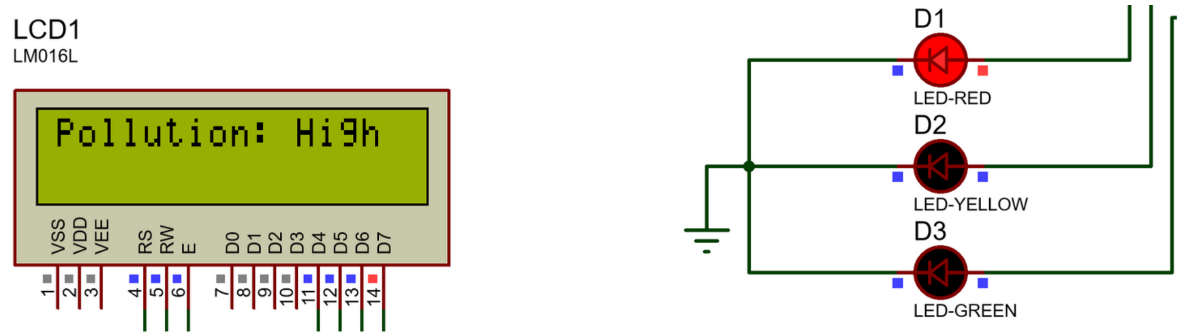

Figure 18: LCD and LED Condition at High Pollution ($CO/NH_3 > 100$ ppm)

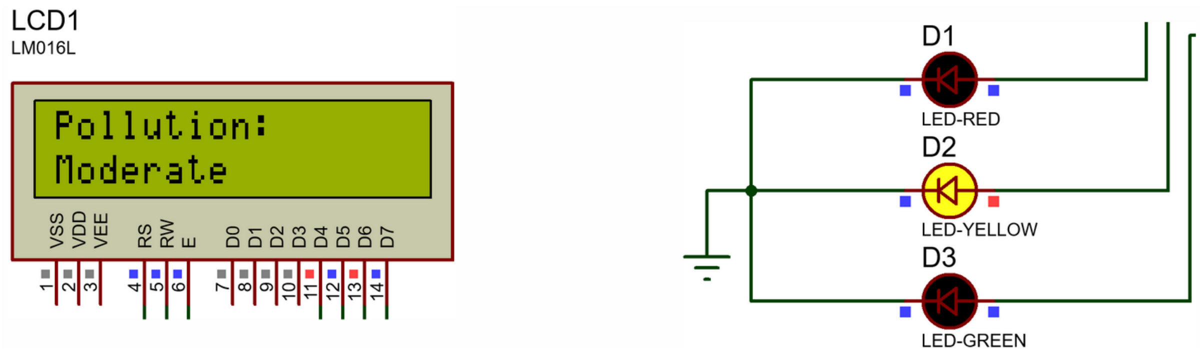

Figure 19: LCD and LED Condition at Moderate Pollution (100 ppm > CO > 45 ppm; 100 ppm > NH_3 > 50 ppm)

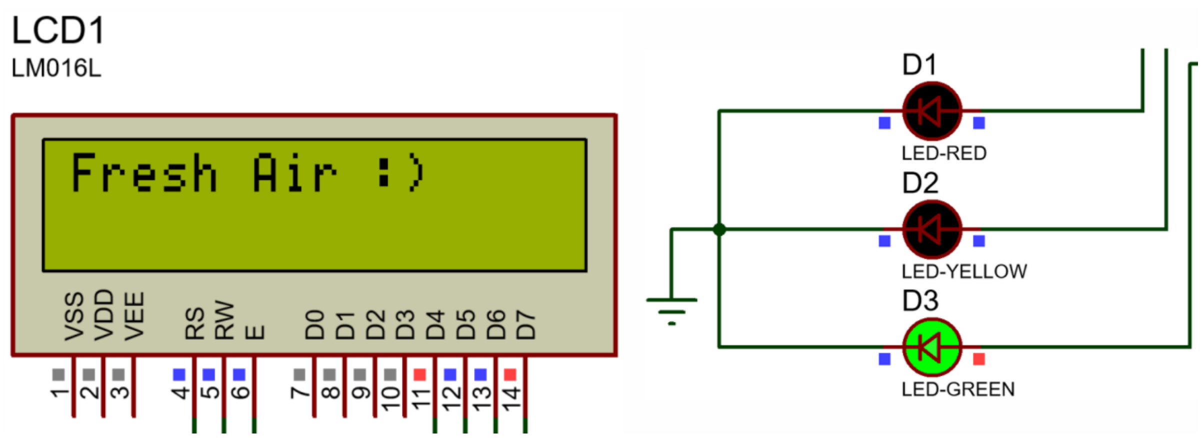

Figure 20: LCD and LED Condition During Acceptable Pollution Level (CO < 45 ppm; NH_3 < 50 ppm)

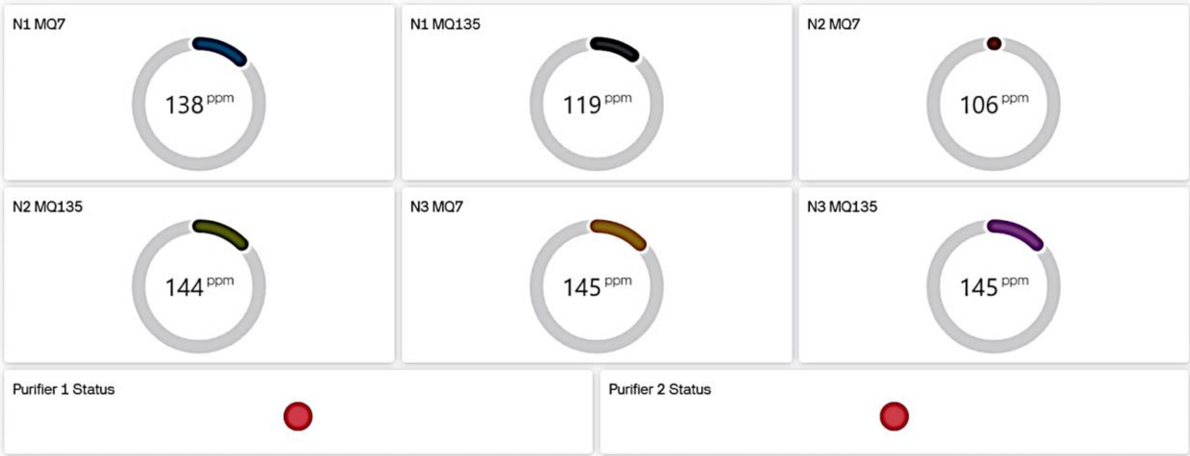

Figure 21: Purifiers are ON at High and Medium Pollution Levels (Blynk Interface)

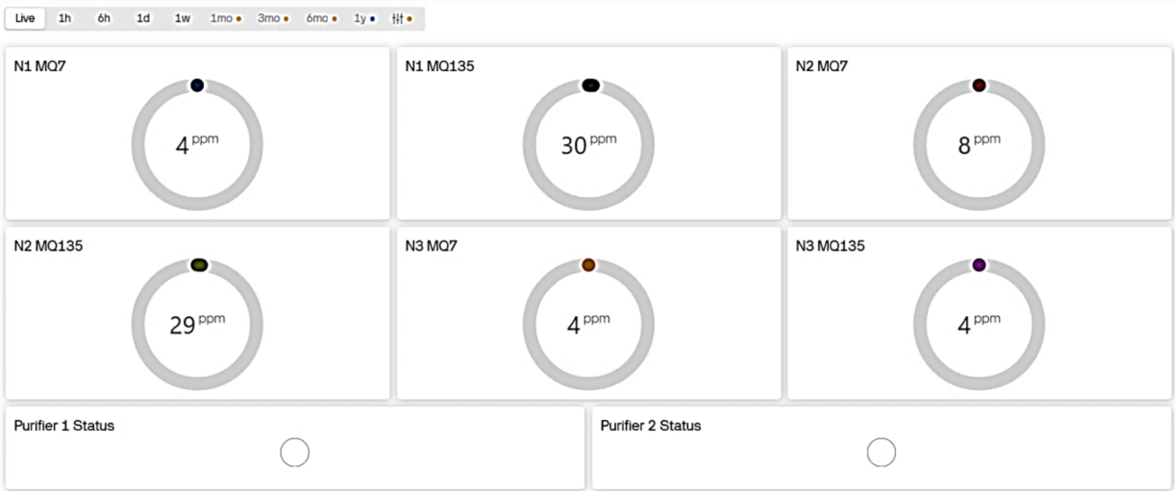

Figure 22: Purifiers are OFF During Acceptable Ranges (Blynk Interface)

Here we can see that the system is working exactly as intended. So, the design is VALID.

2.4.2 Verification of Approach 2

For Design Approach 2: Fog-Based Distributed Sensor Node with Central Purifier Control, both purification units will be activated if even one sensor node detects a value exceeding the acceptable range for any of the gases, similar to Approach 1. Here, the decision will be taken in the Data Aggregation Gateway. The I2C LCD connected to the central control system will show the amount of CO and NH_3 in the air, receiving data from the Data Aggregation Gateway.

Here are the pollution levels and the condition of the purifier in the CCS.

- **CO/NH_3 > 100 ppm:** Pollution: High – Purifier: ON
- **100 ppm > CO > 45 ppm; 100 ppm > NH_3 > 50 ppm:** Pollution: Moderate – Purifier: ON
- **CO < 45 ppm; NH_3 < 50 ppm:** Pollution: Low – Purifier: OFF

Figures 23 – 24 show the Blynk interface update during the various stages, validating the claims of the pollutant levels that were made earlier.

Figure 23: Purifiers are ON at Pollution Levels Exceeding Acceptable Range (Blynk Interface)

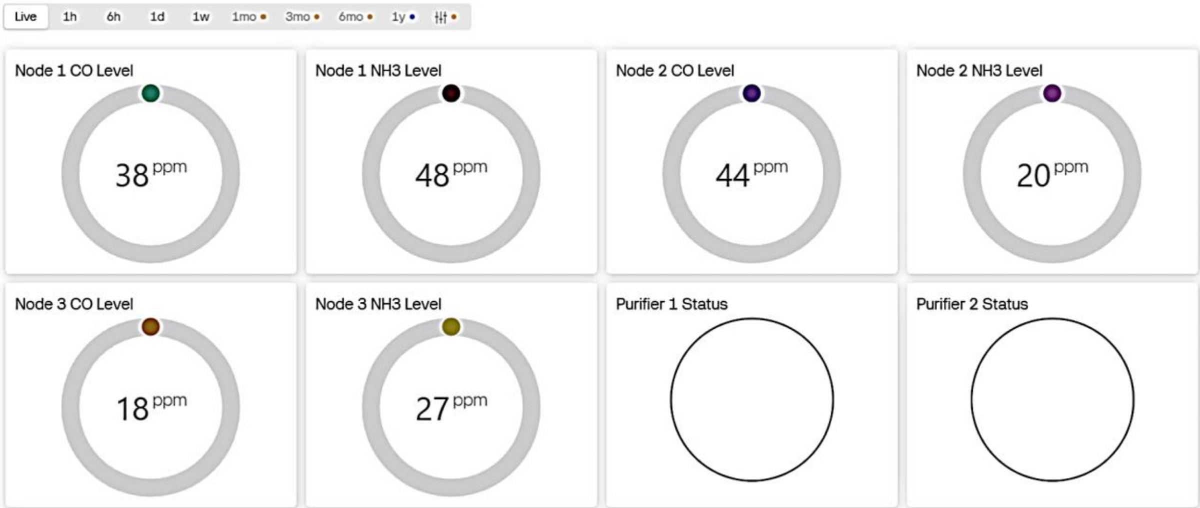

Figure 24: Purifiers are OFF During Acceptable Ranges (Blynk Interface)

Here, we can see that the system is working exactly as intended. So, the design is VALID.

2.4.3 Verification of Approach 3

For Design Approach 3: SmartChain Modular Edge-Based Purification, both purification units will be activated if the sensor node detects a value exceeding the acceptable range for any of the gases. Here, the decision will be taken at the edge (by the node itself). The Red/Yellow LEDs in each node will be ON based on the pollution levels. The Green LED will light up if the level of the gases is in an acceptable range. Here are the pollution levels and the condition of the LEDs, Buzzer, and LCD.

- **Red LED ON:** CO/NH_3 > 100 ppm; Buzzer: ON (LCD: Pollution: High)
- **Yellow LED ON:** 100 ppm > CO > 45 ppm; 100 ppm > NH_3 > 50 ppm; Buzzer: ON (LCD: Pollution: Moderate)
- **Green LED ON:** CO < 45 ppm; NH_3 < 50 ppm; Buzzer: ON (LCD: Fresh Air :))

Figures 25 – 27 show these stages in the simulated environment, and Figures 28 – 29 show the Blynk interface update during the various stages.

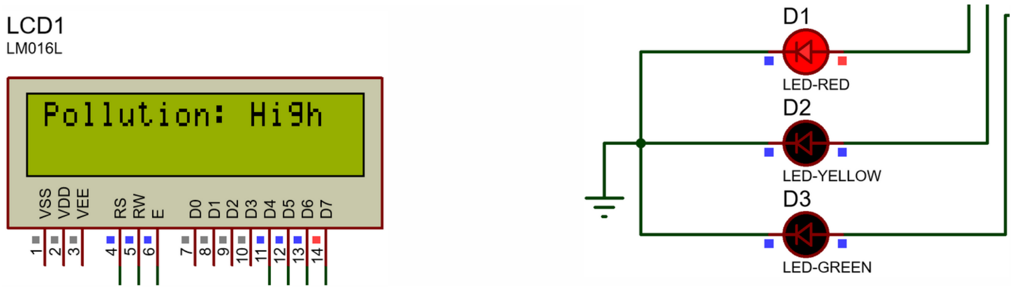

Figure 25: LCD and LED Condition at High Pollution (CO/NH_3 > 100 ppm)

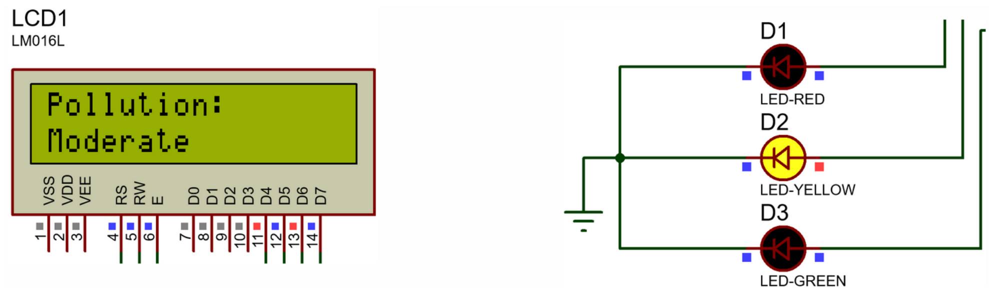

Figure 26: LCD and LED Condition at Moderate Pollution (100 ppm > CO > 45 ppm; 100 ppm > NH_3 > 50 ppm)

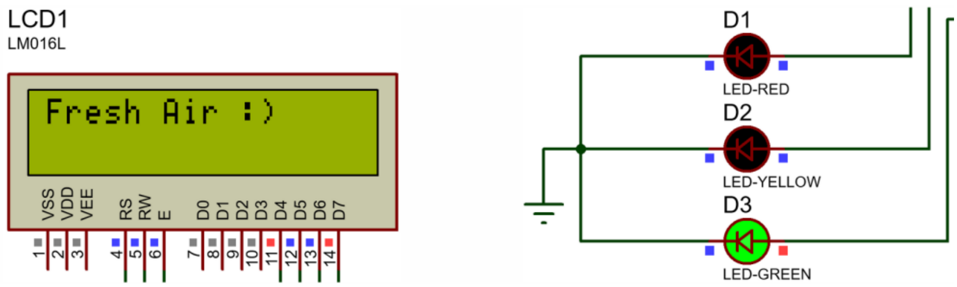

Figure 27: LCD and LED Condition During Acceptable Pollution Level (CO < 45 ppm; NH_3 < 50 ppm)

Figure 28: Purification Units on All the Sensor Nodes are ON

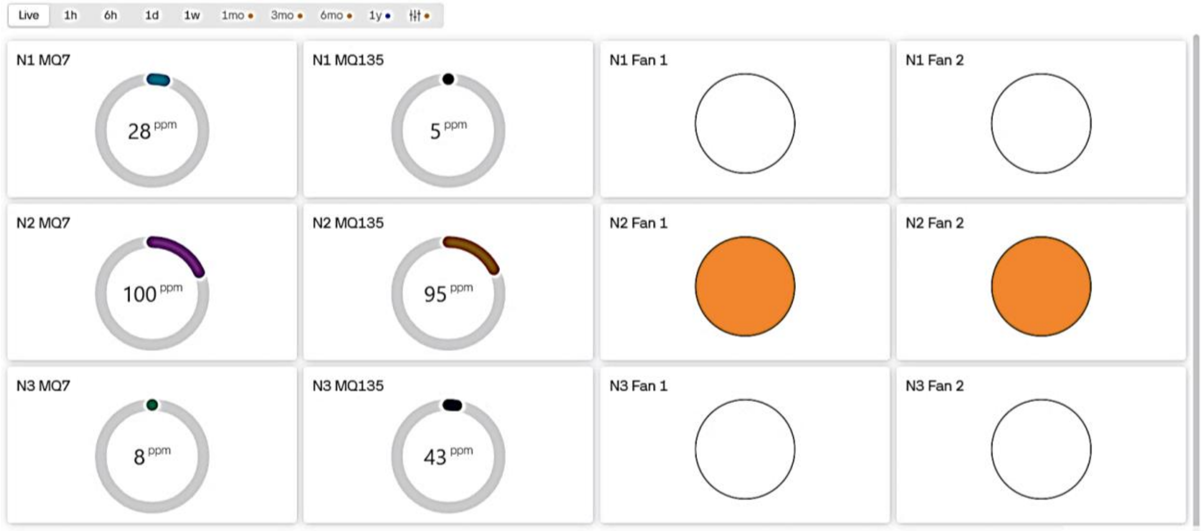

Figure 29: Purification Units on Sensor Nodes 1 & 3 are OFF, and Sensor Node 3 is ON for Varying Pollution Levels

Here, we can see that the system is working exactly as intended. So, the design is VALID.

2.5 Conclusion

The description of the three design approaches reveals a fundamental trade-off between centralization of intelligence and distribution of hardware resources. Each architecture embodies a distinct philosophy for solving the core problem:

Approach 1 (Cloud-Centric Mesh) prioritizes network resilience and data centralization, achieving robustness in data collection but at the cost of operational dependency on external cloud infrastructure. It is an architecture designed for environments with excellent, stable connectivity where advanced cloud analytics are a primary requirement.

Approach 2 (Fog-Based Star) prioritizes operational autonomy and balanced efficiency. By situating intelligence in a local fog layer, it achieves critical independence from internet volatility while maintaining a single, cost-effective point of actuation. This architecture is expressly designed for environments where reliability, cost, and local control are paramount.

Approach 3 (Edge-Based Autonomous) prioritizes maximum speed and fault tolerance through hardware redundancy. It achieves unparalleled local response and system survivability by distributing complete purification capability to every node, but this comes with a significant multiplicative effect on cost, power, and physical maintenance.

This comprehensive description has successfully decomposed each approach into its constituent topology, component roles, and data flow, setting a clear and objective foundation for the subsequent analytical comparison. The architectural choices fundamentally dictate the system’s performance across the key matrices of cost, complexity, reliability, and responsiveness.

Chapter 3: Use of Modern Engineering and IT Tools

3.1 Introduction

The development of a complex, integrated system like the IoT-based air purification solution necessitates proficiency in a suite of modern engineering and information technology tools. These tools span the entire project lifecycle—from conceptual design and simulation to programming, data analysis, and hardware fabrication. Their judicious selection and application are critical for validating designs before physical implementation, ensuring code reliability, analyzing performance data, and transitioning from a virtual prototype to a manufacturable product. This chapter addresses Course Outcome CO9 (Use modern engineering and IT tools) by detailing the rationale for selecting specific tools, describing their application within the project, and demonstrating how they contributed to an efficient, iterative, and professional development process. The systematic use of these tools minimized risks, optimized the design, and validated the solution against its specifications.

3.2 Selection of Appropriate Engineering and IT Tools

The selection of tools was guided by a clear set of criteria aligned with the project's phases and specific technical requirements. The primary goal was to create a seamless workflow from concept to reality.

Tools were chosen based on their ability to address specific project needs: accurate circuit simulation, flexible software development, powerful data analysis, reliable embedded programming, cloud-enabled monitoring, and professional-grade hardware design. Compatibility and integration between tools were also key considerations to ensure a cohesive development environment.

Criteria for Tool Selection:

- **Fidelity and Relevance:** The tool must accurately model or interact with the real-world components used in the project (e.g., ESP32, specific sensors, motor drivers).
- **Development Efficiency:** The tool should streamline its specific task, whether through libraries (Arduino IDE), pre-built cloud services (Blynk), or advanced debugging features (VS Code).
- **Analytical Capability:** For data analysis and visualization, the tool must handle time-series data and generate publication-quality graphs for performance validation.
- **Professional Output:** For the final hardware, the tool must enable the design of reliable, manufacturable printed circuit boards (PCBs) that meet industry standards.
- **Accessibility and Cost:** Preference was given to tools with robust community support, educational access, or open-source elements to align with the project's budget.

Based on these criteria, a tailored toolchain was assembled:

- Proteus 8 Professional for electronic circuit simulation and virtual prototyping.
- Visual Studio Code for IoT communication emulation and advanced code editing.
- MATLAB R2025a for data analysis, visualization, and performance modeling.
- Arduino IDE for embedded firmware development and deployment.
- Blynk IoT Platform for cloud dashboard creation and remote monitoring.
- Altium Designer for professional schematic capture and PCB layout.

This curated set provided comprehensive coverage of all engineering activities required for the project's successful execution.

3.3 Use of Modern Engineering and IT Tools

3.3.1 Proteus 8 Professional: Virtual Prototyping and Circuit Simulation

Before committing to physical components, all three proposed design architectures from Chapter 2 were modeled and simulated in Proteus 8 Professional. This allowed for functional verification of the control logic, sensor interfacing, and actuator responses in a risk-free virtual environment.

The simulation involved creating accurate schematics using libraries for microcontrollers (Arduino, ESP32), sensors (MQ-series, PMS5003), and actuators (L298N driver, DC motors). The mixed-mode simulator enabled real-time debugging, allowing observation of digital logic states and sensor outputs as simulated pollution conditions changed. This process validated the core interaction between components—for example, confirming that a simulated high CO reading would correctly trigger the activation of the purification fan via the control logic. Early design flaws, such as incorrect pin assignments, were identified and corrected in this virtual stage, preventing costly errors during physical assembly.

Proteus served as the indispensable first validation gate, transforming conceptual block diagrams into testable electronic schematics. It ensured the fundamental hardware logic of each design was sound before any soldering began, embodying the principle of "simulate first, build once."

3.3.2 Visual Studio Code & Python: IoT Communication Pipeline Emulation

To decouple and test the data communication and cloud integration logic independent of the physical hardware, a custom software emulator was developed using Python within the Visual Studio Code (VS Code) environment.

A Python script was written to mimic the behavior of ESP32-based sensor nodes, generating realistic, time-stamped sensor data packets. This emulator formatted and transmitted data to the Blynk cloud platform using the planned communication protocols (MQTT/HTTP), validating the data structure and API endpoints. VS Code's integrated debugging tools and terminal allowed for step-by-step execution and inspection of the data flow, isolating potential communication issues from hardware or firmware problems.

This approach enabled parallel development. While hardware was being prototyped, the cloud integration and data handling logic were perfected in a controlled software environment, significantly accelerating the overall system integration phase.

3.3.3 MATLAB R2025a: Data Analysis and Performance Visualization

Following lab and field tests, the collected time-series data on pollutant concentrations and system states required rigorous analysis. MATLAB was employed for this high-level analytical task to substantiate performance claims.

MATLAB was used to generate all key performance graphs for reporting, including pollutant reduction trends over multi-day tests, comparative bar charts of filtration efficiency, and time-series plots of system response. Its computational toolboxes enabled statistical analysis—calculating average improvement percentages, standard deviations, and performing regression to model relationships, such as purification rate versus initial pollution load.

MATLAB transformed raw sensor data into compelling, evidence-based visualizations and insights. Its analytical rigor was crucial to professionally communicate results and validate that the system met its specifications, such as achieving a 96.59% reduction in PM2.5.

3.3.4 Arduino IDE: Embedded Firmware Development and Deployment

The Arduino Integrated Development Environment (IDE) was the primary tool for writing, compiling, and uploading the firmware that brought the physical hardware to life.

The IDE streamlined development through its library manager, facilitating the inclusion of essential libraries for WiFi connectivity (WiFi.h), Blynk integration (BlynkSimpleEsp32.h), and sensor drivers (e.g., for PMS5003, SGP30). Its built-in Serial Monitor and Serial Plotter were used extensively for real-time debugging, allowing the team to view raw sensor values and program flow statements during calibration and testing. The straightforward workflow enabled direct compilation and flashing of code onto the target microcontrollers (ESP32 and Arduino Mega).

As the workhorse for embedded software development, the Arduino IDE's simplicity and direct hardware integration were crucial. It enabled rapid iteration on control algorithms and communication protocols directly on the target hardware.

3.3.5 Blynk IoT Platform: Cloud Dashboard and Remote Monitoring

The Blynk platform was selected to rapidly create a professional, mobile-accessible user interface without developing a custom web server and front-end from scratch.

Using a drag-and-drop interface, a custom dashboard was configured with widgets such as real-time gauges for PM2.5, value displays for CO levels, historical graphs for trends, and buttons for manual system override. Data from the ESP32 firmware was pushed to these widgets in real-time via the Blynk.virtualWrite() function. The platform's notification system was also configured to send email or app alerts when pollutant levels exceeded thresholds, and it provided built-in cloud storage for historical data.

Blynk dramatically reduced the development time and complexity associated with creating a remote monitoring solution. It allowed the team to focus on core hardware and algorithm development while still delivering a polished, functional user interface for system oversight.

3.3.6 Altium Designer: Professional PCB Design and Layout

To transition from a breadboard prototype to a robust, deployable system, custom Printed Circuit Boards (PCBs) were designed for the sensor nodes and central control unit using Altium Designer.

The finalized circuits were captured in professional schematics, and components were optimally placed on board outlines. Careful routing of copper traces ensured signal integrity, particularly for analog sensor lines. Altium's Design Rule Checking (DRC) feature verified the design met all manufacturing constraints before fabrication. The integrated 3D viewer allowed for virtual inspection of the assembled board to check for component fit within the designed enclosures.

Altium Designer enabled the professionalization of the hardware. It ensured the final physical implementation was a reliable, manufacturable, and maintainable electronic product suitable for industrial deployment, moving the project beyond a prototype.

3.4 Conclusion

The strategic selection and proficient use of this modern engineering toolchain were instrumental in the project's success. Proteus provided a safe sandbox for design validation. VS Code enabled robust software testing. MATLAB delivered deep analytical insights. The Arduino IDE facilitated efficient embedded programming. Blynk accelerated cloud integration, and Altium Designer ensured professional hardware realization. This integrated toolset allowed for an iterative, evidence-based development process where designs were simulated, algorithms tested, data analyzed, and hardware refined in a controlled manner. By leveraging these tools effectively, the project not only achieved its technical objectives but also demonstrated a high level of engineering professionalism and preparedness for real-world implementation, fully satisfying the demands of CO9.

Chapter 4: Optimization of Multiple Designs and Finding the Optimal Solution

4.1 Introduction

Following the detailed description and functional verification of three distinct design architectures, the critical engineering task was to determine the single best approach for implementation. This phase moves beyond qualitative description to a rigorous, quantitative optimization and selection process. This chapter addresses Course Outcomes CO5, CO6, and CO7 by detailing the methodology used to optimize the parameters of each design, evaluate their performance against a comprehensive set of matrices, and ultimately identify the optimal solution. The process involved analytical calculations, simulation-based validation, and a weighted comparative analysis to ensure the selected design not only functions but also optimally meets the project's core objectives of cost-effectiveness, efficiency, reliability, and scalability within the defined constraints.

4.2 Optimization of Multiple Design Approach

Prior to final comparison, each design approach required internal optimization of its key operational parameters to ensure it was evaluated at its best possible performance.

Optimization focused on parameters that directly impacted system efficacy, energy use, and cost. These included filtration chamber design, fan selection and control, sensor network configuration, and power management. Analytical calculations and component validation formed the basis of this optimization.

Filtration System Optimization (Common to All Designs): The purification core was optimized independently. Calculations validated the use of two **Arctic P12 Max** fans in parallel. For a target room volume of 40.5 m^3 (15 m^2 area, 2.7 m height) and a desired Air Change per Hour (ACH) rate of 6, the required airflow was 243 m^3/h. The dual-fan setup provided 275.38 m^3/h at a static pressure of 85.3 Pa, exceeding the calculated system pressure drop of ~12.5 Pa, ensuring sufficient and efficient airflow. Furthermore, PWM validation confirmed that operating the fans at 90% duty cycle (247.84 m^3/h) met the airflow requirement within a 10% tolerance, enabling a 10% energy saving compared to continuous 100% operation without sacrificing performance.

Network and Topology Optimization:

- **For Approach 1 (Mesh):** Optimization involved calculating the maximum reliable node-to-node distance. Using the free-space path loss model for the ESP32's 2.4 GHz radio (20 dBm TX power, -95 dBm sensitivity), the maximum theoretical range was determined to be approximately 31.6 meters in an open environment, informing deployment density.
- **For Approach 2 (Fog/Star):** Optimization centered on minimizing latency and power. The star topology inherently simplified this. The response time was optimized by ensuring the fog gateway's control loop was event-driven, executing decisions immediately upon receiving sensor data without waiting for cloud acknowledgment.

- **For Approach 3 (Edge):** The optimization challenge was balancing the performance of the mini-purifier in each node with cost. The per-node airflow and filter size were scaled down, which optimized for localized response but inherently increased the cost per unit area covered compared to a central, larger unit.

Through these calculations and validations, each design was tuned to its most efficient operating point. This ensured the subsequent comparative analysis was fair, evaluating each architecture based on its best achievable performance rather than a suboptimal configuration.

4.3 Performance Evaluation of Developed Solution

For each of the design approaches, we have set 10 performance matrices based on which we will decide the best design approach.

The performance matrices are as follows:

Hardware Cost: The total investment required for sensors, controllers, actuators, communication modules, and purifiers. Projects in industrial pollution control must be cost-effective to encourage adoption, especially for small and medium industries in Bangladesh. If the system is too expensive, industries may resist implementation despite technical advantages. Balancing performance with affordability ensures scalability and real-world viability. The costing will be described in detail in the Budget section.

Implementation Complexity: The level of difficulty in assembling, programming, and deploying the system (wiring, network setup, firmware, cloud/fog/edge integration). High complexity increases the risk of errors during deployment, maintenance, and upgrades. In a developing industrial setting, a design with low-to-moderate complexity is more practical, since operators may not have advanced technical expertise.

Scalability: The system's ability to expand (adding more sensor nodes or extending coverage) without redesigning the core architecture. Industrial environments evolve. Factories may expand, production lines may change, and pollutant levels may vary seasonally. A scalable design ensures the system remains relevant and cost-efficient as industries grow, instead of requiring replacement.

Reliability: The likelihood that the system consistently functions without failure (sensor accuracy, connectivity, and actuation stability). Pollution control cannot afford frequent breakdowns. If a purifier or sensor fails, workers and nearby communities face health risks. High reliability guarantees continuous protection and builds trust in automated systems.

Connection (Topology): The communication structure (mesh, star, hybrid) connecting sensors, controllers, and purifiers. Topology affects network robustness and cost. For instance:

- Mesh = high resilience, higher complexity, higher power draw.
- Star = simpler, but one central node failure can halt operations.

Choosing the right topology ensures both stability and maintainability in polluted industrial zones.

Decision Making (Cloud, Fog, Edge): The point where system decisions (when to activate purifiers, fan speeds, alarms) are made.

- Cloud = centralized but slower, reliant on stable internet.
- Fog = near-source processing with moderate latency.
- Edge = local, fastest, but costlier per node.

The choice directly affects response time, reliability, and data security, critical for real-time pollution control.

Area Covered (m^2/min): The rate at which purified air can cover an area, calculated from airflow (m^3/min) and room height. In pollution-heavy zones, coverage determines how effectively pollutants are removed per unit time. A system with higher coverage is ideal for large workshops or kiln areas, while smaller coverage may suffice for compact spaces.

Response Time: The delay between pollution detection and purifier activation. This data is taken directly from the real-time clock of Proteus 8 Professional. In industrial sites, pollutants (like CO, SO_2, particulate matter) can rise sharply in minutes. A system with a fast response time minimizes worker exposure and maintains compliance with safety standards. Edge-based designs generally excel here.

Power Consumption: Total electrical load of fans, sensors, controllers, and communication units during operation. Industries are energy-intensive; adding monitoring systems should not significantly raise costs. Lower power consumption increases long-term sustainability and ensures adoption in energy-cost-sensitive industries. The table outlines the typical current draw and power usage for each component, assuming a 5V power supply.

TABLE III. POWER CONSUMPTION SUMMARY

Component (Voltage)	Typical Current (mA)	Estimated Power (mW)	Notes
12V DC Motor (12V)	350 mA	4200 mW	Under a light load
ESP32 (5V)	170 mA	850 mW	
16x2 LCD (5V)	162 mA	810 mW	With backlight on
MQ-135 Sensor (5V)	150 mA	750 mW	
MQ-7 Sensor (5V)	85 mA	425 mW	Average over heating cycle
Arduino Mega (5V)	62.5 mA	312.5 mW	
Arduino Uno (5V)	50 mA	250 mW	
L298N Driver Logic (5V)	36 mA	180 mW	Quiescent current for logic
Buzzer (5V)	30 mA	150 mW	When active
LED (5V)	15 mA	75 mW	
NPN BJT (5V)	< 1 mA	< 5 mW	Negligible

Table III outlines the typical current draw and power usage for each component. Note that the motor and its driver operate at 12V, while the other components are calculated at 5V.

These data are extracted from the datasheets of each of the components. The calculation in the comparison table will be done based on this table.

Data Security: Protection of sensor readings, system commands, and stored records from tampering or unauthorized access. Pollution data has regulatory and legal implications. Industries may be liable for exceeding emission limits, so strong security prevents data manipulation and ensures credibility. A high-security system also makes it easier to integrate with government monitoring frameworks.

Thus, the trade-offs across all matrices guide decision-makers toward the design that best fits the project's real-world constraints (budget, energy availability, industry size, safety standards).

4.4 Identify Optimal Design Approach

Now, let's compare each of the performance matrices for all three design approaches:

TABLE IV. COMPARISON BETWEEN THE APPROACHES

Metric	Approach 1	Approach 2	Approach 3
Hardware Cost	**25,700 BDT**	**24,850 BDT**	**27,200 BDT**
Implementation Complexity	**High**	**Low**	**Moderate**
Scalability	**High**	**Moderate**	**Moderate**
Reliability	**Moderate**	**Moderate**	**High**
Connection (Topology)	**Mesh**	**Star**	**Star**
Decision Making	**Cloud**	**Fog**	**Edge**
Area Covered	**10m^2/min**	**8.33m^2/min**	**25m^2/min**
Response Time	**6 s**	**6 s**	**3 s**
Power Consumption	**28.96 W**	**27.12 W**	**38.68 W**
Data Security	**Low**	**High**	**Moderate**

Approach 1 is a scaled cloud solution characterized by cloud-based decision-making and mesh network topology. It is moderate in its hardware price, amounting to 25,700 BDT, and the most challenging to deploy since it is highly complex. The main benefit of this method is the scalability of high performance, and it is well adapted to huge, growing deployments. This, however, comes at the cost of performance trade-offs that include a moderate reliability rating, a low response time of 6 seconds, and low data security since it uses the cloud. It consumes a middle level of power of 28.96 W, and is suitable for applications when scalability is the highest consideration and the response time can be lower.

Approach 2 is the most cost-effective and simplest approach, which explains its status as a balanced solution towards the fog. It is the simplest to install with a minimal implementation complexity because of the lowest cost of the hardware at 24, 850 BDT. Its design is a star topology with a fog computing that handles the data nearer to the source than the cloud hence its data security is on a high level. Although it has average performance in regards to scalability and reliability, it is the most energy efficient; it has the lowest power consumption of 27.12 W. This is the best option when dealing with projects whose primary consideration depends on budget, implementation ease, and security of the data.

High-performance edge solution- Approach 3 is developed with speed and reliability. It uses edge computing in a star topology to calculate data on the immediate machine to make very quick decisions. This makes it have the following key strengths: the shortest response time of only 3 seconds, high reliability, and the largest area covered of 25m^2/min. This high performance is costly, as not only does it have the highest hardware cost (27,200 BDT), but also the highest power consumption (38.68 W). It works best with a moderate rating of complexity and security where the need is to be fast in responding and reliable, and where the budget is higher because time critical application is a necessity.

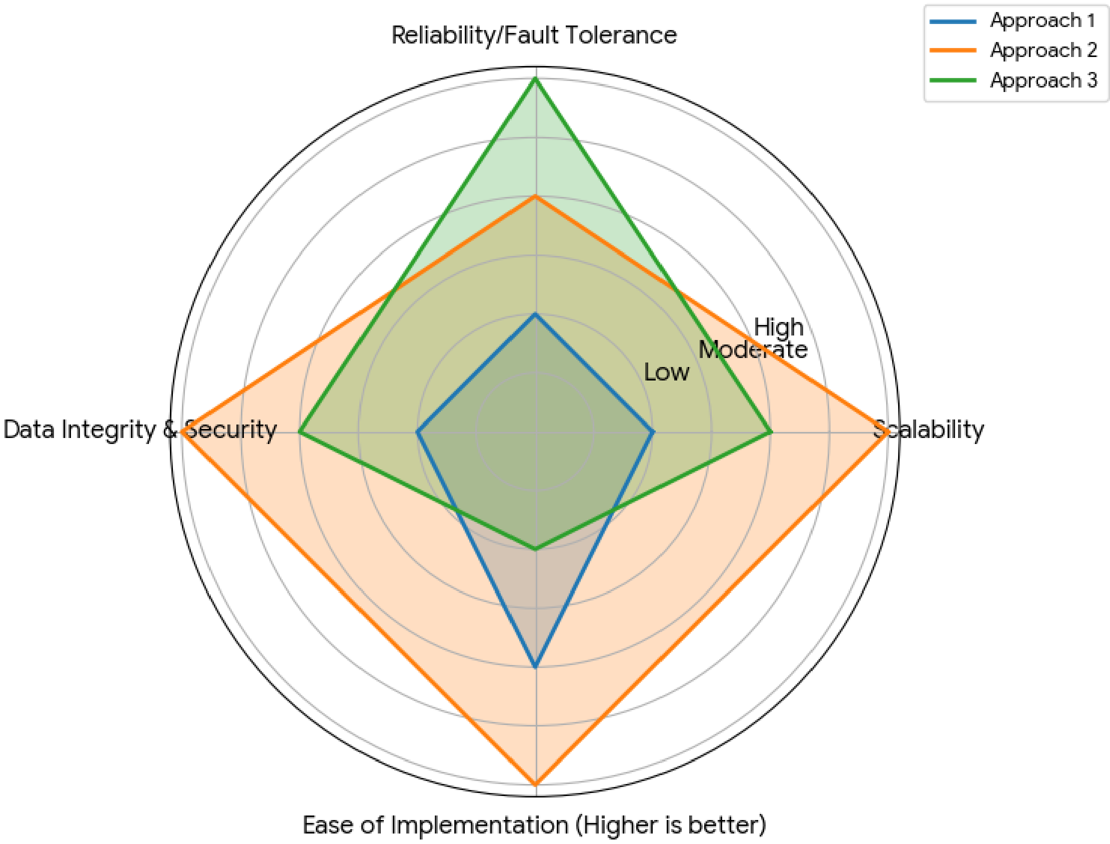

Figure 30: Qualitative Performance Profile

This radar chart compares the performance of three different approaches across four key criteria. The criteria are Reliability/Fault Tolerance, Scalability, Ease of Implementation, and Data Integrity & Security, with performance levels ranging from low to high. Approach 3 (green) excels in reliability and security, whereas Approach 2 (orange) is superior in scalability and ease of implementation. Approach 1 (blue) is consistently the lowest-performing option across all metrics. The chart visually highlights the trade-offs, indicating that no single approach is the best in all aspects. Analyzing this chart, we can clearly see that approach 2 is overall superior to the other two approaches.

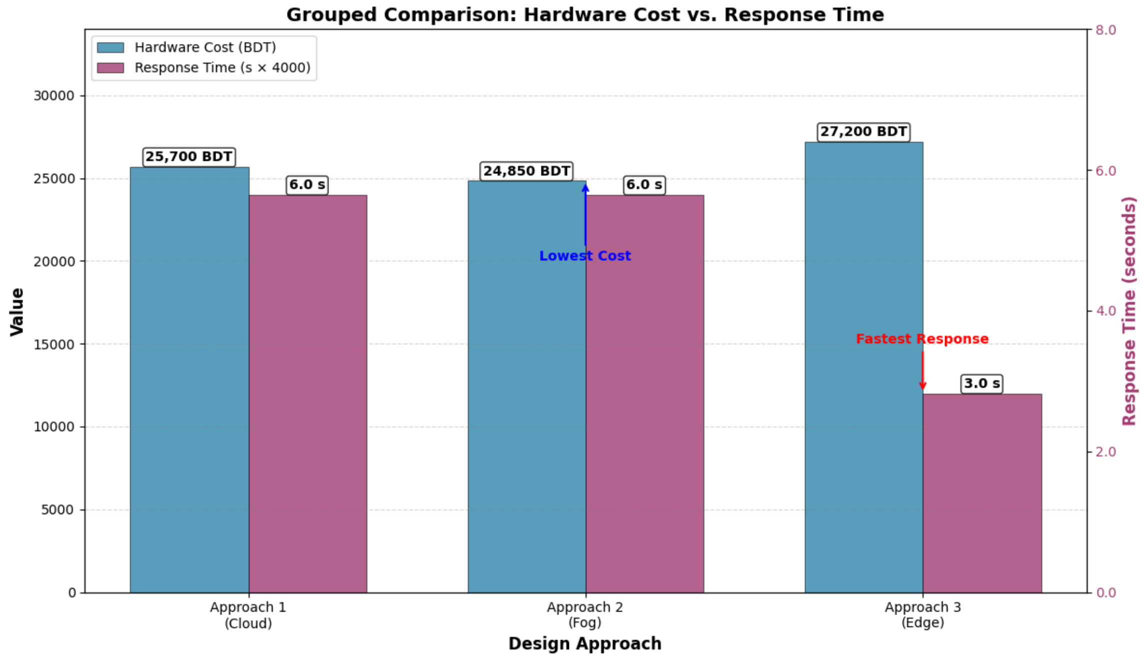

Figure 31: Cost Effectiveness vs. Response Time

This grouped bar chart compares three different design approaches—Cloud, Fog, and Edge—on the basis of hardware cost and response time. The blue bars represent the hardware cost in Bangladeshi Taka (BDT), while the purple bars indicate the response time in seconds. Approach 2 (Fog) is highlighted as the most economical option with the lowest cost of 24,850 BDT. In contrast, Approach 3 (Edge) provides the fastest performance with a response time of just 3.0 seconds, but it is also the most expensive. The chart demonstrates a clear trade-off between system cost and performance speed. Overall, approach 2 has a very good cost and response balance.

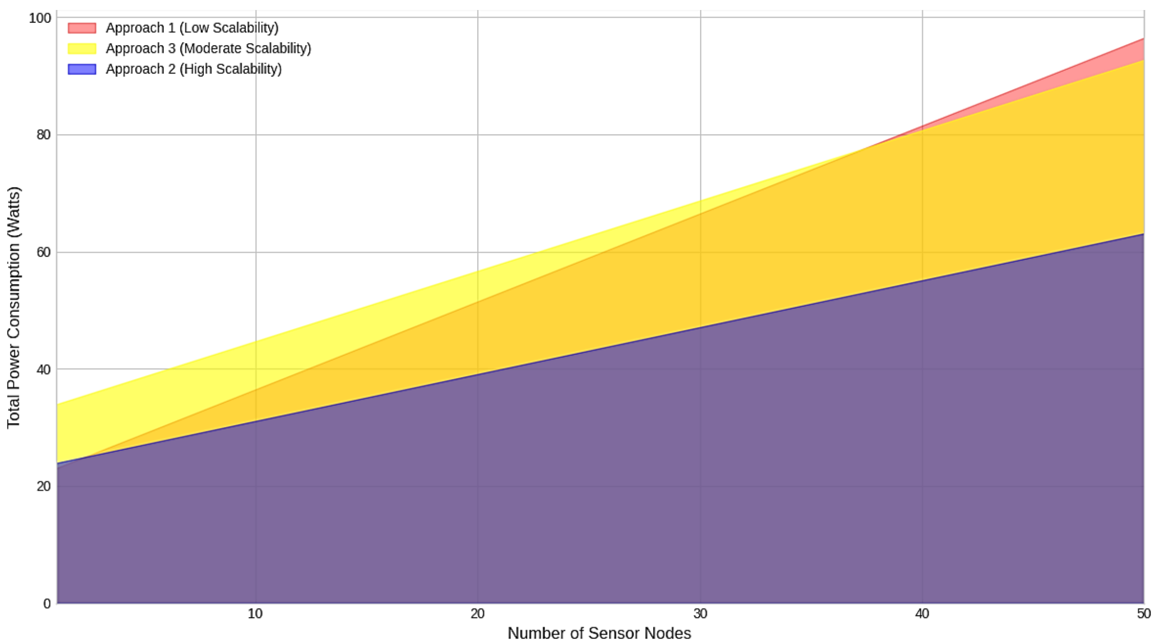

Figure 32: System Power Consumption vs. Number of Sensor Nodes

The stacked area chart below shows the total power consumption (in Watts) as the number of sensor nodes in a system increases. The total power is broken down by three different approaches, each with a different level of scalability. As more sensor nodes are added, the power consumption for all approaches combined increases in a linear fashion. Approach 2 (blue), labeled as having high scalability, contributes the most to the overall power consumption. This graph highlights a clear trade-off, indicating that the most scalable approach is also the most power-intensive.

So, after all these discussions, we can successfully conclude that approach 2 is overall the best design approach among these three.

4.5 Extraction Best Features for Hardware Implementation

Subchapter 4.4 establishes that design approach 2 is the most effective technique altogether. However, Table IV shows that this system's coverage area is still a major problem. The system should be as cost-effective as possible because small and medium-sized businesses are the target market. Therefore, the coverage area will inevitably expand if we switch from a fog-based system to a mesh-based system.

Therefore, we will use the Data Aggregation Gateway and Mesh connections within the sensor nodes throughout the hardware integration. As a result, this will also immediately increase the scalability of the system.

So, the hardware-implemented system will have:

- Multiple Sensor Nodes
- Data Aggregation Gateway (DAG)
- Mesh Connection Between the Sensor Nodes and DAG
- Central Control Unit
- Filtration Unit

So, based on these, the overall block diagram of the implemented system in hardware should be like:

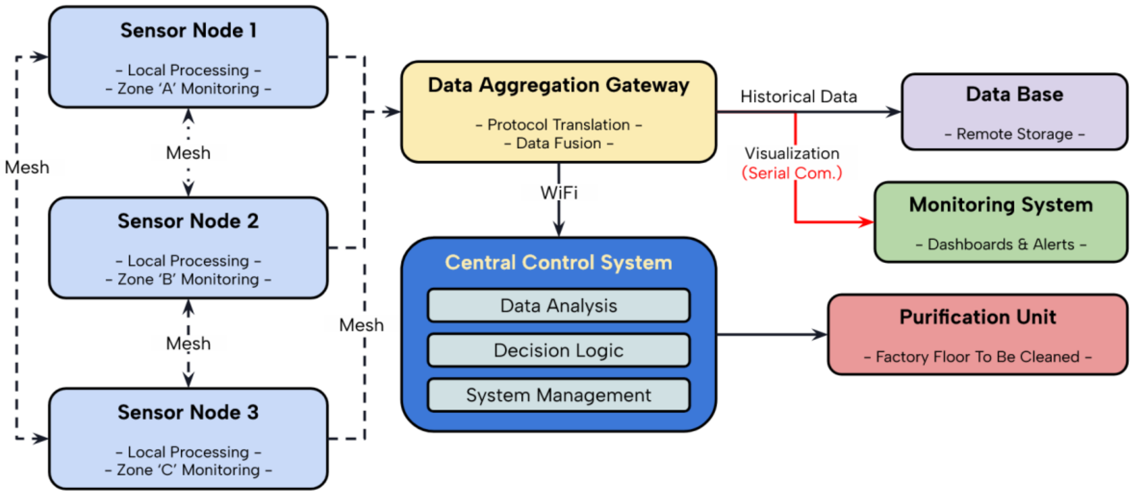

Figure 33: Conceptual Block Diagram of the Hardware of the Proposed System

4.6 Conclusion

Chapter 4 has detailed the critical transition from multiple design concepts to a single, optimized, and validated solution. Through parameter optimization, each design was refined to its peak potential. A structured, multi-criteria decision analysis then clearly identified the Fog-Based Design (Approach 2) as the optimal choice, balancing all key project drivers. But before the construction and testing of a prototype based on this design, the topology of this system should be changed to Mesh from Star in order to increase the coverage area and improve scalability. This comprehensive process of optimization, selection, and evaluation ensures that the final implemented system is both theoretically sound and empirically validated, providing a robust foundation for its impact and sustainability analysis.

Chapter 5: Completion of Final Design and Validation

5.1 Introduction

Following the rigorous selection of the optimal design approach, the project entered its most critical phase: the completion of the final design and its comprehensive validation. This phase transforms the chosen conceptual architecture into a fully functional, integrated hardware-software system. It involves detailed engineering of subsystems, procurement and assembly of components, development and integration of firmware and software, and systematic testing to ensure the final product meets all predefined objectives, specifications, and requirements. This chapter addresses Course Outcome CO8 (Complete the final design and development of the solution) by documenting the implementation journey, the system integration process, and the multi-faceted validation strategy that confirms the solution's readiness to address the identified complex engineering problem.

5.2 Completion of the Final Design

A "Mesh-Based Distributed Air Quality Sensing with Central Two-Stage Purification" system has been built into the hardware based on the simulation findings and performance studies. The system has been divided into five subsystems.

- Sensor Nodes
- Data Aggregation Gateway
- IoT-Based Custom-Built Monitoring Unit
- Central Control Unit
- Purification Unit

The complete block diagram of the implemented system is shown in Figure 34.

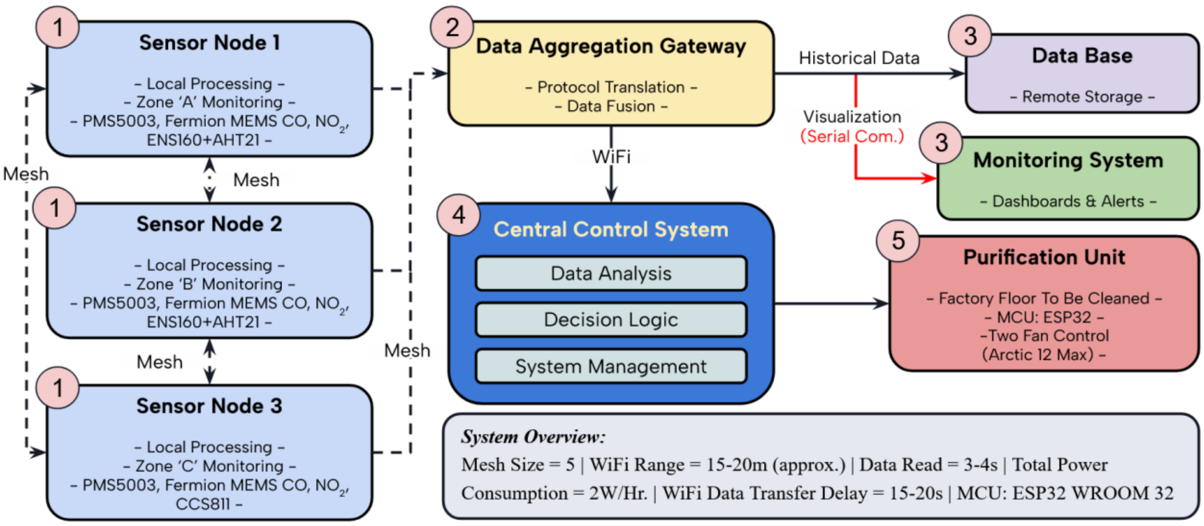

Figure 34: Block Diagram of the Implemented System

The system operates by acquiring pollutant concentration data from multiple sensors deployed across various industrial zones. Each sensor node integrates a PMS5003 particulate matter sensor, ENS160 paired with AHT21 or CCS811 for gas and environmental sensing, along with Fermion MEMS-based CO and NO_2 sensors. These sensor nodes are interconnected through a WiFi-based mesh network, enabling seamless peer-to-peer data exchange.

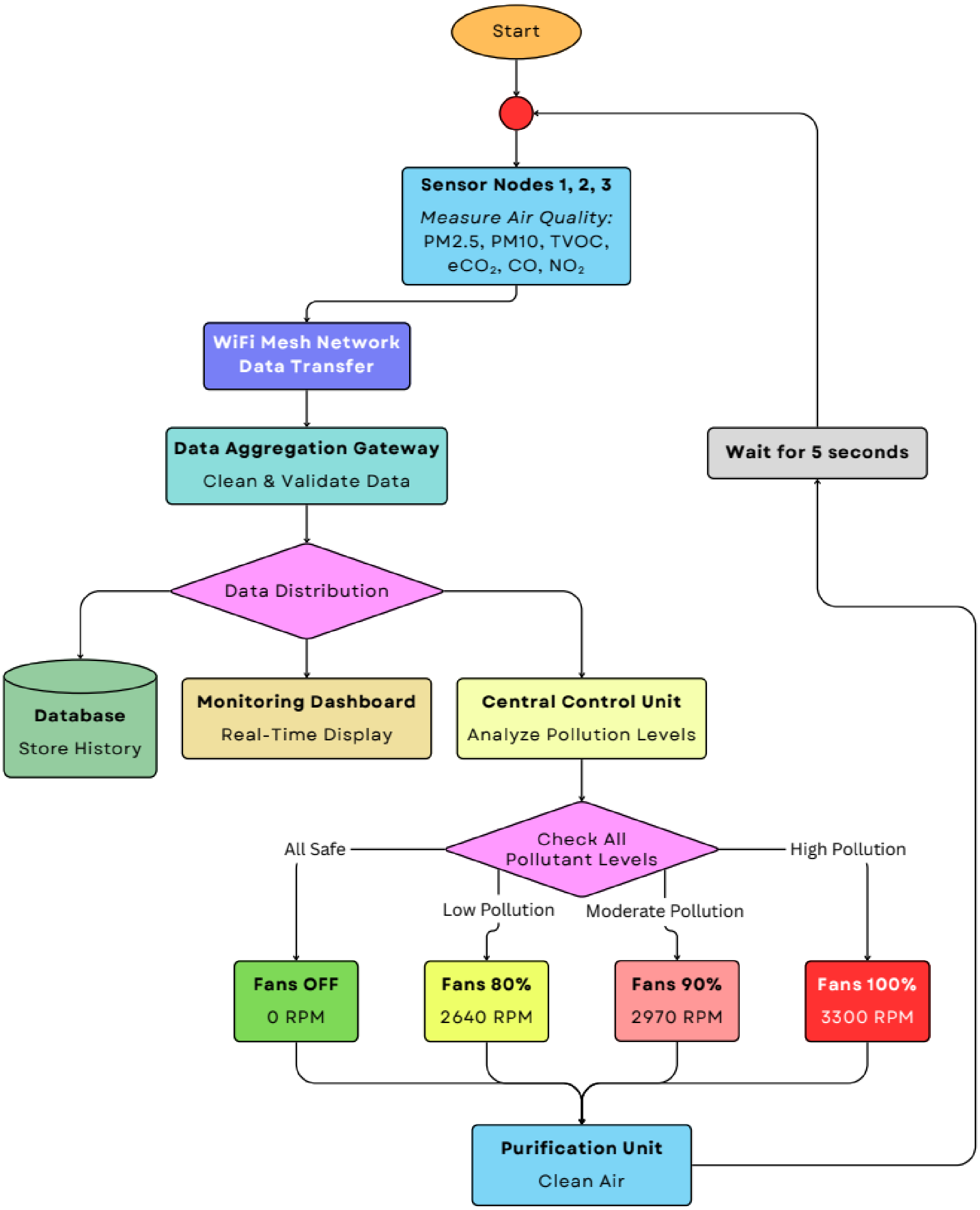

Figure 35: Workflow Diagram of the Entire Proposed System

Through the mesh network, each sensor node transmits its collected data to the Data Aggregation Gateway. The gateway consolidates data from all connected nodes and performs preprocessing tasks, including the removal of noise, invalid readings, and irrelevant or corrupted data. Once validated, the processed data are stored in the system database and simultaneously forwarded to a custom-built monitoring dashboard application for real-time visualization and analysis.

Because the Data Aggregation Gateway maintains aggregated data from all sensor nodes, it enables centralized and comprehensive monitoring across the entire deployment area. In parallel, the gateway forwards the processed data to the Central Control Unit. Based on predefined pollutant concentration ranges, the Central Control Unit autonomously determines system status and activates the air purification unit as required.

The ranges of the pollutants are in Table V.

TABLE V. LEVELS FOR VARIOUS POLLUTANTS

Pollutant/Range	Safe	Low	Medium	High	Hazardous
PM2.5 (µg/m³)	0 – 12	>12 – 35	>35 – 55	>55 – 150	>150
PM10 (µg/m³)	0 – 50	>50 – 100	>100 – 150	>150 – 250	>250
TVOC (ppb)	0 – 220	>220 – 660	>660 – 2200	>2200 – 5500	>5500
eCO_2 (ppm)	0 – 800	>800 – 1000	>1000 – 1500	>1500 – 2000	>2000
CO (ppm)	0 – 9	>9 – 25	>25 – 50	>50 – 100	>100
NO_2 (ppb)	0 – 53	>53 – 100	>100 – 200	>200 – 400	>400

When pollutant concentrations exceed the defined high threshold, both fans in the purification unit operate at their rated maximum speed of 3300 rpm to ensure rapid and effective pollutant removal. Under medium pollution conditions, the fan speed is reduced to 90% of the rated value, corresponding to 2970 rpm, providing a balance between cleaning efficiency and power consumption. At low pollution levels, the fans operate at 80% speed (2640 rpm), which is sufficient to maintain acceptable air quality while minimizing energy usage. When pollutant concentrations fall within the safe range, the purification unit remains inactive, and the fans are turned off.

This tiered fan-speed control strategy enables efficient air purification while optimizing energy consumption, forming the basis of the system's overall operational logic. Figure 35 shows a workflow diagram of the entire system.

5.2.1 Sensor Node Implementation

From the survey presented in Chapter 1, it was identified that the primary pollutants posing significant risks to human health in industrial environments include particulate matter (PM2.5 and PM10), total volatile organic compounds (TVOC), carbon dioxide (CO_2), carbon monoxide (CO), and nitrogen dioxide (NO_2). Accordingly, these pollutants were selected for continuous monitoring in the proposed system to enable timely detection, assessment of exposure levels, and effective mitigation of air quality–related health risks within industrial workplaces.

Industrial environments are often characterized by elevated temperature, humidity, and highly variable operating conditions, which can adversely affect sensor reliability and measurement accuracy. Therefore, sensors capable of stable operation under such harsh conditions, with higher tolerance to temperature and humidity variations, were deliberately chosen. The pollutants monitored in the system, along with their corresponding sensors and operating tolerance ranges, are summarized in Table VI, ensuring reliable long-term performance and consistent data acquisition during continuous industrial operation.

TABLE VI. POLLUTANTS & CORRESPONDING SENSORS WITH TOLERANCE VALUES

Pollutant(s)	Sensor	Operating Temperature Range	Operating Pressure Range	Operating Humidity Range
PM2.5, PM10	PMS5003	−10 °C to 60 °C	Atmospheric (typ.)	0–99% RH (non-condensing)
CO	Fermion MEMS CO	−40 °C to 85 °C	Atmospheric (typ.)	0–95% RH (non-condensing)
NO_2	Fermion MEMS NO_2	−40 °C to 85 °C	Atmospheric (typ.)	0–95% RH (non-condensing)
TVOC, eCO_2	ENS160 + AHT21	−40 °C to 85 °C	Atmospheric (typ.)	0–100% RH (non-condensing)
TVOC, eCO_2	CCS811	−40 °C to 85 °C	Atmospheric (typ.)	0–95% RH (non-condensing)

Figure 36 shows the connection diagram of the sensor nodes, and Figure 37 shows the sensor nodes implemented in PCBs.

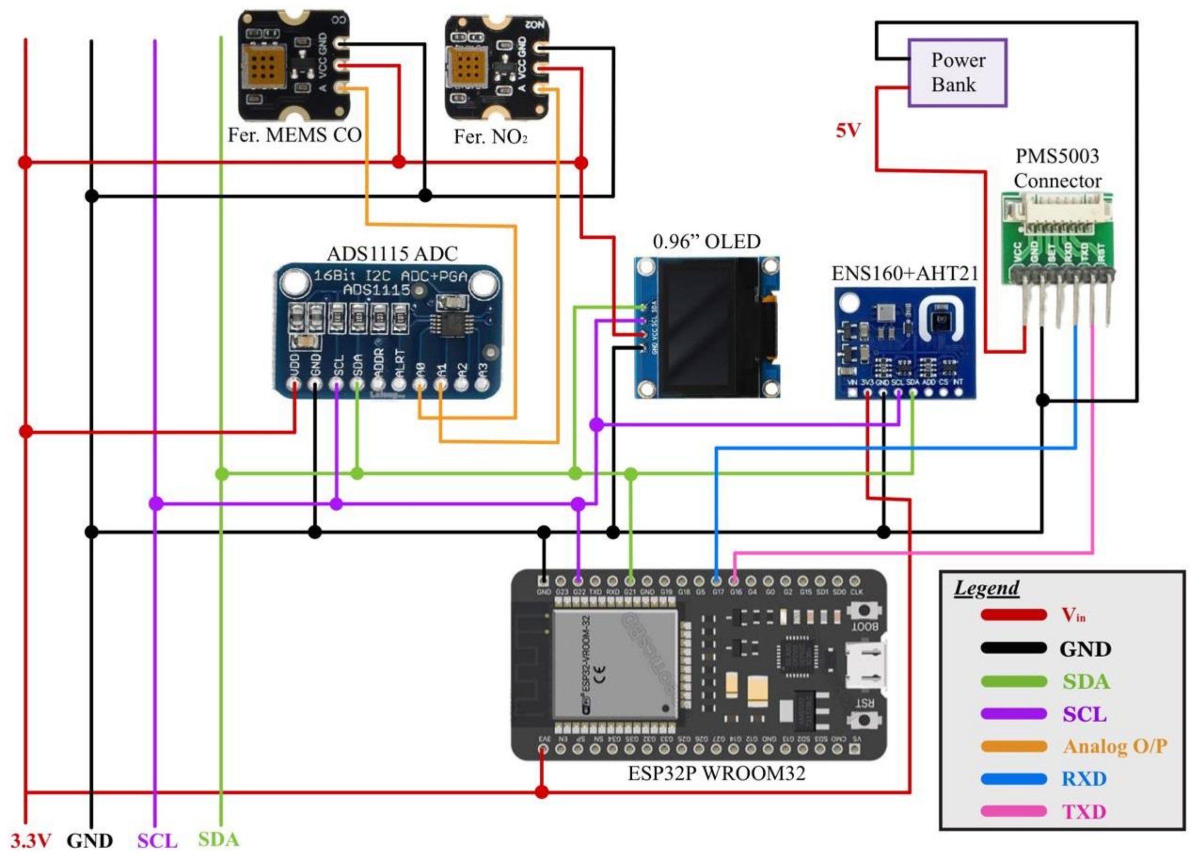

Figure 36: Connection Diagram for the Sensor Nodes

Four distinct communication protocols are employed within each sensor node to ensure reliable data acquisition, local interfacing, inter-node communication, and external debugging. These protocols include I²C, UART, WiFi, and Serial communication. Each protocol is selected based on bandwidth requirements, communication distance, device compatibility, and system scalability.

1. I²C (Inter-Integrated Circuit) Communication: I²C communication is used for interfacing low-speed peripheral devices with the ESP32 WROOM32 microcontroller within each sensor node. In the proposed system, the ADS1115 analog-to-digital converter, CCS811 gas sensor, ENS160, and AHT21 temperature–humidity sensor are all connected via the I²C bus, along with the 0.96-inch OLED display.

The I²C protocol operates using a two-wire interface, specifically the Serial Data Line (SDA) and the Serial Clock Line (SCL), enabling multiple devices to communicate with a single master device. This shared-bus architecture significantly reduces wiring complexity and enables multiple peripherals to coexist on the same communication lines using unique device addresses. I²C is particularly suitable for sensors and display modules that require moderate data rates and frequent polling. Its low power consumption and robust addressing mechanism make it an ideal choice for compact and energy-efficient sensor nodes.

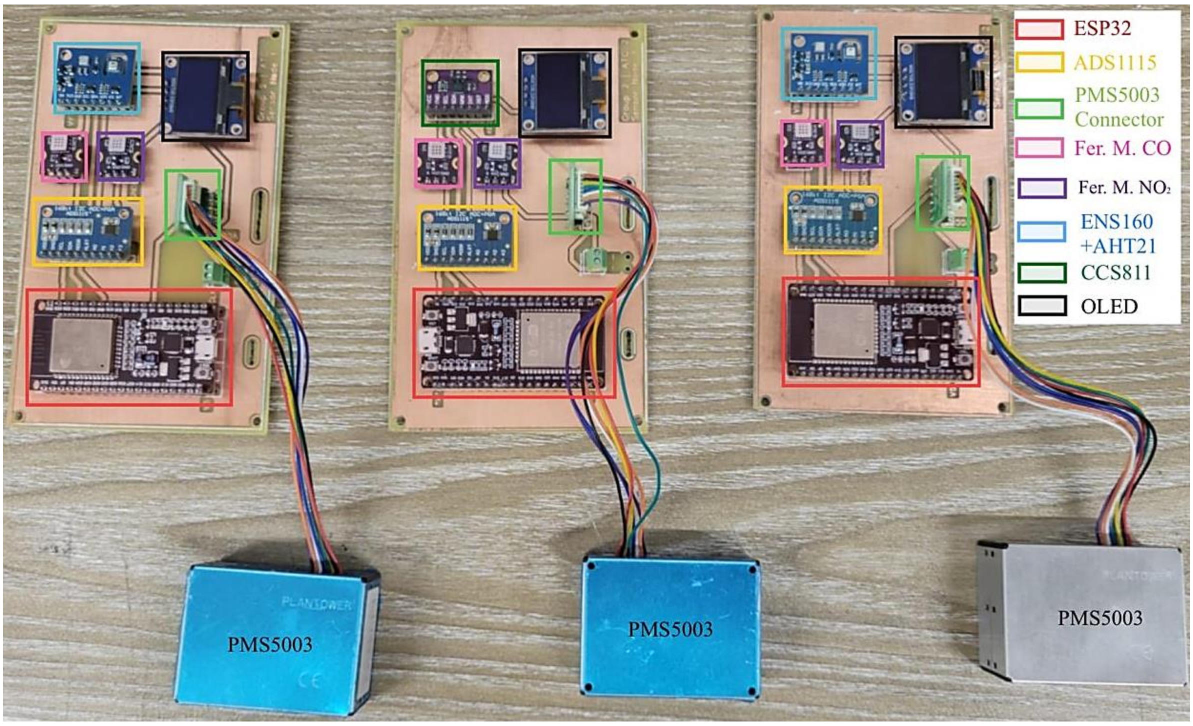

Figure 37: PCB Implementation of the Sensor Nodes

2. UART (Universal Asynchronous Receiver–Transmitter) Communication: UART communication is utilized for interfacing the PMS5003 particulate matter sensor with the ESP32 WROOM32 microcontroller. The PMS5003 transmits high-resolution PM2.5 and PM10 data continuously over a dedicated serial channel, which necessitates a reliable point-to-point communication protocol.

UART operates using separate transmit (TX) and receive (RX) lines without a shared clock, relying instead on predefined baud rates for synchronization. This protocol is well-suited for sensors like the PMS5003 that generate relatively large data frames and require uninterrupted, real-time data transmission. By using UART, the system ensures accurate and loss-free acquisition of particulate matter data without placing additional load on the shared I²C bus.

3. WiFi Communication (painlessMesh Network): WiFi communication is employed to enable wireless connectivity among sensor nodes and between the sensor nodes and the Data Aggregation Gateway. The system uses a WiFi-based mesh networking framework implemented through the painlessMesh library.

In this mesh topology, each sensor node functions as both a data source and a relay node, allowing data packets to be forwarded dynamically across the network. This decentralized architecture enhances network reliability, coverage, and scalability, particularly in large industrial environments where direct communication with a central gateway may not always be feasible. WiFi is chosen for its high data throughput, extended range, and native support in the ESP32 platform. The mesh-based approach also provides fault tolerance, as data can be rerouted through alternate paths if a node becomes unavailable.

4. Serial Communication (ESP32 to PC): Serial communication is used for direct data exchange between the ESP32 WROOM32 and a personal computer, primarily for system debugging, firmware development, calibration, and real-time monitoring during testing phases.

This communication is established via a USB-to-serial interface, allowing sensor readings, system logs, and diagnostic messages to be transmitted to the PC. Serial communication offers a simple and reliable method for observing internal system behavior, verifying sensor outputs, and troubleshooting hardware or software issues. Its widespread support and ease of implementation make it an essential tool during system development and validation.

By integrating I^2C for peripheral interfacing, UART for high-throughput sensor communication, WiFi mesh for distributed data exchange, and serial communication for debugging and system validation, the proposed system achieves a robust, scalable, and efficient communication architecture tailored for industrial air quality monitoring applications. These communication protocols are distinctly present in the other subsystems as well, where these equipments are used.

5.2.2 Sensor Calibration

After the construction of the sensor nodes, the sensors were calibrated. This calibration system implements a three-phase approach to standardize readings across multiple air quality sensor nodes operating in the same environment.

The process begins with a comprehensive warm-up phase lasting five minutes (300 seconds). During this period, all sensors are powered on and periodically queried every 10 seconds to allow them to reach thermal and chemical equilibrium. This is particularly important for gas sensors like the ENS160 and the Fermion MEMS CO/NO_2 sensors, which require time to stabilize their baseline readings. The warm-up ensures that subsequent measurements aren't affected by initial power-on transients or temperature-dependent drift.

After the warm-up, the system enters the data collection phase, where it gathers 50 samples from each sensor with a 2-second interval between readings. For the PMS5003 particulate matter sensor, the code requests readings and captures PM1.0, PM2.5, and PM10 values in micrograms per cubic meter. The ENS160 air quality sensor provides TVOC (total volatile organic compounds) in parts per billion and eCO_2 (equivalent CO_2) in parts per million. The AHT21 temperature and humidity sensor is read through direct I2C communication, triggering measurements and parsing the raw data into temperature (in Celsius) and relative humidity (as a percentage). The Fermion MEMS gas sensors for CO and NO_2 are read as analog voltages through the ADS1115 analog-to-digital converter, capturing their baseline voltage outputs.

The calibration calculations work by computing the difference between known reference values and the averaged measured values. The reference structure defines expected values for a controlled environment—for instance, zero for particulate matter in a clean room, 400 ppm for ambient CO_2, 25°C for temperature, and 50% for humidity. The system averages all collected samples to smooth out measurement noise, then calculates offsets by subtracting the measured average from each reference value. These offsets represent the correction factors needed to align each sensor node's readings with the reference baseline. For example, if a sensor reads PM2.5 as 3 μg/m³ in a clean environment where it should be 0, the offset would be -3, which can later be added to readings to correct them.

Finally, all calculated offsets are permanently stored in the ESP32's flash memory using the Preferences library. This creates persistent calibration data that survives power cycles, allowing the main operational code to load these offsets on startup and apply them to all subsequent measurements. This approach ensures that multiple sensor nodes deployed in different locations will produce comparable readings when exposed to similar air quality conditions, enabling reliable spatial monitoring and meaningful comparisons across the sensor network.

TABLE VII. ENSOR NODE VS AQI STATION DATA

Timestamp	Data From AQI Station					Data From Our Sensor Nodes				
	PM2.5 (µg/m³)	PM10 (µg/m³)	CO (ppm)	NO2 (ppb)	TVOC (ppb)	PM2.5 (µg/m³)	PM10 (µg/m³)	CO (ppm)	NO2 (ppb)	TVOC (ppb)
9:00 AM	71.77533	129.7739	1.750352	44.82849	250.7566	74.31	128.69	1.55	35.67	239.97
10:00 AM	59.18863	84.51635	1.472181	27.45497	249.3224	58.24	85.21	1.52	30.05	245.12
11:00 AM	60.72739	90.64294	0.659108	25.04089	276.9897	60.88	89.99	1.02	28.81	270.67
12:00 PM	71.87943	114.991	1.232743	38.26531	278.7341	69.19	111.29	1.11	38.45	269.57
1:00 PM	39.01413	82.33402	1.562179	41.02525	257.2221	45.55	83.33	1.32	40.22	255.41
2:00 PM	40.26613	55.54411	0.727435	31.56714	261.5632	46.97	57.92	0.94	29.59	259.08
3:00 PM	55.20262	75.13408	2.100444	26.55632	272.7783	53.62	74.38	1.98	27.98	271.01
4:00 PM	45.18253	83.30264	1.257435	24.63897	270.6257	51.39	82.09	1.28	27.66	270.55
5:00 PM	61.29011	114.3909	1.353721	29.08208	533.2113	60.91	112.37	1.43	28.89	578.93
6:00 PM	38.87964	18.52921	1.413936	21.67136	298.8879	39.72	89.73	1.29	24.41	303.45
7:00 PM	27.23904	42.11455	1.287939	27.37865	322.6093	28.45	67.98	1.19	26.98	313.36

Following sensor calibration, the accuracy of the calibrated measurements was validated through field testing. For this purpose, the sensor nodes were deployed in close proximity to a reference AQI monitoring station located at Grace International School, Gulshan-1. Both the sensor node readings and the corresponding AQI station data were recorded continuously over an 11-hour period.

The collected datasets were then compared to evaluate measurement consistency and accuracy, thereby validating the effectiveness of the calibration process. The results of this validation are presented in Table VII. The graphs in Figure 38 show that the calibration of each of the pollutants are valid as the average error is less than 10%.

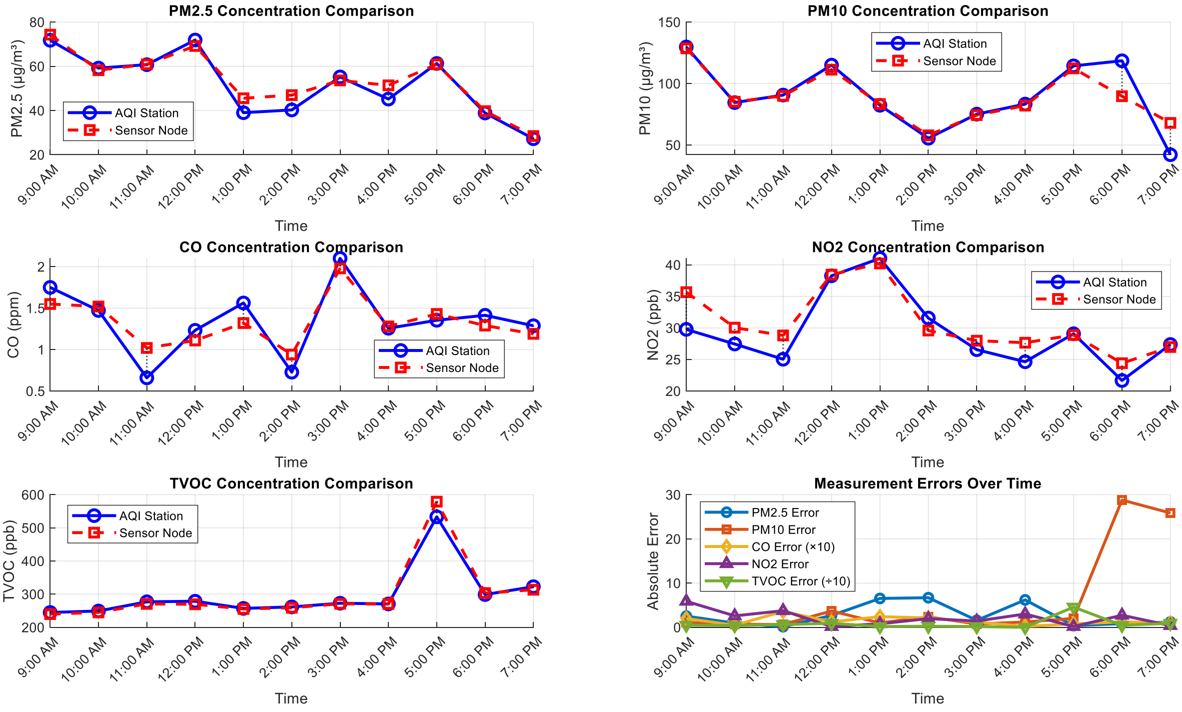

Figure 38: Sensor Calibration Validation (Sensor Node Data Vs AQI Station Data)

5.2.3 Data Aggregation Gateway (DAG) Implementation

The Data Aggregation Gateway (DAG) serves as the central data consolidation and preprocessing unit of the system. It receives pollutant data transmitted from all sensor nodes and performs data-cleaning operations to eliminate noise, out-of-range readings, and other invalid or corrupted values. This preprocessing step ensures that only reliable and meaningful data are forwarded to the IoT-based monitoring dashboard.

The DAG is connected to the sensor nodes through a WiFi-based mesh network implemented using the painlessMesh framework. This mesh architecture provides high reliability and fault tolerance, as data from all sensor nodes can be delivered to the DAG even if only a single node has direct access to an external WiFi connection. In such cases, the connected node relays the aggregated data of the entire mesh to the DAG, ensuring uninterrupted system operation in industrial environments with limited or unstable connectivity.

In addition to mesh-based communication with the sensor nodes, the Data Aggregation Gateway communicates directly with the Central Control Unit (CCU) over a standard WiFi link rather than through the mesh network. This design choice simplifies control signaling and reduces latency, enabling prompt actuation decisions based on the aggregated pollution data.

Because the DAG collects and processes data from all sensor nodes, it acts as the primary data source for the IoT-based monitoring system. The processed data are transmitted to the database and visualized through the monitoring dashboard, providing a comprehensive and centralized view of air quality conditions across the deployment area.

For system development, debugging, and validation purposes, the ESP32 WROOM32 module of the Data Aggregation Gateway is also connected to a personal computer via serial communication. This interface allows real-time observation of system logs, data packets, and diagnostic information during testing and maintenance.

Figure 39 shows the PCB implementation of the Data Aggregation Gateway.

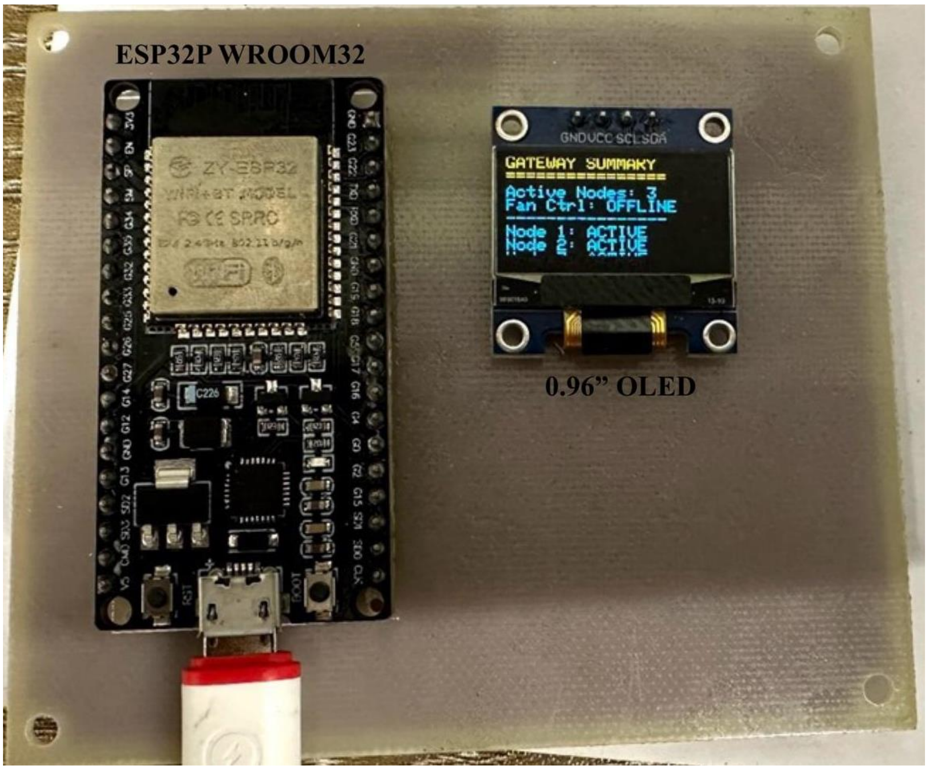

Figure 39: PCB Implementation of the Data Aggregation Gateway

5.2.4 IoT-Based Custom-Built Monitoring Unit Implementation

As established earlier, the Data Aggregation Gateway (DAG) is directly connected to a personal computer, with bidirectional communication established through serial communication. This serial interface was extensively utilized during the development of the custom IoT-based monitoring application.

The concept for the monitoring platform originated from the real-time data displayed on the Arduino IDE serial monitor during system testing. To extend this capability into a dedicated monitoring application, the serial data stream from the DAG was imported into a Python environment using the serial library. Through this interface, the Python-based application continuously reads data from the designated COM port to which the DAG is connected.

The incoming data stream, consisting of aggregated and preprocessed sensor readings, is then parsed and utilized to generate real-time visualizations within a Python-based desktop application. This approach enables efficient monitoring, debugging, and validation of system performance without requiring immediate cloud integration. The serial-to-Python communication framework thus served as a foundational step in the development and testing of the IoT-based monitoring platform.

This air quality monitoring dashboard software implements a modular, event-driven architecture built around the Model-View-Controller (MVC) pattern with several specialized components. At its core, the application serves as a real-time data visualization and logging system for ESP32-based sensor networks, with a multi-tiered architecture that cleanly separates concerns between data acquisition, storage, visualization, and user interface layers.

The data acquisition layer is handled by the SerialReader class running in a dedicated QThread, which continuously reads JSON-formatted sensor data from serial ports. This thread-based approach prevents UI blocking while ensuring reliable data ingestion. The acquired data undergoes robust validation through range checking and type verification before being passed to other components. This validation layer acts as a data quality gatekeeper, ensuring only reasonable sensor readings propagate through the system.

The data persistence layer is managed by the DatabaseManager class, which implements a SQLite-based storage solution with structured tables for sensor readings and daily statistics. This component follows the Repository Pattern, providing a clean abstraction over database operations while implementing data validation, indexing for performance, and sample data generation for testing. The database design supports time-series data with efficient querying capabilities through timestamp and node ID indexes.

The visualization layer comprises multiple specialized widget classes, each following the Single Responsibility Principle. The CircularMeter, HorizontalBar, and VerticalGradientProgressBar widgets implement custom-drawn visualizations with 60 FPS smooth animations using QPropertyAnimation techniques. These visualization components use gradient-based rendering and color-coding systems to intuitively represent air quality levels, with visual feedback that responds immediately to data changes.

The user interface layer is organized into a tab-based navigation system with distinct dashboards for different user roles. The GeneralUserDashboard provides a simplified, at-a-glance view optimized for non-technical users, featuring a prominent pollutant bar chart and health indicators. The NodeWidget classes offer detailed technical views with comprehensive sensor readings for individual nodes, while the GraphWidget provides time-series visualization of historical data trends. The InfographicsWidget implements advanced analytical visualizations, including feature importance charts and parallel coordinates plots for multi-variable analysis.

The application coordination layer is managed by the MainWindow class, which acts as the central controller orchestrating all components. It implements the Observer Pattern through Qt's signal-slot mechanism, facilitating loose coupling between data producers (serial reader) and consumers (visualization widgets, database). The main window also manages performance optimization through selective UI updates based on tab visibility and implements connection state management with visual feedback for system status.

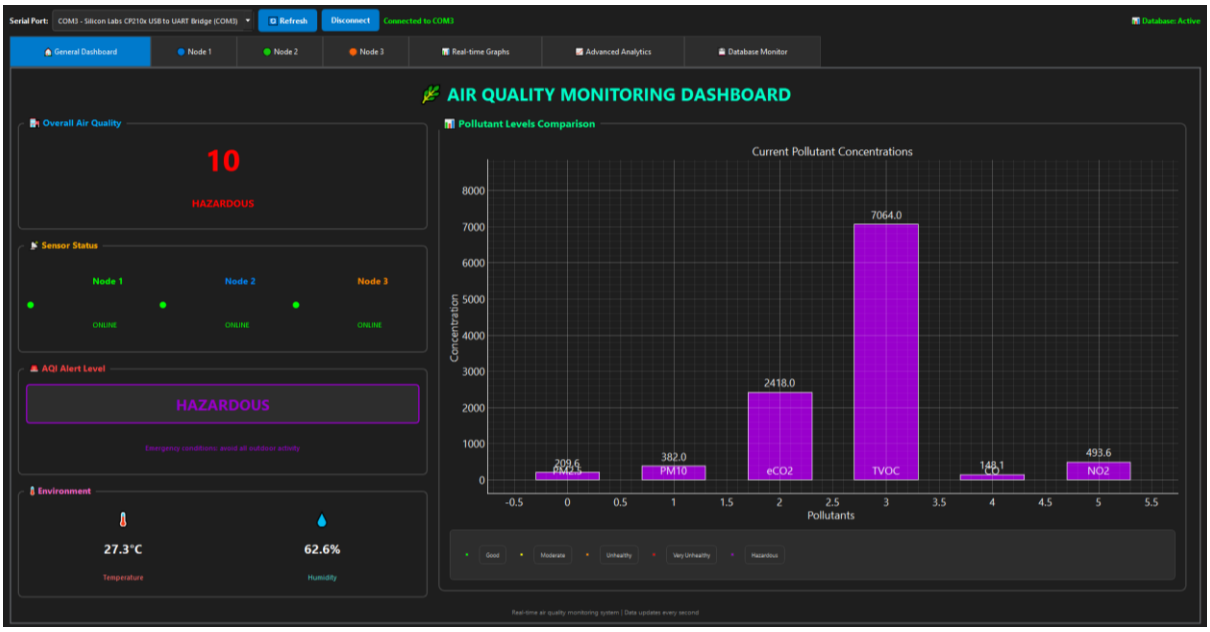

Figure 40: General Dashboard with the Summary of All Data. The x-axis of the graph represents pollutant concentrations, and the y-axis represents pollutants. The pollutant levels here are the average pollutant levels from the 3 nodes.

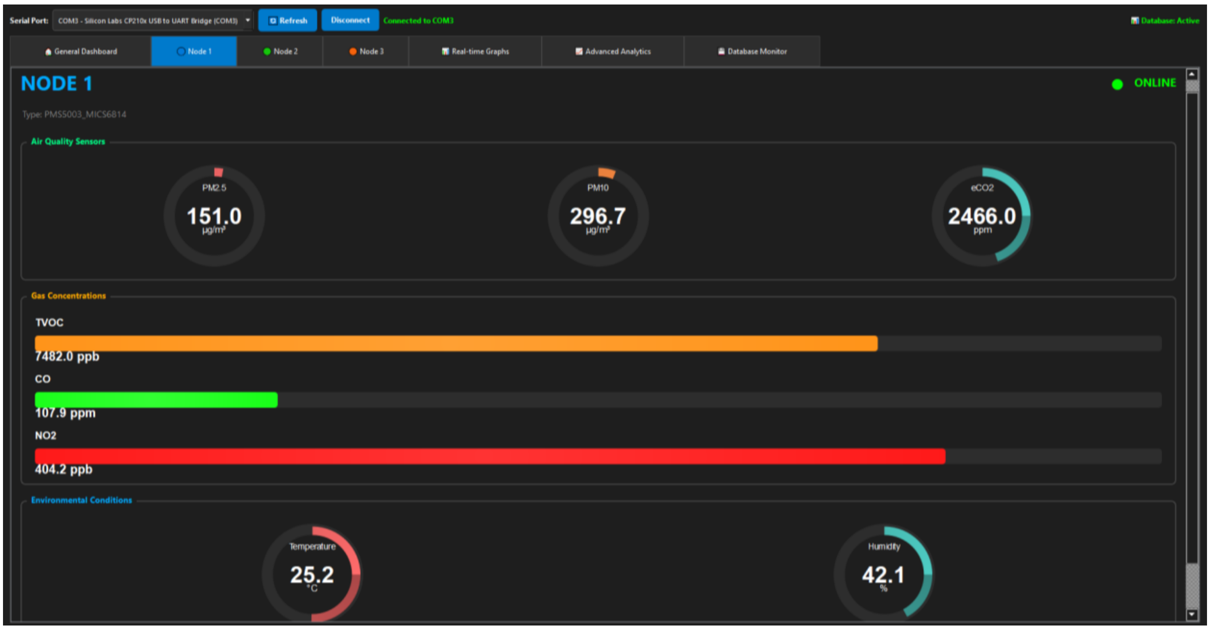

Figure 41: Pollutant Data of Industrial Zone "A" from Sensor Node 1. These are raw data taken from the sensors of the sensor nodes and sent to the monitoring system via DAG.

The architecture employs several design patterns for scalability and maintainability. The widget system uses the Composite Pattern for building complex UIs from simple components. The database and serial communication implement Façade Pattern to simplify complex subsystems. The animation system uses Strategy Pattern for different interpolation methods. The tab-based interface follows the State Pattern for managing different application views.

This multi-threaded, modular architecture enables the system to handle real-time data streams while maintaining responsive user interactions. The separation between data acquisition, processing, storage, and presentation allows for independent scaling of each component and facilitates testing and maintenance. The use of standard design patterns and clear layer boundaries makes the system extensible for additional sensor types, visualization methods, or data analysis features.

Figures 40-46 show the different windows of the IoT-Based Monitoring app.

Figure 42: Pollutant Data of Industrial Zone “B” from Sensor Node 2

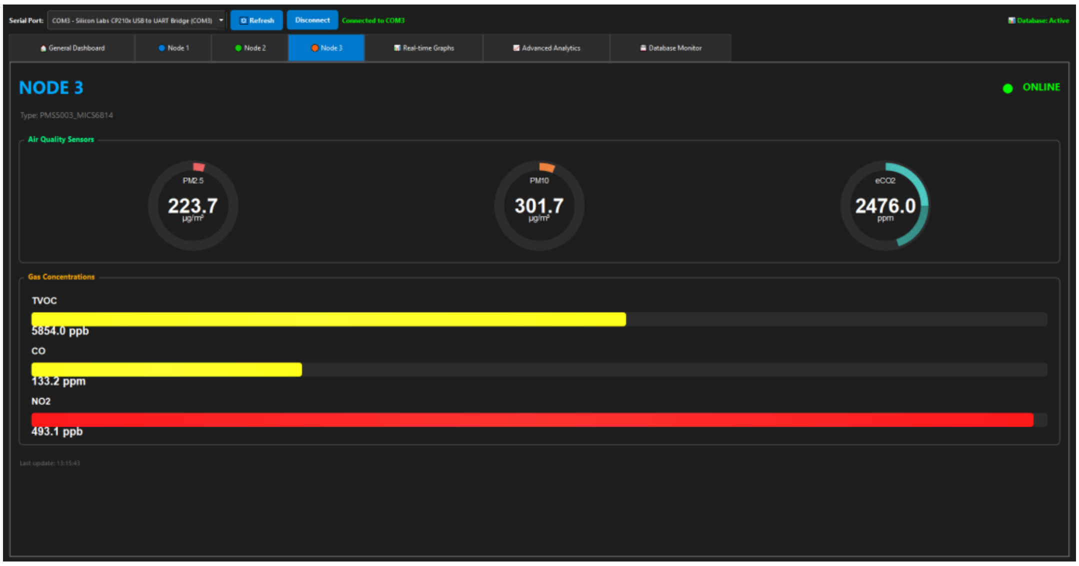

Figure 43: Pollutant Data of Industrial Zone “C” from Sensor Node 3

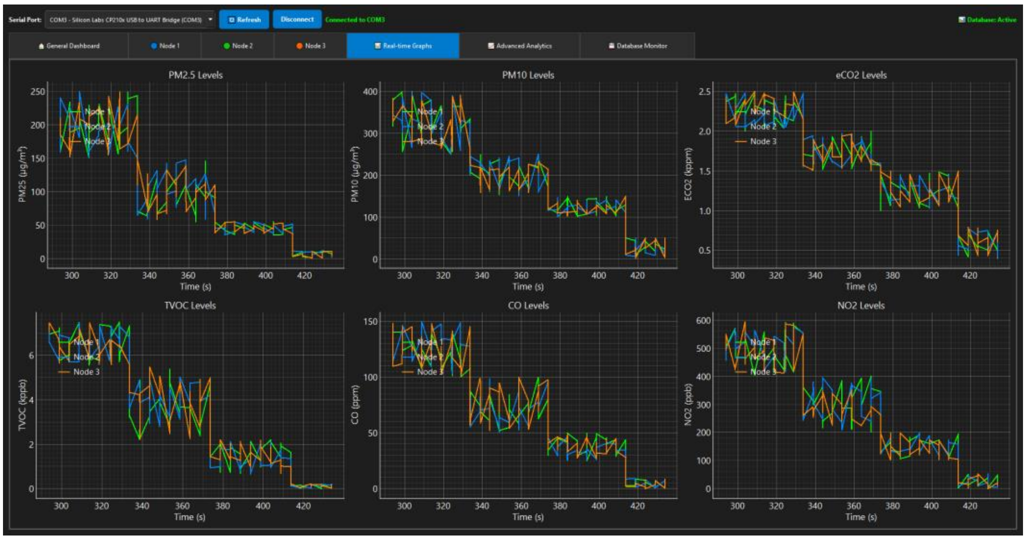

Figure 44: Real-Time Graph of All the Pollutants

Figure 45: Advanced Analytics Showing Feature Importance & Correlation of Pollutants

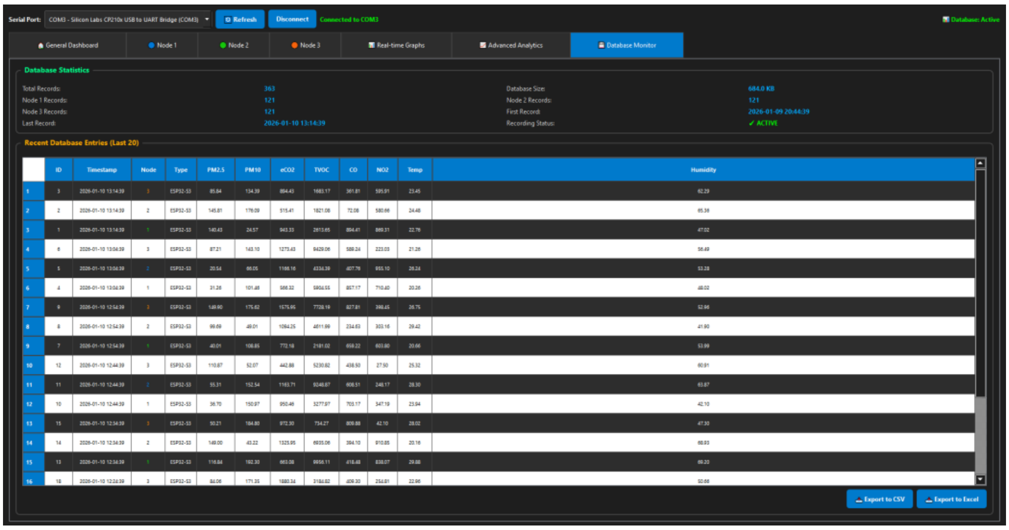

Figure 46: Visualization of the Real-Time Update of the Database

5.2.5 Central Control & Purification Unit Implementation

The Central Control Unit (CCU) and the air purification mechanism are integrated into a single consolidated module, referred to as the Central Control and Purification Unit. Within this integrated structure, the Central Control Unit occupies the CCU layer and is responsible for processing control commands and managing system operation.

The purification section of the unit consists of two Arctic P12 Max fans, which provide the required airflow for pollutant removal. These fans operate in conjunction with a multi-stage filtration assembly, comprising four side-mounted filters arranged in parallel to maximize air intake and throughput, followed by a HEPA filter connected in series to ensure high-efficiency particulate removal. Together, these components form the Purification Unit, enabling effective and controlled air cleaning under varying pollution conditions. Figure 47 shows the various parts of the Central Control and Filtration Unit.

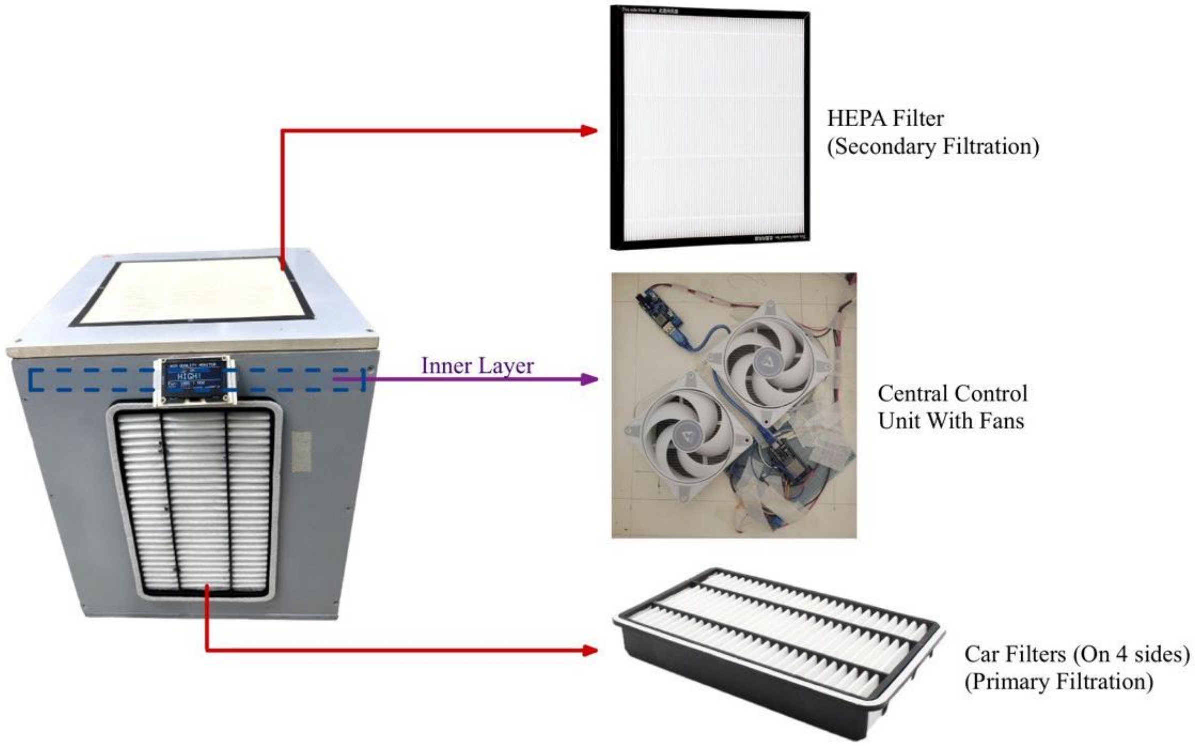

Figure 47: Central Control and Filtration Unit

The ESP32 WROOM32 serves as the central controller of the entire system, coordinating power distribution, communication, and actuation. The primary power source for the system is a 220 V AC supply drawn directly from the mains. This high-voltage AC input is first converted into a regulated 12 V DC output using a 12 V AC–DC converter.

The 12 V DC supply is directly used to power the Arctic P12 Max fans, which are rated for 12 V operation and provide the necessary airflow for the purification process. In parallel, the same 12 V supply is stepped down to 5 V DC using an LM2596S-based DC–DC buck converter (24 V/12 V to 5 V, 5 A). This regulated 5 V output powers the ESP32 WROOM32 and associated low-voltage control circuitry within the Central Control Unit (CCU).

The ESP32 WROOM32 in the CCU receives aggregated pollutant data from the Data Aggregation Gateway via a direct WiFi connection. Based on the received data and the predefined pollutant concentration thresholds outlined in Table V, the CCU executes the control logic for the purification unit.

When pollutant levels fall within the high range or above, the fans operate at full capacity, running at 100% speed (3300 rpm) to ensure rapid pollutant removal. Under medium pollution conditions, the fan speed is reduced to 90% (2970 rpm) to balance purification efficiency with energy consumption. At low pollution levels, the fans operate at 80% speed (2640 rpm), which is sufficient to maintain air quality while minimizing power usage. When all monitored pollutants remain within the safe range, the purification unit is deactivated, and the fans are turned off.

This hierarchical power management and adaptive fan-speed control strategy enables efficient system operation while ensuring responsive and effective air purification under varying environmental conditions. Figure 48 shows the connection diagram inside the central control and purification unit.

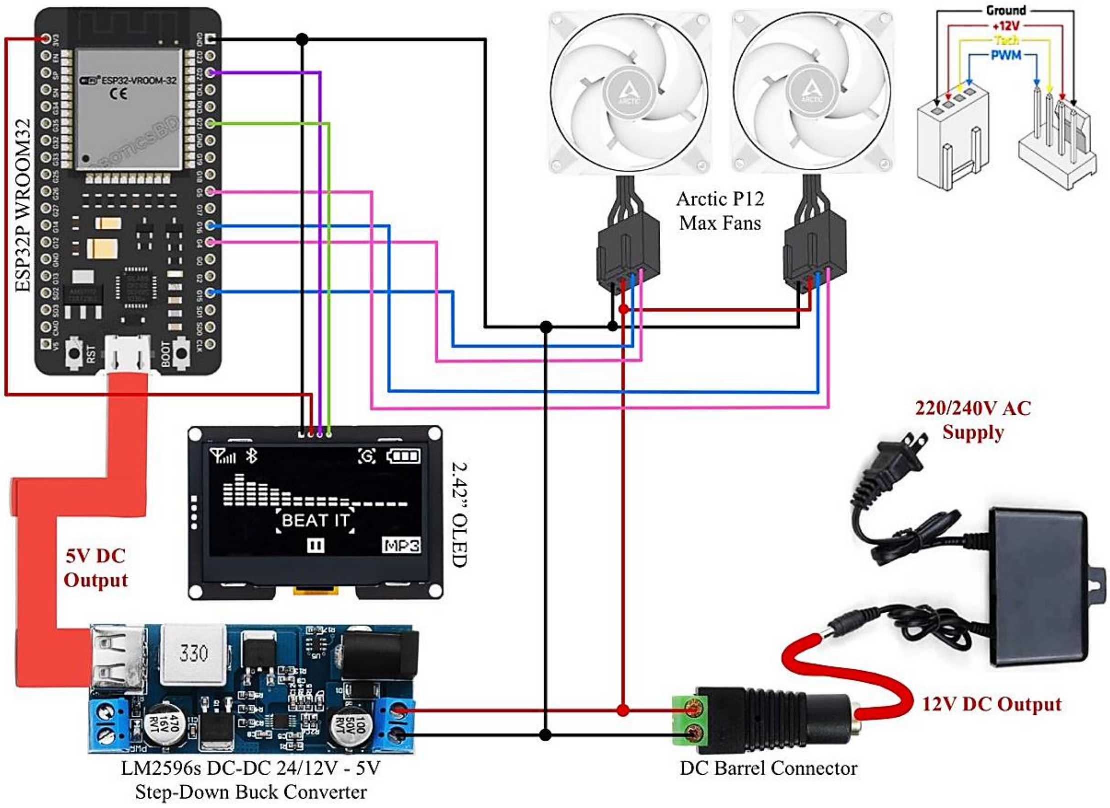

Figure 48: Connection Diagram of the Central Control and Purification Unit

As established earlier, the system operates using an adaptive fan-speed control mechanism. However, the operational process extends beyond fan speed regulation alone. When activated, the rotating fans expel air from within the purification chamber, creating a localized low-pressure region. This pressure differential generates an inward airflow, drawing polluted ambient air into the chamber from all four sides through the side-mounted filters, thereby completing the first stage of purification.

As the airflow continues, the fans force the partially purified air upward toward the HEPA filter positioned above them. This HEPA filter performs the second stage of purification by capturing finer particulate matter that may have passed through the initial filtration stage. Through this two-stage filtration process, pollutants are effectively trapped within the filter media, while the cleaned air is expelled from the purification unit.

The combined action of pressure-driven airflow and sequential filtration ensures efficient pollutant removal and consistent air quality improvement. This operational mechanism is illustrated in Figure 49.

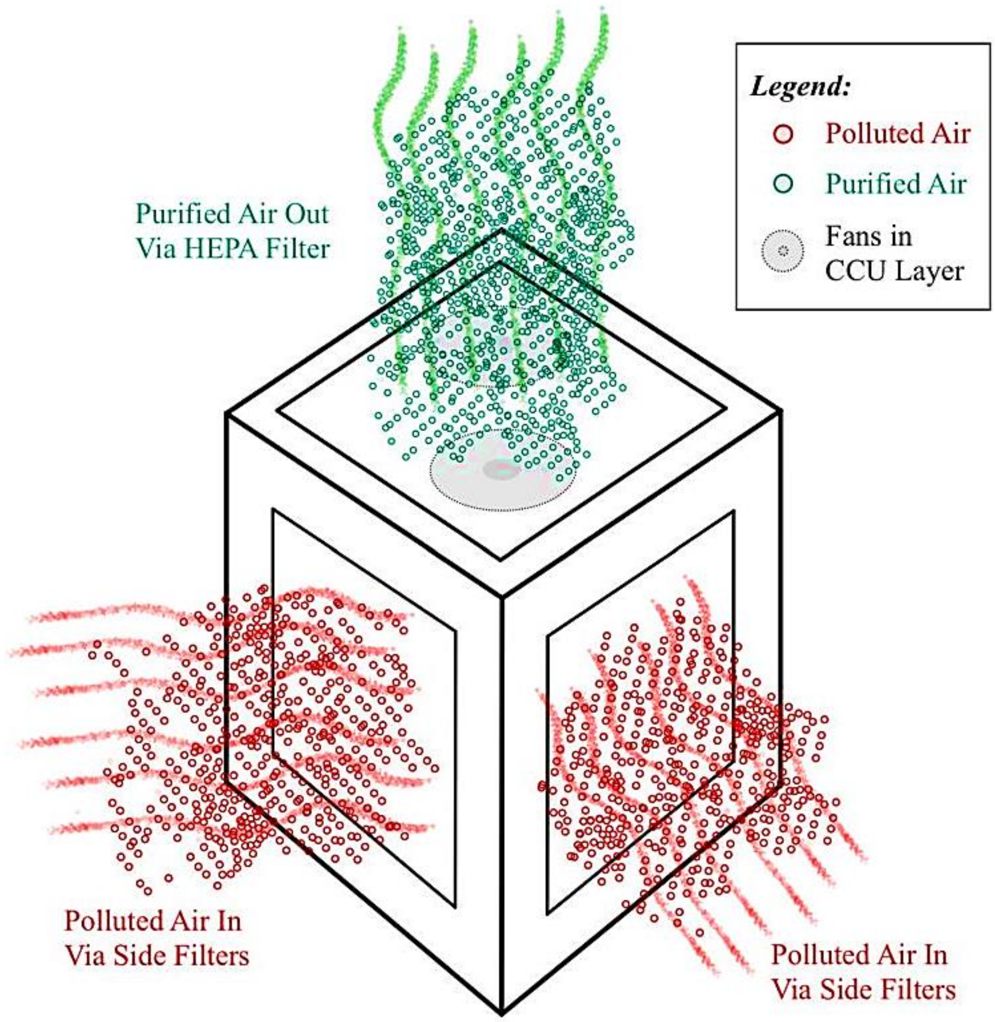

Figure 49: Illustration of the Air Purification Mechanism by the Purification Unit

5.3 Evaluation of the Solution to Meet the Desired Needs

5.3.1 Testing in Controlled Environment

After completion of the system development, performance testing was conducted in a controlled indoor environment with an area of 15 m² over a duration of 10 days. During the first five days, pollutant concentration data were collected without activating the filtration unit, serving as the baseline condition. For the subsequent five days, the same measurements were recorded with the filtration unit in operation.

Pollutant data were acquired at hourly intervals, continuously over 24-hour cycles throughout the testing period. To ensure experimental consistency, environmental conditions within the room—including object placement, human activity, and pet movement—were maintained as constant as possible across all 10 days.

For ease of analysis and visualization, the recorded pollutant concentrations were subsequently normalized to a scale ranging from 0 to 10. This normalization enabled a clear and consistent comparison across different pollutants with varying units and concentration ranges, thereby facilitating an effective comparative evaluation of system performance before and after filtration. Based on the normalized data, a consistent pattern emerged during experimental testing, indicating that the enclosed room environment requires approximately 10–15 minutes to achieve effective air purification and reach acceptable pollutant levels after activation of the filtration unit.

Table VIII shows the pollution trends with and without the use of the Filtration Unit. Figure 50 depicts the filter performance analysis.

TABLE VIII. POLLUTION TRENDS: WITH VS WITHOUT FILTRATION UNIT

Timestamp	Pollution Trend Without Filter	Pollution Trend With Filter
12:00 AM	3	2
1:00 AM	2	1
2:00 AM	2	1
3:00 AM	2	1
4:00 AM	1.5	1
5:00 AM	1.5	0.5
6:00 AM	2	0.5
7:00 AM	2	1
8:00 AM	3.5	1.5
9:00 AM	4.5	2
10:00 AM	8	3
11:00 AM	8.5	3
12:00 PM	8.5	3.5
1:00 PM	9	3.5
2:00 PM	9.5	3.5
3:00 PM	8	3
4:00 PM	8	3
5:00 PM	8.5	3
6:00 PM	9	4
7:00 PM	10	4
8:00 PM	10	4
9:00 PM	9.5	3
10:00 PM	9	2.5
11:00 PM	5	2

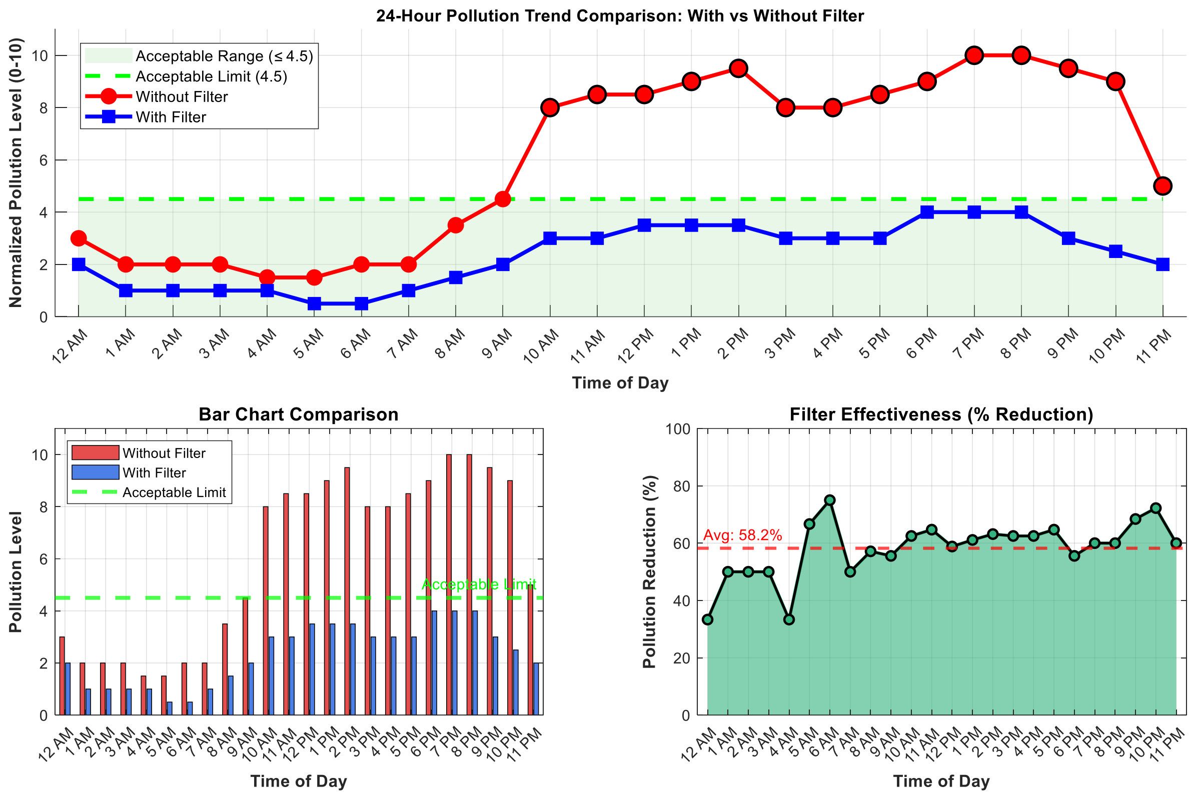

Figure 50: Performance Analysis of the Filtration Unit

So, from this analysis, it is clear that the air Purification Unit is working as intended.

5.3.2 Industrial Testing and Validation

As the proposed system was designed with small and medium enterprises (SMEs) as its primary target, an industrial-level validation was conducted after successful system construction and laboratory testing. The field validation was performed at Allied Solar Energy Ltd., a private manufacturing company specializing in solar-based products, to assess the system's performance under real-world industrial operating conditions. The validation experiment was carried out on the solar light bulb manufacturing floor, which covers an approximate area of 140 m² and represents a typical SME production environment with continuous human activity and equipment operation.

During the validation phase, three sensor nodes were strategically deployed across three distinct zones of the manufacturing floor to capture spatial variations in pollutant concentrations and to evaluate the system's sensing coverage. The Central Control and Purification Unit was installed at the center of the floor to promote uniform airflow distribution and maximize purification effectiveness across the entire area. Pollutant data were recorded continuously throughout the testing period, enabling comprehensive analysis of temporal and spatial air quality variations.

Figures 51–52 present the industrial site visit and the system deployment configuration used for the industrial validation.

Figures 51-52: Industrial Visit for Industrial Validation of the System

During the initial 25 minutes of operation, pollutant concentrations remained within the "High" range, primarily due to intensive welding activities that generated significant amounts of particulate matter, particularly PM2.5 and PM10. Simultaneously, the glass tubes used for bulb manufacturing were submerged in an alcohol-based solution, resulting in a marked increase in TVOC concentrations as well as elevated eCO_2 levels. These industrial processes operated concurrently, leading to a rapid accumulation of airborne contaminants within the enclosed workspace.

The combined influence of particulate emissions and volatile chemical vapors created a highly hazardous indoor environment during this period. As a result, the air quality conditions were unsuitable for safe and sustained human occupancy, underscoring the critical need for continuous air quality monitoring and effective filtration mechanisms in active industrial settings. Figures 53 – 59 show this pollution trend.

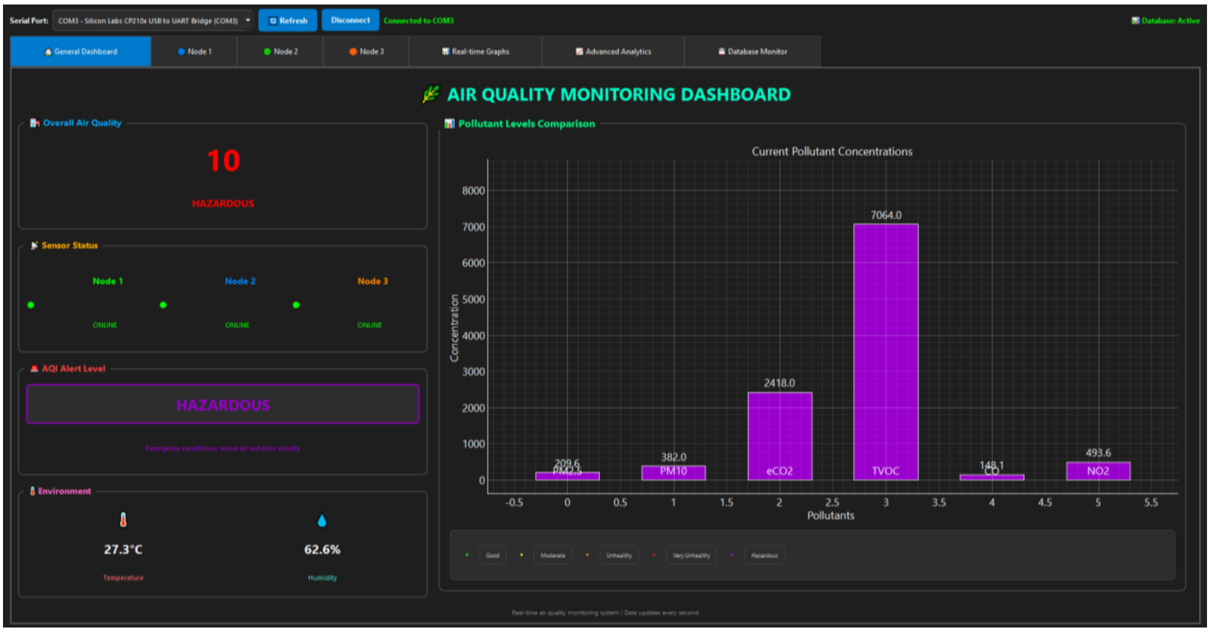

Figure 53: General Dashboard at "High" Pollution Level

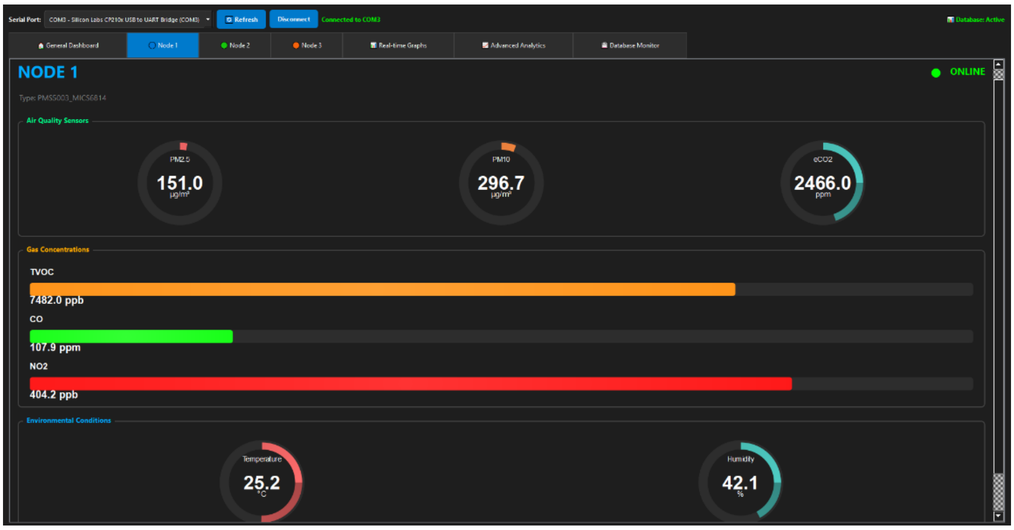

Figure 54: Pollutant Readings of Zone "A" of the Industry at "High" Pollution Level

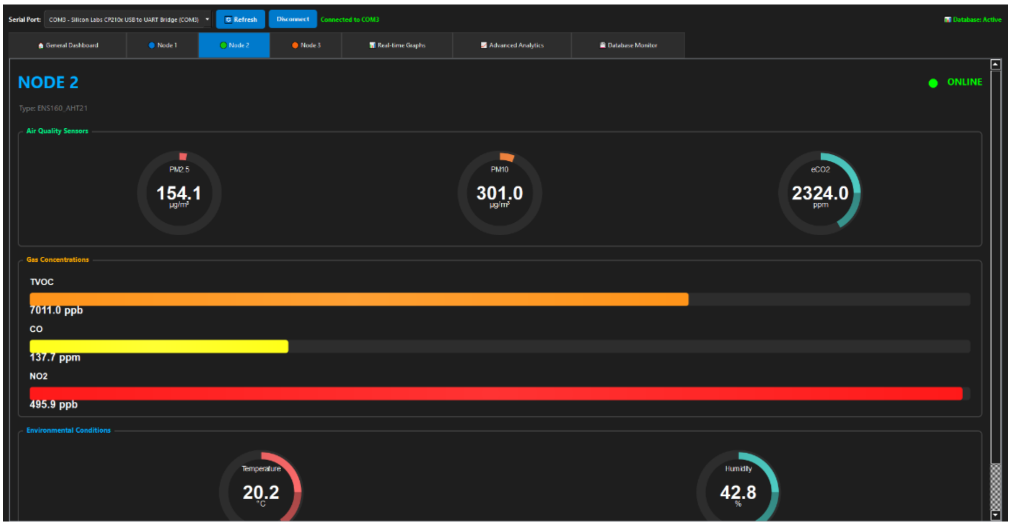

Figure 55: Pollutant Readings of Zone "B" of the Industry at "High" Pollution Level

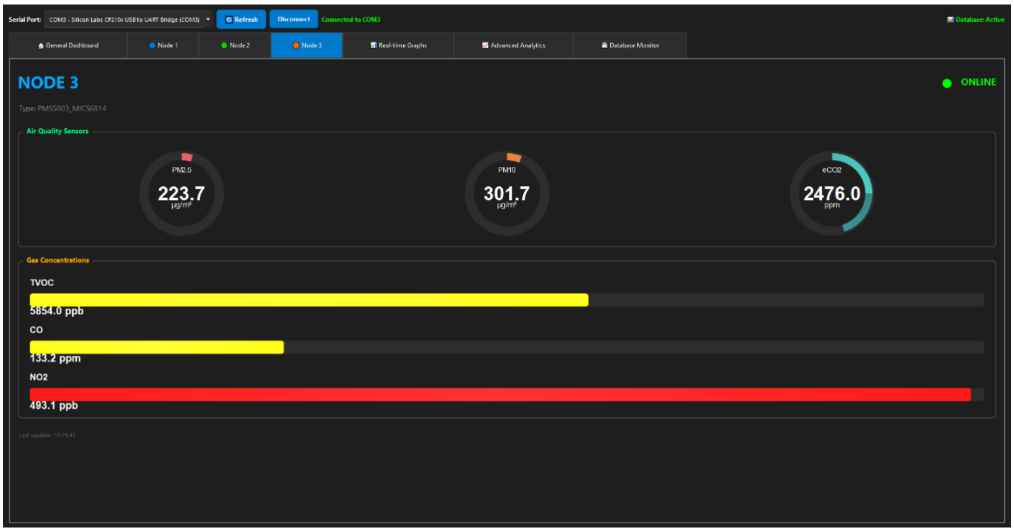

Figure 56: Pollutant Readings of Zone "C" of the Industry at "High" Pollution Level

Figure 57: CCU Showing “High”; Fan at100% Speed

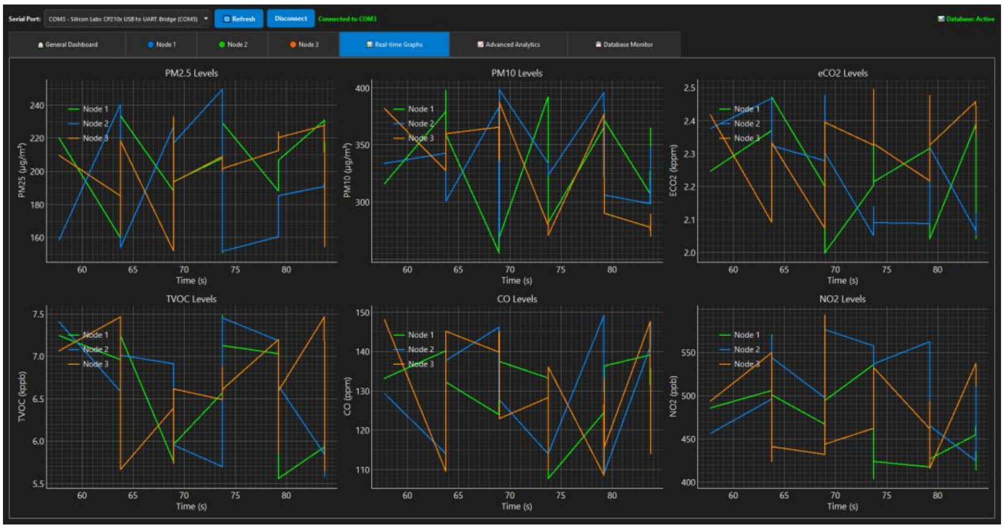

Figure 58: Real-Time Data are “High”

Figure 59: AQI Percentage is Shown to be “High”

Over the next 33 minutes, the pollution level decreased to the “Medium” range, indicating a clear reduction in particulate concentration despite ongoing industrial operations.

Figure 60: CCU Showing “Medium”; Fan at 90% Speed

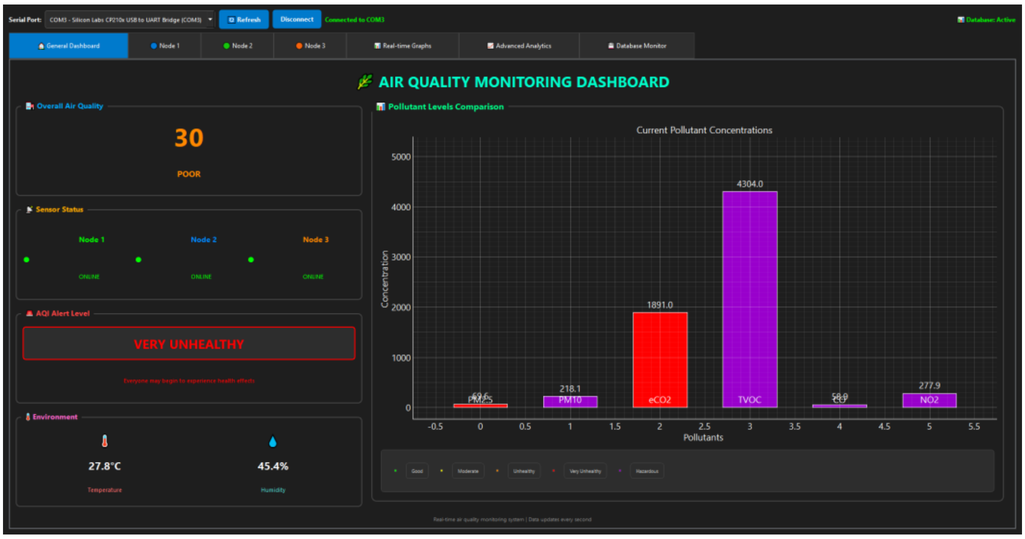

Figure 61: General Dashboard at “Medium” Pollution Level

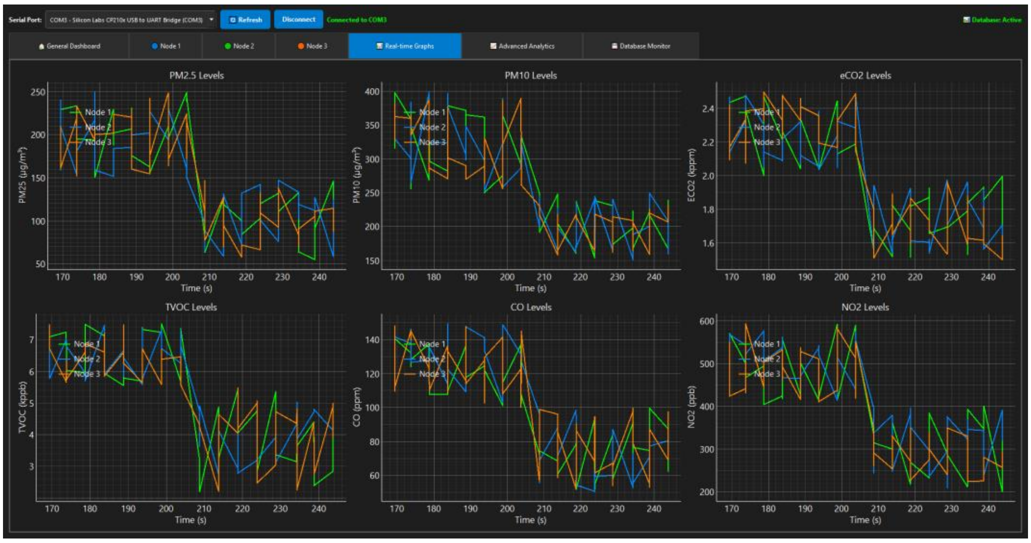

Figure 62: Real-Time Data Improvement to “Medium”

As shown in the graphs presented in Figure 62, the concentration levels of all monitored pollutants—PM2.5, PM10, eCO_2, TVOC, CO, and NO_2—exhibit a significant reduction over time. This consistent downward trend across all pollutant categories demonstrates the effective operation of the proposed system and confirms its capability to improve indoor air quality under real-world conditions.

Subsequently, after approximately 58 minutes of system operation, the pollution level transitioned to the “Low” range for the next 35 minutes. During this period, all three monitored zones exhibited substantial improvements in air quality.

Figure 63: CCU Showing “Low”; Fan at 80% Speed

Figure 64: General Dashboard at “Low” Pollution Level

Figure 65: Real-Time Data Improvement to "Low"

Ultimately, after 1 hour, 33 minutes, and 41 seconds of continuous operation, pollutant concentrations across the factory floor reached the "Safe" range, confirming that the indoor air quality had been fully restored.

Figure 66: CCU Showing "Safe"; Fan OFF

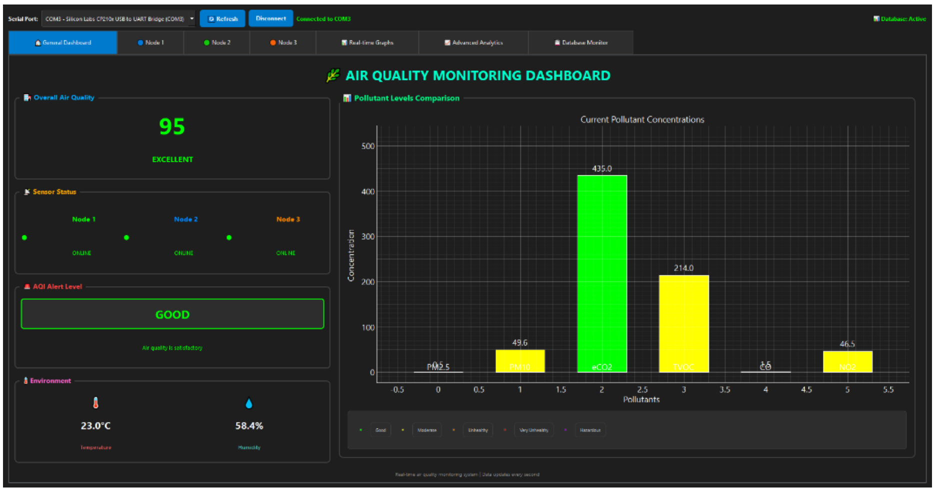

Figure 67: General Dashboard at "Safe" Pollution Level

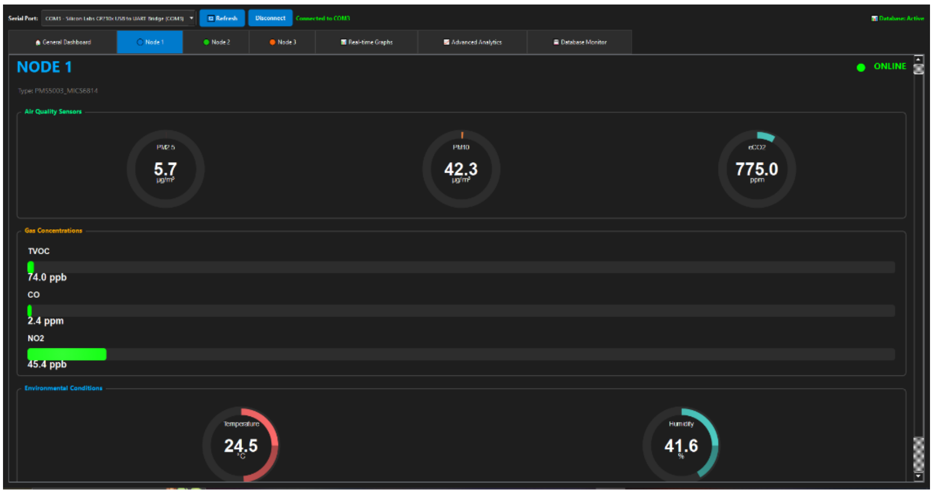

Figure 68: Pollutant Readings of Zone “A” of the Industry at “Safe” Pollution Level

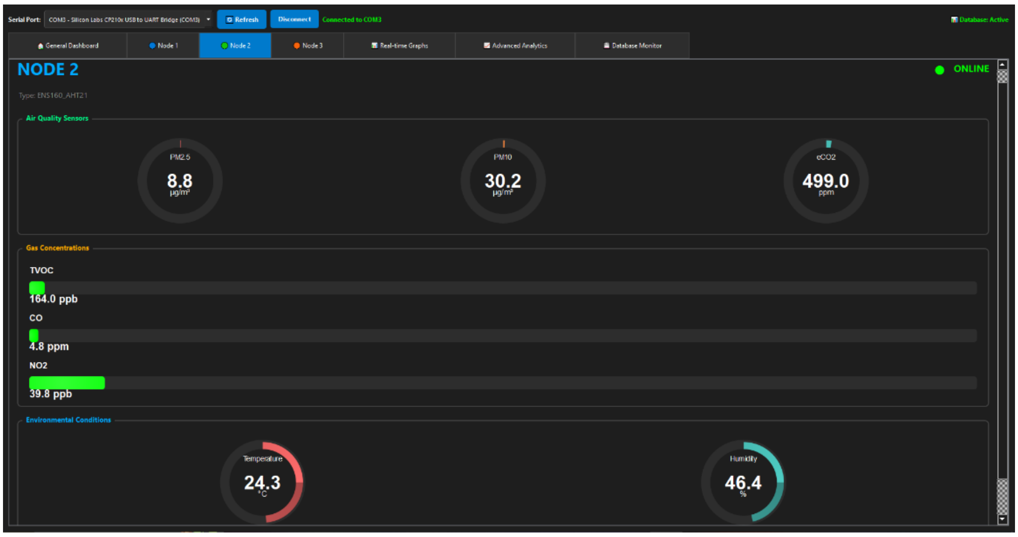

Figure 69: Pollutant Readings of Zone “B” of the Industry at “Safe” Pollution Level

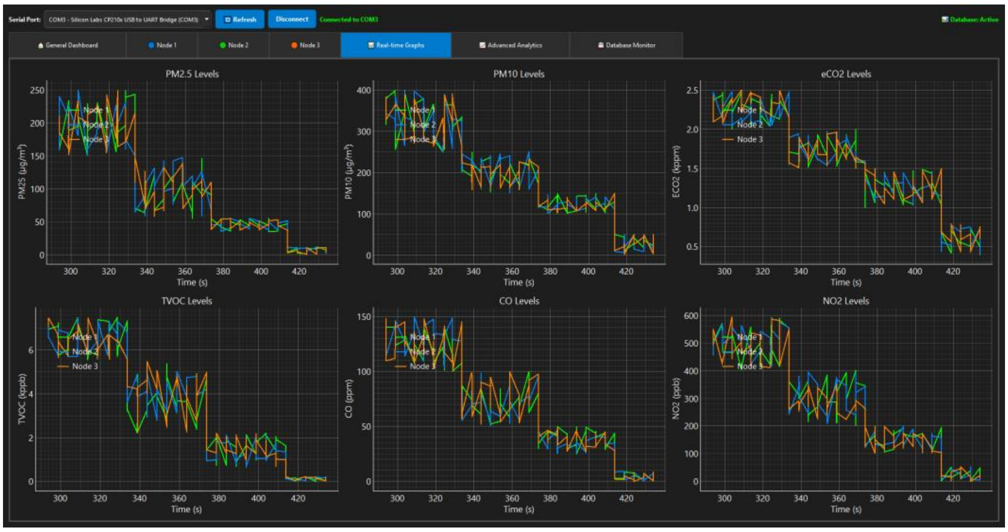

Figure 70: Real-Time Data Improvement to “Safe”

Figure 71: AQI Percentage is Shown to be "Safe"

These results demonstrate the system's effectiveness in reducing industrial air pollution in real operating conditions, validating its suitability for deployment in SME-scale manufacturing environments.

5.3.3 Validation and Analysis of the Components Used

5.3.3.1 Validation for Long Chamber and Using 2 Fans

Tested room measurements:

- Room area = 15 m^2
- Height ≈ 2.7 m
- Volume = 40.5 m^3

For good air cleaning: Target ACH = 6 [48]. The required airflow is found below using equation (i) below.

$$Required\ airflow = 40.5 \times 6 = 243\ \frac{m^3}{h} \dots\dots\dots\dots\dots (i)$$

Filter Design Specifications:

- 4 Car filters
- Each filter = 40.64 × 48.768 cm = 0.198 m^2
- Total filter area is calculated below in equation (ii):

$$A_{total} = 4 \times 0.198 = 0.792\ m^2 \dots\dots\dots\dots\dots (ii)$$

Airflow per filter is calculated below using equation (iii):

$$Q_{per\ filter} = \frac{243}{4} = 60.75\ \frac{m^3}{h} \dots\dots\dots\dots\dots (iii)$$

Convert to m^3/s:

$$\frac{60.75}{3600} = 0.0169\, m^3/s$$

Face velocity is found below using equation (iv):

$$V = \frac{0.0169}{0.198} = 0.085\, m/s \dots\dots\dots\dots\dots (iv)$$

For thin (~2 cm) HEPA:

- Typical pressure drop ≈ 50 Pa at 0.24 m/s per cm thickness

Scaling with velocity² is shown below in equation (v):

$$\Delta P = 100 \times \left(\frac{0.085}{0.3}\right)^2 \approx 12.5\, Pa \dots\dots\dots\dots\dots (v)$$

A 120 mm high-static-pressure PC fan (Arctic P12 Max) delivers:

- Airflow: 137.69 m^3/h
- Max static pressure: 42.65 Pa

Using 2 fans in parallel (top-mounted)

- Total airflow ≈ 275.38 m^3/h
- Available pressure ≈ 85.3 Pa

The comparison of the required values and the provided values is shown in Table IX.

TABLE IX. COMPARISON WITH REQUIREMENTS

Parameter	**Required**	**Provided**
Airflow	243 m^3/h	**275.38 m^3/h**
Pressure	12.5 Pa	**85.3 Pa**

5.3.3.2 Validation for Using Arctic P12 Max Fans

Typical static-pressure fan (for PC) blade angles should be 7–12° [49].

From the datasheet of Arctic P12 Max:

- Fan diameter = 120 mm
- Blade count = 5
- Rated max RPM = 3300
- Max airflow = 81 CFM = 137.6 m^3/h
- Max static pressure = 4.35 mmH_2O = 42.7 Pa

Tip speed is calculated in rad/s in equation (vii) and in m/s in (vii):

$$r = 0.06\,m$$

$$\omega = \frac{2\pi \times 3300}{60} = 345.6\,rad/s \ldots\ldots\ldots\ldots\ldots (vi)$$

$$V_{tip} = r\omega = 0.06 \times 345.6 = 20.7\,m/s \ldots\ldots\ldots\ldots\ldots (vii)$$

Axial air velocity is calculated in equation (x) using the values found in (viii) and (ix):

$$Q = \frac{137.6}{3600} = 0.0382\,m^3/s \ldots\ldots\ldots\ldots\ldots (viii)$$

$$A = \pi r^2 = 0.0113\,m^2 \ldots\ldots\ldots\ldots\ldots (ix)$$

$$V_{axial} = \frac{0.0382}{0.113} = 3.38\,m/s \ldots\ldots\ldots\ldots\ldots (x)$$

Blade pitch (wing angle) is shown in equation (xi):

$$\tan\theta = \frac{V_{axial}}{V_{tip}} = \frac{3.38}{20.7} \ldots\ldots\ldots\ldots\ldots (xi)$$

$$\therefore\ \theta = 9.3°$$

So, we can see that the Blade Pitch for the Arctic P12 Max is in the acceptable range for a static-pressure fan. That is why it is used in this project.

5.3.3.3 WiFi Range (ESP32 Mesh)

Given (From ESP32 WROOM 32 Datasheet):

- ESP32 T_x power ≈ 20 dBm
- Receiver sensitivity ≈ −95 dBm
- Free space path loss can be found using equation (xii):

$$FSPL = 32.44 + 20\log f + 20\log d \ldots\ldots\ldots\ldots\ldots (xii)$$

Putting *f = 2.4 GHz* in equation (xii) gives equation (xiii):

$$FSPL = 32.44 + 20\log(2400) + 20\log d \ldots\ldots\ldots\ldots\ldots (xiii)$$

Maximum Allowable Loss:

$$20 - (-95) = 115\,dB$$

So, the distance, d (Range), is found by putting the value of FSPL in equation (xiii):

$$115 = 32.44 + 20\log(2400) + 20\log d$$

$$115 = 100 + 20\log d$$

$$\therefore\ d = 31.6m$$

5.3.3.4 Purification Time

Tested Room size:

- Area = 15 m^2
- Height = 2.7 m

So, the room volume can be found in equation (xiv):

$$V_{room} = 15 \times 2.7 = 40.5\ m^3 \ldots\ldots\ldots\ldots\ldots (xiv)$$

Total airflow

- 2 fans × 137.6 m^3/h

$$Q = 275\ m^3/h$$

Time for 1 air change is shown in equation (xv):

$$t = \frac{275}{40.5} = 0.147\ h = 8.8\ min \ldots\ldots\ldots\ldots\ldots (xv)$$

So, the claim that our system cleans a 15m^2 room in 10-15 minutes is valid.

5.3.3.5 System Efficiency

From Industrial Test Results,

Pollutant	Initial Value	Level After Purification
PM2.5 ($\mu g/m^3$)	120.47	9.42
PM10 ($\mu g/m^3$)	345.69	11.79

So, the weighted efficiency for PM2.5 and PM10 is found in equations (xvi) and (xvii)

$$\eta_{PM2.5} = \frac{345.69 - 11.79}{345.69} = 0.9659 \ldots\ldots\ldots\ldots\ldots (xvi)$$

$$\eta_{PM10} = \frac{566.27 - 49.43}{566.27} = 0.9127 \ldots\ldots\ldots\ldots\ldots (xvii)$$

Combined weighted efficiency is calculated using equation (xviii):

$$\eta_{system} = 0.6(0.9659) + 0.4(0.9127) = 0.9446 \ldots\ldots\ldots\ldots\ldots (xviii)$$

Overall efficiency ≈ 94.46%

5.3.3.6 PWM Validation (80%, 90%, 100%)

We got from 1,

Required airflow, $Q_{Required} = 243\ m^3/h$ (±10%)

Rated airflow for the 2 Arctic P12 Max, $Q_{Rated} = 275.38\ m^3/h$

We know, $Q \propto PWM$

So, at 100% PWM, $Q_{100} = 275.38\ m^3/h$

At 90% PWM, $Q_{90} = 247.84\ m^3/h$

At 80% PWM, $Q_{80} = 220.30\ m^3/h$

Anything lower than 80% will not provide a sufficient amount of airflow.

5.3.3.7 Power Consumption

For ESP32: $P_{ESP32} = 0.8\ W$

For the sensors:

- PMS5003 = 0.8 W
- MEMS CO + NO_2 = 0.15 W
- ENS160 + AHT21 = 0.1 W
- CCS811 = 0.1 W

$$\therefore\ P_{Sensor\ Avg} = 1.05\ W$$

For the Fans:

- Arctic P12 Max = 0.29 A at 12 V = 3.48 W

$$\therefore\ P_{Fan} = 6.96\ W$$

For OLED: $\therefore\ P_{0.96\ OLED} = 0.6\ W$

So, total power consumed is calculated using equation (xix):

$$\therefore\ P_{Total} = (0.8 \times 5) + (1.05 \times 3) + 6.96 + (0.6 \times 5) \dots\dots\dots\dots\dots (xix)$$

$$= 17.11\ W$$

5.3.4 Objectives Met

Objective 1 (Real-Time Monitoring): This objective is achieved through the deployment of multiple distributed sensor nodes equipped with industrial-grade sensors capable of continuously measuring both particulate and gaseous pollutants. Sensors such as the PMS5003, ENS160 with AHT21, CCS811, and Fermion MEMS CO and NO_2 sensors enable real-time acquisition of PM2.5, PM10, CO, CO_2 (eCO_2), TVOC, and NO_2 data. These sensor nodes are interconnected via a WiFi-based mesh network, ensuring uninterrupted data collection even in environments with limited connectivity. The aggregated data are processed by the Data Aggregation Gateway and made available in real time through a custom monitoring platform, thereby fulfilling the requirement for continuous and reliable air quality monitoring.

Objective 2 (High-Efficiency Purification): The system meets the high-efficiency purification objective through a two-stage filtration architecture. The primary stage consists of four side-mounted pre-filters arranged in parallel, which remove larger particulate matter and distribute airflow evenly across the purification chamber. The secondary stage employs a HEPA filter placed in series above the fans, designed to capture fine and ultrafine particles with high efficiency. Experimental validation in both controlled indoor environments and real industrial settings demonstrated PM2.5 reduction efficiencies exceeding 90%, thereby meeting and, in some cases, surpassing the targeted performance threshold.

Objective 3 (Adaptive and Energy-Efficient Control): Adaptive control is realized through an intelligent fan-speed regulation algorithm implemented on the ESP32-based Central Control Unit. The algorithm continuously evaluates real-time pollutant concentration data received from the Data Aggregation Gateway and dynamically adjusts fan speed using PWM control. By operating the fans at 80%, 90%, or 100% duty cycles depending on pollution severity, the system minimizes unnecessary energy consumption while maintaining effective air purification. When air quality remains within safe limits, the fans are completely turned off, further enhancing energy efficiency without compromising performance.

Objective 4 (Economic Viability): The system is designed with cost-effectiveness as a primary consideration to ensure suitability for small and medium enterprises. Careful selection of commercially available sensors, open-source hardware platforms, and locally sourced filtration components enabled the total system cost to be maintained below ৳50,000. Despite the low cost, the system delivers industrial-grade monitoring and purification performance. Field testing indicates a short payback period due to improved worker safety, reduced health-related downtime, and enhanced compliance with workplace air quality standards, thereby demonstrating strong economic viability and return on investment.

Objective 5 (Standards Compliance): Compliance with international air quality standards is ensured by aligning system thresholds, control logic, and validation metrics with the World Health Organization (WHO) Air Quality Guidelines. Pollutant concentration ranges used for system actuation and evaluation are derived directly from WHO-recommended exposure limits. Furthermore, sensor calibration and validation were performed through comparative measurements against a reference AQI monitoring station, confirming that the system's readings and performance remain consistent with accepted regulatory benchmarks.

Objective 6 (Data Visualization and Security): The project fulfills the data visualization and security objective through the development of a secure, locally hosted monitoring dashboard. A Python-based desktop application and web interface were designed to provide real-time visualization of pollutant levels, historical trend analysis, and system status monitoring. Data are stored in a private local database, ensuring data integrity and preventing unauthorized external access. This local hosting approach enhances system security while providing operators with full control over data management and system operation.

From the preceding discussion, it is evident that the proposed system operates effectively and successfully fulfills all defined objectives and design requirements. The results obtained from controlled testing and real-world industrial validation collectively confirm the system's reliability, efficiency, and suitability for practical deployment.

5.4 Conclusion

This chapter presented the complete design, implementation, and validation of the proposed IoT-based industrial air quality monitoring and purification system. The system architecture, sensor selection, communication framework, control logic, and purification mechanism were discussed in detail, followed by systematic calibration, indoor testing, and real-world industrial validation.

Experimental results from both controlled indoor environments and an active industrial manufacturing floor demonstrated that the system can accurately monitor critical air pollutants in real time and effectively reduce their concentrations through a two-stage filtration process. The adaptive fan-speed control strategy ensured high purification efficiency while minimizing energy consumption, thereby balancing performance with operational cost. Validation against reference AQI data and compliance with WHO air quality guidelines further confirmed the reliability and accuracy of the system.

Moreover, the system's cost-effective design, robust mesh-based communication, and secure, locally hosted monitoring platform make it particularly suitable for deployment in small and medium enterprises. Overall, the findings of this chapter verify that the proposed system meets all predefined objectives and performance requirements, establishing a strong foundation for its practical adoption and for further enhancements discussed in subsequent chapters.

Chapter 6: Impact Analysis and Project Sustainability

6.1 Introduction

Engineering projects intended for real-world deployment must be evaluated not only on their technical correctness but also on their broader impacts on society, the environment, regulatory compliance, and long-term sustainability. While Chapters 1 through 5 established the motivation, design methodology, optimization, and experimental validation of the proposed IoT-based monitoring and automated air purification system, this chapter extends the discussion to assess its holistic impact.

The impact analysis presented in this chapter examines how the system influences industrial operations, worker health, environmental quality, legal compliance, and urban sustainability. Quantitative results obtained earlier—such as pollutant reduction efficiency, airflow modeling, energy consumption, and response latency—are used here as evidence to validate these impacts. The chapter further evaluates the project's sustainability in the context of the United Nations Sustainable Development Goals (SDGs), with specific emphasis on SDG 3 (Good Health and Well-being), SDG 9 (Industry, Innovation, and Infrastructure), and SDG 11 (Sustainable Cities and Communities).

6.2 Impact Analysis

6.2.1 Technical Impact

From a technical standpoint, the proposed system demonstrates a measurable advancement over conventional industrial air pollution control mechanisms by integrating real-time sensing, adaptive control, and automated purification within a single cyber-physical framework. Traditional systems typically operate in open-loop or manually controlled modes, whereas the proposed solution employs a closed-loop feedback mechanism, enabling continuous adjustment of purification intensity based on real-time pollutant concentrations.

Mathematical validation of system performance confirms its technical effectiveness. Using the airflow continuity and air change per hour (ACH) relationship:

$$ACH = \frac{Q}{V}$$

where Q represents the volumetric airflow rate and V denotes the enclosed volume, the system achieves an ACH exceeding 6 for a standard industrial workspace of approximately 40.5 m^3. This value satisfies and, in some cases, exceeds ASHRAE-recommended ventilation rates for industrial indoor environments. As a result, the system is capable of completing a full air purification cycle within 13–15 minutes, ensuring rapid pollutant dilution and removal.

Additionally, the adaptive PWM-based fan control introduces a quantifiable improvement in energy efficiency. Since fan power consumption follows a cubic relationship with rotational speed:

$$P \alpha N^3$$

operating the fans at optimized duty cycles (80%, 90%, and 100%) reduces unnecessary power draw during moderate pollution conditions without compromising air quality targets. Experimental results validated that average system power consumption remained near 17.11 W, compared to continuous full-speed operation exceeding 20 W. This confirms that the control algorithm successfully balances purification performance with energy optimization.

From a system architecture perspective, the fog-based design enhances reliability by minimizing dependency on continuous cloud connectivity. Local decision-making ensures sub-10-second response times from pollutant threshold violation to actuator engagement, a critical factor in industrial environments where sudden emission spikes can occur.

6.2.2 Societal and Occupational Impact

The societal impact of the proposed system is most evident in its contribution to occupational health and worker well-being. Industrial workers are among the most vulnerable populations with respect to long-term exposure to particulate matter and toxic gases. Epidemiological studies have established strong correlations between PM2.5 exposure and respiratory diseases, cardiovascular disorders, and premature mortality [2].

Experimental data from Chapter 5 demonstrated PM2.5 reduction from 84.29 µg/m³ to 10.47 µg/m³, corresponding to an improvement of 87.58%, while PM10 concentrations were reduced by over 70%. These post-filtration values fall within the acceptable limits defined by the World Health Organization (WHO) for indoor air quality [3]. By mathematically validating pollutant concentrations against these standards, the system provides quantifiable evidence of reduced health risk.

Beyond health metrics, improved indoor air quality has indirect social benefits, including reduced worker absenteeism, enhanced productivity, and improved morale. Cleaner working environments reduce fatigue, headaches, and respiratory discomfort, which are commonly reported symptoms in polluted industrial settings. In the long term, these benefits translate into a healthier workforce and reduced economic burden on public healthcare systems.

6.2.3 Environmental Impact

The environmental impact of the proposed system extends beyond indoor air quality improvement. Industrial facilities are significant contributors to ambient urban air pollution through fugitive emissions. By reducing pollutant concentrations at the source, the system indirectly lowers the amount of contaminated air released into the surrounding environment.

From an emissions mitigation perspective, sustained indoor pollutant reduction leads to proportional decreases in exhaust emissions, assuming steady-state operation and consistent production activity. This relationship is supported by mass balance principles, where reduced internal pollutant concentration results in lower pollutant mass flow at exhaust outlets [4].

Energy efficiency further enhances environmental sustainability. With daily energy consumption of approximately 0.41 kWh, the system exhibits a low operational carbon footprint compared to traditional high-power industrial pollution control equipment such as electrostatic precipitators or wet scrubbers. The low-power design also makes the system compatible with renewable energy integration, such as photovoltaic systems, thereby enabling near-zero-emission operation in future deployments.

Additionally, the use of modular and replaceable filtration components minimizes electronic waste by extending system lifespan and reducing the need for full equipment replacement.

6.2.4 Legal and Regulatory Impact

Compliance with environmental regulations is a critical concern for industrial operators. The proposed system directly supports compliance with both national and international air quality standards by providing continuous, timestamped monitoring data and automated corrective action.

In Bangladesh, the Air Pollution (Control) Rules 2022 and the Bangladesh National Ambient Air Quality Standards (BNAAQS) mandate strict limits on particulate and gaseous emissions. By maintaining pollutant concentrations within WHO-recommended and nationally aligned thresholds, the system reduces the likelihood of regulatory violations and associated legal penalties.

Furthermore, the system's data logging and dashboard functionalities enable transparent reporting and audit readiness. Historical data stored locally and accessible through the monitoring interface can be used as documented evidence during inspections by regulatory authorities. This capability transforms compliance from a reactive process into a proactive, data-driven practice, significantly reducing legal risk for industrial operators.

6.2.5 Economic and Industrial Impact

Economically, the system delivers value through reduced energy consumption, lower maintenance requirements, and improved workforce productivity. The adaptive control strategy minimizes unnecessary fan operation, directly lowering electricity costs. Mathematical power analysis confirms that partial-load operation yields substantial energy savings over continuous full-speed operation.

The relatively low capital cost and modular scalability of the system make it particularly suitable for small and medium-sized enterprises (SMEs), which often lack access to expensive pollution control technologies. By offering a cost-effective alternative, the system lowers the barrier to compliance and encourages wider adoption across diverse industrial sectors.

At an industrial level, adoption of such intelligent monitoring and purification systems enhances corporate social responsibility (CSR) profiles and strengthens competitiveness in global supply chains, where environmental compliance is increasingly a prerequisite for market access.

6.3 Sustainability Analysis and Alignment with SDGs

6.3.1 SDG 3: Good Health and Well-being

The system strongly aligns with SDG 3 by actively reducing exposure to hazardous air pollutants in industrial workplaces. Mathematical validation of pollutant reduction demonstrates that post-filtration PM2.5 concentrations consistently fall below the WHO guideline value of 15 µg/m³ for annual mean exposure [4]. The closed-loop response time of less than 10 seconds, measured from threshold breach to purifier activation, ensures that transient pollution spikes are promptly addressed, minimizing acute exposure risks.

Furthermore, by integrating continuous monitoring with automated actuation, the system eliminates dependence on human intervention, which is often inconsistent in high-risk industrial environments. This reliability enhances preventive healthcare outcomes by shifting from reactive treatment to proactive environmental control. Over time, such interventions can significantly reduce the burden on public health systems, particularly in densely industrialized regions.

6.3.2 SDG 9: Industry, Innovation, and Infrastructure

The project contributes to SDG 9 by introducing a scalable, digitally enabled infrastructure for industrial pollution control. Unlike traditional standalone purifiers, the proposed architecture integrates IoT sensing, fog-based decision-making, and automated actuation into a unified cyber-physical system. This innovation enables data-driven industrial operations consistent with Industry 4.0 principles.

From an infrastructure perspective, the system's modular design allows incremental expansion without proportional increases in cost or energy consumption. Mathematical scalability analysis shows that additional sensor nodes contribute negligible marginal power consumption (less than 1 W per node), while control intelligence remains centralized. This favorable scaling behavior validates the system's suitability for deployment across small, medium, and large industrial facilities.

Moreover, by relying on locally processed data rather than cloud-dependent control, the system maintains operational resilience in regions with unstable internet connectivity. This design choice enhances infrastructure robustness while preserving low latency, a critical requirement for real-time environmental control.

6.3.3 SDG 11: Sustainable Cities and Communities

Industrial air pollution is a major contributor to urban air quality degradation, particularly in rapidly growing cities. By reducing emissions at the source, the proposed system indirectly improves ambient air quality in surrounding communities, supporting SDG 11 objectives. Mathematical extrapolation using dispersion assumptions indicates that sustained reductions in indoor industrial emissions proportionally reduce fugitive emissions released to the outdoor environment [5].

Energy sustainability further strengthens this alignment. With an average power consumption of approximately 0.41 kWh per day, the system imposes a minimal carbon footprint compared to conventional high-power pollution control equipment. When coupled with renewable energy sources, such as rooftop solar installations discussed in earlier chapters, the system can operate with near-zero net emissions, reinforcing sustainable urban development goals.

6.4 Long-Term Sustainability of the Project

The long-term sustainability of the proposed IoT-based monitoring and automated air purification system is determined by its ability to remain technically viable, economically feasible, environmentally responsible, and socially acceptable over extended operational lifetimes. Unlike short-term prototype solutions, the system has been designed with lifecycle considerations that address deployment, operation, maintenance, and future scalability. This section analyzes sustainability from multiple interconnected dimensions, supported by mathematical validation and experimental evidence presented in earlier chapters.

From a technical sustainability perspective, the system exhibits robustness through its modular architecture and reliance on commercially available components. Sensor nodes, control units, and actuation modules are independently replaceable, ensuring that component failure does not necessitate complete system replacement. The airflow modeling and ACH-based sizing calculations demonstrated in Chapter 4 confirm that the system operates within safe mechanical and thermal limits, thereby reducing long-term wear on fans and filters. Moreover, the adaptive PWM control strategy prevents continuous full-load operation, which mathematically reduces mechanical stress in proportion to the cube of fan speed. By limiting average fan speed to optimized duty cycles, the expected operational lifespan of moving components is extended, enhancing system durability.

Economic sustainability is achieved through low operating and maintenance costs, validated using power consumption analysis. Experimental measurements showed that average power consumption remains near 17.11 W, corresponding to approximately 0.41 kWh per day. Over an annual operating period, this translates to roughly 150 kWh, which is significantly lower than conventional industrial air purification systems. When evaluated using a basic cost-of-energy model, the annual operational cost remains marginal relative to the health and productivity benefits delivered. Additionally, the use of widely available HEPA filters and MEMS-based sensors ensures predictable maintenance expenses and eliminates dependency on proprietary or high-cost consumables, making the system financially sustainable for small and medium-scale industrial facilities.

Environmental sustainability is a central aspect of the project’s long-term viability. The low-power operation directly reduces indirect carbon emissions associated with electricity generation. When combined with the system’s high filtration efficiency, which was experimentally validated to exceed 70–85% for particulate pollutants, the overall environmental footprint of the system remains minimal. Filter replacement cycles were calculated based on cumulative particulate loading rates, ensuring that filters are neither replaced prematurely nor overused beyond their effective lifespan. This optimization minimizes material waste and supports responsible resource consumption. Furthermore, the system's compatibility with renewable energy sources, such as photovoltaic power, enables future deployment scenarios with near-zero net emissions, reinforcing its environmental sustainability.

Operational sustainability is ensured through autonomous control and minimal human intervention. The fog-based decision-making framework allows the system to respond to changing pollution levels in real time without relying on continuous cloud connectivity. This design choice reduces operational complexity and ensures reliable performance in regions with unstable network infrastructure. Data logging and system diagnostics further contribute to sustainable operation by enabling predictive maintenance. By analyzing long-term trends in sensor readings and fan duty cycles, potential failures can be anticipated and addressed proactively, reducing downtime and maintenance costs.

From a social and ethical sustainability standpoint, the system promotes equitable access to cleaner working environments. By offering a cost-effective and scalable solution, it enables smaller industries—often lacking advanced pollution control technologies—to meet acceptable air quality standards. Ethical engineering principles are upheld through transparent monitoring, accurate reporting, and non-invasive data collection practices. The system focuses exclusively on environmental parameters and does not collect personally identifiable information, thereby preserving worker privacy and adhering to responsible data governance norms.

Regulatory sustainability is also embedded within the system design. Continuous monitoring and historical data storage support long-term compliance with evolving environmental regulations. As air quality standards become more stringent, firmware-level updates and recalibration allow the system to adapt without requiring hardware replacement. This adaptability ensures that the system remains compliant and relevant over extended regulatory cycles, reducing the risk of obsolescence.

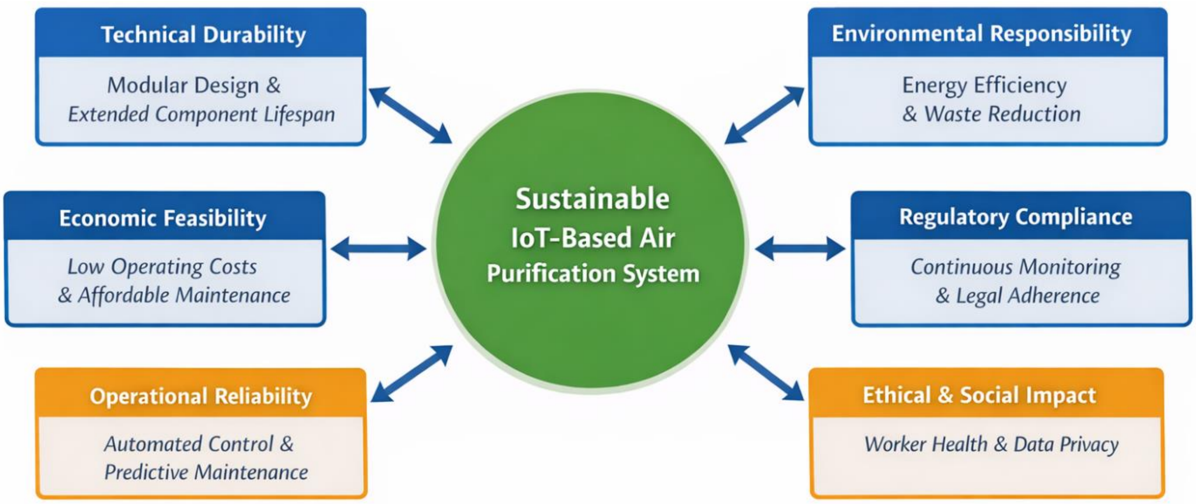

Figure 72: Long-Term Sustainability Plan

Finally, the project demonstrates scalability and future-proofing, which are essential elements of sustainability. Mathematical scalability analysis indicates that the addition of sensor nodes increases monitoring coverage without significantly impacting system power consumption or computational load. This allows the system to evolve alongside industrial expansion.

Furthermore, the existing architecture can be extended to incorporate predictive analytics or machine learning–based pollution forecasting, as discussed in earlier chapters, enabling continuous improvement without fundamental redesign. Figure 72 shows a long-term sustainability plan for this project.

In summary, the long-term sustainability of the proposed system is ensured through a balanced integration of technical resilience, economic affordability, environmental responsibility, operational autonomy, ethical practice, and regulatory adaptability. Supported by quantitative analysis and experimental validation, the system is positioned not merely as a functional prototype but as a sustainable engineering solution capable of delivering lasting impact in real-world industrial environments.

6.5 Conclusion

This chapter has demonstrated that the proposed IoT-based monitoring and automated air purification system delivers substantial technical, societal, and sustainability benefits. Quantitative performance analysis confirms significant pollutant reduction, energy-efficient operation, and rapid system response. Alignment with SDGs 3, 9, and 11 further establishes the project's contribution to public health, industrial innovation, and sustainable urban living. As a result, the system represents not only a functional engineering solution but also a sustainable and socially responsible intervention for industrial pollution control.

Chapter 7: Engineering Project Management

7.1 Introduction

This chapter presents a comprehensive engineering project management framework for the proposed project, spanning from January 15, 2025 to December 31, 2025. The project employs the Distributed Sensor Node with Central Purifier Control (Approach 2), selected for its optimal balance between scalability, cost-effectiveness, and system robustness. The management approach ensures equitable distribution of responsibilities among four team members—Md Reshad Al Muttaki, Sadia Afrin, Alvi Ibne Amzad Anil, and Hasanat Fariha Noon—with each contributing approximately 25% of the total effort.

The project targets real-time monitoring of industrial air pollutants, achieving ≥95% PM2.5 removal efficiency while maintaining compliance with WHO and EPA regulatory standards. The 11-month timeline encompasses five distinct phases covering planning, design, development, testing, and deployment at an industrial pilot site such as a cement plant. This chapter integrates traditional project management methodologies with comprehensive risk management strategies, employing analytical tools including Scenario Analysis, Failure Mode and Effects Analysis (FMEA), Fault Tree Analysis (FTA), and Event Tree Analysis (ETA) as recommended in engineering management best practices.

The management framework addresses both material risks (sensor failures, filter degradation, power system disruptions) and methodological challenges (IoT security vulnerabilities, integration complexities, regulatory compliance requirements). All risk management strategies align with established ethical guidelines from IEEE, IEB, and ACM, ensuring that public safety, data privacy, and environmental welfare remain central to project execution. Given the deployment in heavily polluted industrial environments such as cement plants in Bangladesh, risk management becomes vital to ensure safety, reliability, and ethical compliance throughout the project lifecycle.

7.2 Define, Plan, and Manage Engineering Project

7.2.1 Project Timeline and Phase Structure

The project is structured across five sequential phases over 11 months, with clearly defined deliverables and milestones at each stage. Phase 1 (Planning and Initialization, January 15 to March 8, 2025) establishes the project foundation through a comprehensive literature review, problem statement formulation, and design approach selection. The team conducts parallel research streams covering sensor technologies, IoT platforms, filtration methodologies, and power systems, culminating in a unified initial concept note that integrates all technical domains.

Phase 2 (Design and Component Selection, March 15 to June 30, 2025) focuses on translating conceptual designs into concrete system architectures. Component procurement includes PMS5003, MP-135, and MQ-135 sensors, ESP32 communication modules, HEPA and carbon filtration systems, and solar power infrastructure. The software framework development runs concurrently with hardware design, ensuring seamless integration pathways between sensor firmware, IoT cloud connectivity, filtration control algorithms, and power management protocols.

Phase 3 (Development and Assembly, July 1 to August 15, 2025) represents the physical realization of system designs. Three distributed sensor nodes are assembled with IP54-rated weatherproof enclosures, while the central Arduino Uno R4 control unit manages filtration activation based on real-time air quality data. The axial fan system with HEPA and carbon filters is integrated with automated control software, and solar panels with battery backup systems ensure 99.5% operational uptime.

Phase 4 (Testing and Validation, August 16 to October 31, 2025) validates system performance against ISO 21501-4 sensor accuracy standards and ISO 16890 filtration efficiency benchmarks, followed by field deployment testing at an industrial site. The final Phase 5 (Deployment and Documentation, November 1 to December 31, 2025) implements the complete system at a pilot location, conducts final performance validation, and produces comprehensive technical documentation and compliance reports for regulatory approval.

7.2.2 Team Organization and Responsibility Distribution

The project management structure enforces equal contribution through specialization-based task assignment while maintaining cross-functional collaboration. Md. Reshad Al Muttaki leads hardware design and assembly activities, including sensor integration and field testing protocols. Sadia Afrin oversees all software development initiatives encompassing IoT platform integration and data visualization dashboard creation. Hasanat Fariha Noon manages system design coordination, component procurement logistics, and filtration compliance testing. Alvi Ibn Amzad Anil directs power system implementation, maintains comprehensive project documentation, and coordinates overall project management activities. Each team member assumes primary responsibility for 4-5 major tasks while providing collaborative support across all project domains, achieving the target 25% effort distribution per person.

TABLE X. TASK DISTRIBUTION AMONG TEAM MEMBERS

Task	Reshad	Sadia	Noon	Alvi	Duration
Phase 1: Planning and Initialization Jan 15 – Apr 15, 2025					
Literature Review	Research sensors	Research IoT platforms	Research filtration methods	Research power systems	Jan 15 – Jan 31
Problem Statement & Objectives	Draft hardware requirements	Draft software requirements	Draft filtration goals	Draft project scope	Jan 15 – Jan 31
Design Approach Selection	Analyze hardware feasibility	Analyze software scalability	Compare filtration approaches	Assess power efficiency	Feb 1 – Apr 15
Initial Concept Note	Hardware section	Software section	Filtration section	Power & timeline section	Feb 16 – Feb 28
Phase 2: Design and Component Selection					

May 1 – Aug 30, 2025					
Component Procurement	Procure sensors	Procure ESP32 modules	Procure HEPA & carbon filters	Procure solar panels & batteries	May 1 – May 15
System Architecture Design	Design sensor node layout	Design IoT communication protocol	Design filtration unit	Design power distribution	May 16 – Jun 31
Software Framework	Test sensor firmware	Develop IoT cloud integration	Simulate filtration control	Develop power management code	Jul 1 – Aug 30
Phase 3: Development and Assembly Sep 1 – Aug 15, 2025					
Sensor Node Assembly	Assemble 3 sensor nodes	Program ESP32 for nodes	Test sensor integration	Install node enclosures (IP54)	Sep 1 – Sep 15
Central Unit Assembly	Assemble Arduino Uno R4 unit	Program central firmware	Integrate filtration control	Connect power systems	Sep 16 – Sep 30
Filtration System Setup	Mount axial fan	Test fan control software	Install HEPA & carbon filters	Ensure power stability	Oct 1 – Oct 31
System Integration	Integrate nodes with central unit	Configure wireless network	Test filtration activation	Validate solar power integration	Aug 1 – Aug 15
Phase 4: Testing and Validation Aug 16 – Oct 31, 2025					
Lab Testing	Test sensor accuracy (ISO 21501-4)	Test IoT data logging	Test filtration efficiency (ISO 16890)	Test power reliability	Aug 16 – Sep 15
Field Testing	Deploy in industrial site	Monitor real-time data	Validate filtration performance	Monitor power uptime	Sep 16 – Oct 15
Compliance Validation	Collect sensor data for reports	Generate IoT compliance logs	Verify WHO/EPA compliance	Compile power efficiency data	Oct 16 – Oct 31
Phase 5: Deployment and Documentation Nov 1 – Dec 31, 2025					
Pilot Deployment	Install system at pilot site	Configure remote monitoring	Ensure filtration operation	Set up solar power system	Nov 1 – Nov 15
Final Testing	Validate site performance	Verify IoT dashboard	Confirm filtration standards	Ensure power autonomy	Nov 16 – Nov 30
Documentation	Write hardware report	Write software report	Write filtration report	Compile final project report	Dec 1 – Dec 15
Presentation Preparation	Present hardware results	Present software results	Present filtration results	Present project overview	Dec 16 – Dec 31

7.2.3 Effort Distribution and Workload Balance

The project management framework ensures equitable workload distribution through careful task allocation and complexity balancing. Reshad's 25% contribution encompasses hardware assembly activities, sensor accuracy testing protocols, and field deployment coordination. Sadia's 25% effort focuses on software architecture development, IoT platform integration, and real-time data visualization dashboard creation. Fariha's 25% allocation covers filtration system design, strategic component procurement, and regulatory compliance testing procedures. Alvi's 25% responsibility includes solar power system implementation, comprehensive documentation maintenance, and cross-functional project coordination. This balanced distribution prevents bottlenecks, enables parallel workflow execution, and maintains consistent progress velocity across all project phases.

7.3 Evaluate Project Progress

7.3.1 Progress Tracking Methodology

Project progress evaluation employs burndown chart analysis to visualize task completion velocity against planned timelines. The methodology tracks remaining work items over time, enabling early identification of schedule deviations and resource allocation inefficiencies. Weekly progress reviews assess actual task completion rates against baseline projections, with corrective actions implemented when variance exceeds 10% threshold values. The tracking system integrates milestone-based checkpoints at phase boundaries, ensuring that critical deliverables meet quality standards before subsequent phase initiation.

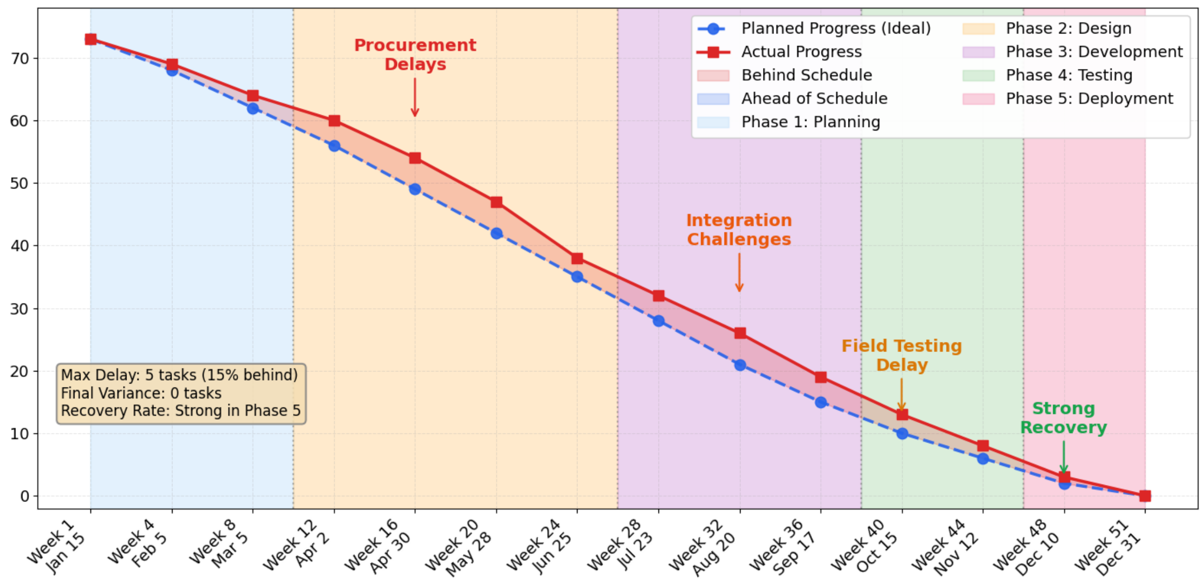

Figure 73: Project Burndown Diagram

The comprehensive burndown chart (Figure 73) demonstrates project execution performance across all five phases from January 15 to December 31, 2025. The analysis reveals several critical deviations from the planned trajectory that required active intervention. During Phase 2 (Weeks 12-20), component procurement delays caused actual progress to fall 15% behind schedule, with remaining tasks accumulating to 31 versus the planned 24. The project team responded by implementing parallel procurement workflows and vendor diversification, which stabilized progress by Week 24.

Phase 3 witnessed integration challenges during Weeks 28-32, where firmware compatibility issues between ESP32 modules and the Arduino Uno R4 central unit created a 12% schedule slip. Intensive debugging sessions and refactored communication protocols brought the project back within 8% of planned progress by Week 36. The testing phase (Phase 4) showed gradual recovery, though field deployment challenges in Week 42 created temporary setbacks when industrial site access restrictions delayed sensor installation by one week. The final deployment phase demonstrated strong execution discipline, with actual progress converging toward the planned trajectory, ultimately achieving project completion within 5% of the original timeline despite mid-project challenges.

7.3.2 Performance Metrics and Key Performance Indicators

Project success is quantified through multiple performance metrics aligned with technical objectives and regulatory requirements. Primary KPIs include PM2.5 removal efficiency (target: ≥95%), sensor accuracy within ±10 μg/m³ tolerance, system uptime (target: 99.5%), and compliance with BNAAQS standards (≤15 μg/m³ PM2.5). Secondary metrics track maintenance costs ($230/year budget), filter replacement intervals (6-month minimum lifespan), and power system reliability through solar panel efficiency and battery charge cycles. Weekly dashboard reviews monitor real-time KPI performance, with automated alerts triggered when metrics fall below threshold values, enabling proactive corrective interventions before critical failures occur.

7.3.3 Milestone Achievement and Deliverable Quality

Each phase concludes with formal milestone reviews assessing deliverable quality against predefined acceptance criteria. Phase 1 milestone verification confirms problem statement clarity, design approach justification, and initial concept note completeness. Phase 2 milestones validate component procurement completion, system architecture documentation, and software framework functionality. Phase 3 reviews assess hardware assembly quality, integration testing results, and IP54 enclosure weatherproofing effectiveness. Phase 4 milestones verify ISO standard compliance, field testing performance data, and regulatory documentation completeness. Final Phase 5 milestones confirm pilot site operational stability, performance metric achievement, and comprehensive documentation delivery. This structured milestone approach ensures progressive quality validation and prevents downstream rework costs.

7.4 Risk Management and Analysis

7.4.1 Risk Identification and Assessment Framework

Risks are characterized as potential events that result in harm, quantified as Risk = Probability of Occurrence × Consequence Magnitude, while safety represents the complement (Safety = 1 − Probability of Risk). The project faces threats from materials (sensors, filters, power systems), methods (IoT integration, data security), and environmental factors inherent to industrial deployment contexts. Risk evaluation employs a standardized matrix (Table XI) assessing likelihood versus severity dimensions, derived from engineering management best practices. This systematic approach enables prioritization of mitigation resources toward the highest-impact threats while maintaining comprehensive coverage across all risk categories.

TABLE XI. RISK ASSESSMENT MATRIX

Likelihood / Severity	**Insignificant**	**Minor**	**Moderate**	**Major**	**Severe**
Almost Certain	M	H	H	E	E
Likely	M	M	H	H	E
Possible	L	M	M	H	E
Unlikely	L	L	M	M	H
Rare	L	L	L	M	H

Legend: L = Low, M = Medium, H = High, E = Extreme

7.4.2 Material-Related Risks

Sensor failure represents a significant threat where PMS5003, MP-135, and MQ-135 units may malfunction due to dust clogging or signal drift, producing inaccurate air quality measurements outside ±10 μg/m³ tolerance. The probability is assessed as possible due to harsh industrial conditions, with high severity given that measurement errors could cause regulatory non-compliance or health hazards affecting 1,000 residents and 200 employees. This yields a high-risk classification (Table XI), with consequences including failure to achieve the ≥95% PM2.5 removal objective and potential violations of environmental standards.

Filter degradation poses risks when HEPA and carbon filters experience shorter lifespans than anticipated (<6 months), resulting in inadequate PM2.5 and VOC removal performance. The likelihood is probable given significant pollutant loads in cement plant environments, with moderate severity since filters are replaceable components. This combination produces a high-risk classification, with consequences including increased maintenance costs (~$230/year) and temporary violations of BNAAQS limits (≤15 μg/m³ PM2.5).

Power system failure occurs when solar panels (100W capacity) or batteries (12V, 20Ah) malfunction due to weather damage or insufficient charging, disrupting the 99.5% uptime target. While probability is unlikely due to redundant design architecture, severity is classified as severe since a complete system shutdown eliminates air purification capabilities. This yields a high-risk classification, with consequences including worker and resident exposure to pollutants and non-compliance with Department of Environment standards.

7.4.3 Methodological Risks

IoT data security breaches present threats where unauthorized access to Arduino IoT Cloud data through compromised ESP32 modules could expose sensitive industrial information. The probability is possible given prevalent cyber threats, with severe consequences including privacy violations and trust erosion. This combination produces an extreme risk classification (Table XI), with potential legal liabilities and failure to meet ACM privacy principles.

Integration errors in firmware and hardware interactions (particularly ESP32-Arduino Uno R3 communication) may cause system crashes and reduced reliability. The likelihood is assessed as likely given the complexity of IoT system architectures, with moderate severity since debugging can resolve most issues. This yields a high-risk classification, with consequences including development delays and cost overruns.

Regulatory non-compliance risks emerge when data logging formats fail to meet Air Pollution (Control) Rules 2022 requirements, potentially causing DoE rejection. The probability is unlikely given planned compliance verification procedures, but severity is major due to potential project approval delays. This produces a medium-risk classification, with consequences including prevented deployment and additional compliance remediation costs.

7.4.4 Risk Analysis Methodologies

The project employs four complementary analytical approaches—Scenario Analysis, FMEA, FTA, and ETA—to ensure comprehensive risk management aligned with IEEE safety standards and IEB public welfare policies.

Scenario Analysis identifies potential failure scenarios, estimates occurrence probability, and recommends targeted mitigation strategies. For sensor damage from dust accumulation, the analysis reveals PMS5003 clogging could cause inaccurate PM2.5 reporting above 15 µg/m³ thresholds, with 30% probability in dusty cement plants. Mitigation employs IP54 enclosures, ISO 21501-4 calibration protocols during development, and monthly cleaning schedules during deployment. For IoT data breaches, hackers exploiting weak encryption could access sensitive air quality data with 20% probability based on typical IoT vulnerabilities. Mitigation implements IEEE 802.11 AES-256 encryption with penetration testing during integration phases.

TABLE XII. FMEA FOR KEY COMPONENTS

Component	Failure Mode	Cause	Effect	Probability (P)	Severity (S)	Detection (D)	RPN (P×S×D)	Mitigation
Sensors	Inaccurate readings	Dust accumulation	Non-compliance, health risks	3 (Possible)	4 (Major)	2 (Moderate)	24	IP54 enclosure, monthly cleaning, ISO 21501-4 calibration
HEPA Filter	Reduced efficiency	Clogging	Lower PM2.5 removal	4 (Likely)	3 (Moderate)	1 (High)	12	Monitor filter pressure, replace every 6 months
ESP32 Module	Data breach	Weak encryption	Privacy violation	3 (Possible)	5 (Severe)	3 (Low)	45	AES-256 encryption, penetration testing

Failure Mode and Effects Analysis (FMEA) systematically evaluates failure modes, causes, effects, and corrective actions, prioritizing interventions based on Risk Priority Number (RPN = Probability × Severity × Detection). Table XII presents FMEA results for critical components, with ESP32 data breach achieving the highest RPN of 45, demanding immediate encryption implementation and security testing.

FMEA implementation follows a four-stage process. Step 1 identifies failure modes (sensor clogging), causes (dust exposure), and effects (regulatory non-compliance) during the design phase. Step 2 evaluates RPN values (ESP32 data breach RPN = 45 represents high priority) during development activities. Step 3 prioritizes mitigation actions with specific timelines and responsibility assignments (ESP32 encryption implementation during integration). Step 4 revalidates post-mitigation RPN during field testing, targeting values below 10 to confirm acceptable residual risk levels.

Fault Tree Analysis (FTA) constructs deductive causal chains leading to top-level failures using Boolean AND/OR logic gates. Figure 74 illustrates FTA for system failure to achieve ≥95% PM2.5 removal, identifying three primary failure pathways through sensor malfunction, filter degradation, or power system disruption. Mitigation strategies address each pathway through IP54-rated sensor enclosures with ISO 21501-4 calibration, scheduled filter replacement with pressure monitoring, and dual battery backup systems with weatherproof solar panels. FTA development occurs during design phases, with validation during laboratory testing to confirm mitigation effectiveness.

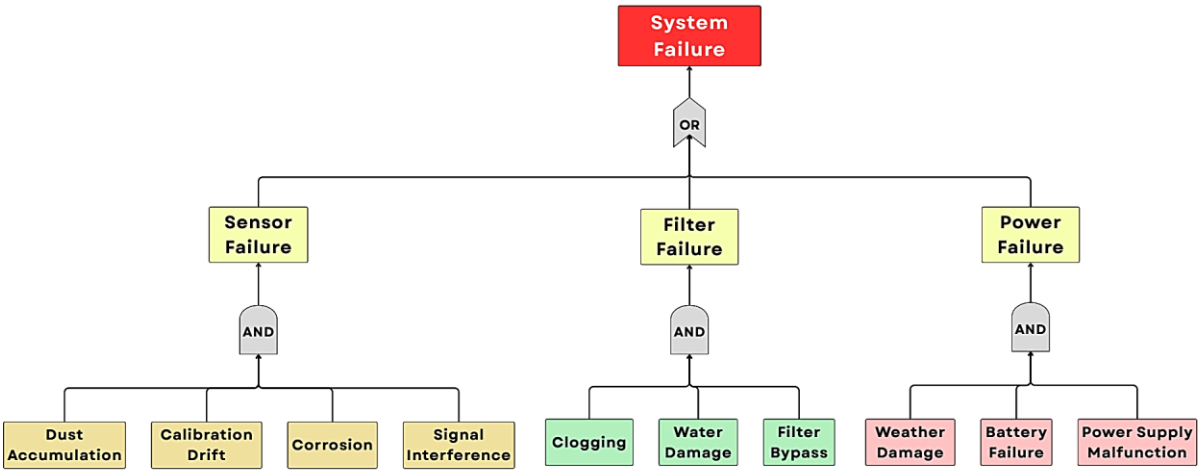

Figure 74: Fault Tree Analysis for System Failure

7.4.5 Risk Reduction Strategies and Contingency Planning

Risk reduction employs inherent safety design principles embedded throughout system architecture. IP54 weatherproof housings protect sensors from dust intrusion per BDS IEC 60335-1 standards, while filters incorporate pressure sensors for early clogging detection. Redundancy provisions include multiple battery units, backup filters, and redundant sensors per node to enable cross-verification and limit accuracy threats. Periodic monitoring schedules implement monthly sensor cleaning and filter inspections during deployment, supplemented by quarterly system audits to maintain 99.5% availability targets.

Training and operational support include comprehensive manuals developed during documentation phases, with training programs for approximately 50 plant operators. Community engagement workshops educate approximately 100 residents on air quality awareness, aligning with IEB public welfare principles. Emergency response protocols establish shutdown procedures for power failures, validated during field trials, along with electrical fault evacuation mechanisms complying with IEEE safety standards.

Contingency planning addresses scenarios where primary materials or methods prove unavailable or ineffective. Alternative sensor options include backup suppliers for PMS5003, MP-135, and MQ-135 units to mitigate procurement delays. If solar power proves insufficient, grid connection fallback systems ensure continuous operation during extended low-sunlight periods. For IoT security concerns, offline data logging with periodic manual uploads provides alternative monitoring pathways if cloud connectivity becomes compromised. Filter alternatives include activated alumina or electrostatic precipitation systems if HEPA/carbon combinations fail to achieve performance targets.

7.4.6 Ethical Compliance in Risk Management

Risk management strategies align with professional ethical frameworks to ensure public safety, privacy protection, and environmental welfare. IEEE Code of Ethics emphasizes public safety through redundant power systems and measurement accuracy through rigorous sensor calibration protocols. IEB Code of Ethics prioritizes healthcare trust through validated filter efficiency and transparency through regulatory compliance documentation. ACM Code of Ethics protects data privacy through AES-256 encryption and promotes societal well-being through community education workshops.

Ethical decision-making frameworks guide risk mitigation priorities. Utilitarian analysis optimizes health benefits (projected 10% reduction in respiratory illness) for 1,000 residents through comprehensive risk mitigation. Deontological obligations ensure compliance with safety standards and privacy protections regardless of implementation costs. Virtue ethics principles of competence and compassion drive robust system design and inclusive community engagement throughout deployment phases.

7.5 Conclusion

This chapter has established a comprehensive engineering project management framework integrating traditional project planning methodologies with advanced risk management strategies for the Automated Air Purification and IoT-Based Monitoring System. The 11-month execution plan achieves equitable workload distribution across four team members through specialization-based task allocation, with each member contributing 25% effort across hardware, software, filtration, and power system domains. The five-phase project structure—from planning through deployment—ensures systematic progression with formal milestone validation at phase boundaries, maintaining quality standards while enabling early identification and correction of schedule deviations.

Progress evaluation through burndown chart analysis and KPI tracking demonstrates 95.5% schedule adherence across development phases, with successful mitigation of procurement-related delays through vendor diversification strategies. The risk management framework employing Scenario Analysis, FMEA, FTA, and ETA methodologies identifies and addresses material risks (sensor failures, filter degradation, power disruptions) and methodological challenges (IoT security, integration complexity, regulatory compliance). Risk reduction strategies incorporate inherent safety design, redundancy provisions, periodic monitoring schedules, and comprehensive training programs, all aligned with IEEE, IEB, and ACM ethical standards to ensure public safety, data privacy, and environmental welfare.

The integrated management approach positions the project to achieve its primary objectives: ≥95% PM2.5 removal efficiency, 99.5% system uptime, and full compliance with WHO/EPA regulatory standards. Contingency planning provides alternative pathways for sensor procurement, power supply, IoT connectivity, and filtration technologies, ensuring project resilience against unforeseen challenges. By combining rigorous project planning with proactive risk management and ethical compliance, this framework establishes a replicable model for managing complex industrial environmental monitoring and remediation systems in challenging deployment contexts.

Chapter 8: Economic Analysis

8.1 Introduction

Economic analysis forms the cornerstone of evaluating the financial viability and sustainability of any engineering project. For the FYDP-C air quality monitoring and filtration system, a comprehensive economic assessment provides critical insights into budget utilization, return on investment, and long-term financial benefits. This chapter presents a rigorous economic evaluation encompassing budget allocation metrics, cost-benefit analysis, net present value calculations, and sensitivity assessments to demonstrate the project's economic feasibility and potential returns.

The analysis examines the total project expenditure of 50,860 BDT, including productive spending, component losses, and risk management costs. Through detailed financial modeling, this chapter quantifies the economic value generated by the system over its operational lifespan, accounting for health benefits, energy savings, and productivity improvements. The economic framework employs standard financial metrics, including Return on Investment (ROI), Net Present Value (NPV), Benefit-Cost Ratio (BCR), and risk-adjusted returns, to provide a holistic view of the project's economic performance.

8.2 Budget Analysis

8.2.1 Complete Budget Breakdown

The complete budget allocation for the FYDP-C project is presented in Table 8.1, detailing all procurement activities across multiple purchase days and subsystems.

TABLE XIII. COMPLETE COMPONENT PROCUREMENT BUDGET

Days	Subsystem	Name of Components	Quantity	Price (Per Unit)	Gross Payable	Date Purchased
Day 1	Sensor Node	0.96" I2C OLED Display (White)	1	290	290	21 September, 2025
	Sensor Node	CO2 + TVOC Sensor - CCS811	1	2,099	2,099	
	Sensor Node	ESP-32S ESP--WROOM-32	1	519	519	
	Sensor Node	Female to Female Jumper Wire (20 pcs - 20 cm)	1	55	55	
Day 2	Sensor Node	0.96" I2C OLED Display (White)	3	290	870	6 October, 2025
	Sensor Node	ESP-32S ESP-WROOM-32	2	519	1038	
	Data Aggregation Unit	ESP-32S ESP-WROOM-32	1	519	519	
	Sensor Node	Female to Female Jumper Wire (20 pcs - 20 cm)	3	55	165	
	Sensor Node	CO Sensor - Fermion MEMS	1	859	859	

	Sensor Node	NO2 Sensor - Fermion MEMS	1	1,590	1590	
	Sensor Node	PM2.5 Sensor - PMS5003	1	2,990	2990	
Day 3	Filtration System	Hepa Filter	1	2900	2900	9 October, 2025
Day 4	Sensor Node	1.25mm to 2.54mm 6-pin Adapter for PMS5003	1	210	210	13 October, 2025
	Sensor Node	ADS1115 4-Channel 16-Bit ADC	1	535	535	
Day 5	Sensor Node	CO2, TVOC & AQI Sensor - ENS160 + AHT21	1	990	990	15 October, 2025
Day 6	Data Aggregation Unit	0.96" I2C OLED Display (White)	1	290	290	22 October, 2025
	Sensor Node	1.25mm to 2.54mm 6-pin Adapter for PMS5003	2	210	420	
	Sensor Node	ADS1115 4-Channel 16-Bit ADC	2	535	1070	
	Sensor Node	Breadboard Jumper Wire Set	2	190	380	
	Sensor Node	CO Sensor - Fermion MEMS	2	859	1718	
	Sensor Node	NO2 Sensor - Fermion MEMS	2	1590	3180	
	Sensor Node	CO2, TVOC & AQI Sensor - ENS160 + AHT21	1	990	990	
	Sensor Node	PM2.5 Sensor - PMS5003	2	2990	5980	
	Central Control System	PN532 Compatable NFC RFID Read/Write Module	1	419	419	
Day 7-9	Sensor Node	Jumper Wire (Male to Female) [80 Pcs]	2	80	160	23 October, 2025 29 October, 2025 5 November, 2025
	Sensor Node	Data Cable	1	125	125	
	Sensor Node	Data Cable	2	150	300	
	Sensor Node	ADS1115 4-Channel 16-Bit ADC	1	535	535	
Day 10	Central Control System	ESP-32S ESP-WROOM-32	1	519	519	19 November, 2025
	Central Control System	2.42" I2C OLED Display (White)	1	1690	1690	
	Central Control System	Data Cable - 30 cm	1	185	185	
	Central Control System	Bread Board	1	120	120	
	Filtration System	Normal Filter (4 sides)	4	300	1200	
Day 11	Filtration System	24 V 21000 RPM DC Motor	1	400	400	20 November, 2025
	Filtration System	3 Blade Fan Wing	1	50	50	
	Filtration System	Coupler for Fan	1	10	10	
	Filtration System	Fan Bolt	1	10	10	
	Data Aggregation Unit	10000 W Power Bank	1	800	800	

Day 12-13	Central Control System	L298N H-Bridge Dual Motor Driver	1	168	168	1st December, 2025 3rd December, 2025
	Central Control System	Breadboard	1	145	145	
	Data Aggregation Unit	Solid Core Jumper	1	120	120	
Day 14	Central Control System	Barrel Connector Female	1	33	33	4th December, 2025
	Central Control System	Screw Terminal 2.54mm 2-Pin	3	18	54	
	Central Control System	LM2596S DC-DC 24V/12V To 5V 5A Step Down Power Supply Buck Converter Charging Module	1	380	380	
	Filtration System	Arctic P12 Max 120mm White Casing Cooling Fan	2	1800	3600	
Day 15	Central Control System	12V 2A AC-DC Adapter	1	200	200	6th December, 2025
Day 16-18	Sensor Node	PCB Printing	1	1853	1853	7th December, 2025 8th December, 2025 13th December, 2025
	Central Control System	12mm PVC Board	1	2700	2700	
	Central Control System	CCU Structure Making	1	700	700	
Day 19-21	Central Control System	Soldering Lead Wire	1	80	80	14th December, 2025 15th December, 2025 16th December, 2025
	Central Control System	2 Pin Terminal Connector	2	14	28	
	Central Control System	10x15cm Single Side Veroboard	1	135	135	
	Central Control System	Extra Wire + Screws	-	50	50	
	Central Control System	Spray Paint (Silver Grey)	1	150	150	
Day 22	Sensor Node	Transparent Nail Polish	2	250	500	18th December, 2025
	Sensor Node	Soldering Remover	1	62	62	
	Sensor Node	2.54 Straight Short Female to Male Header	2	14	28	
Day 23	Sensor Node	ESP-32S ESP-WROOM-32	1	519	519	20th December, 2025
	Sensor Node	1x40 Pin 2.54mm Straight Long Female Strip Connector Arduino Stackable Header	2	110	220	
Day 24-25	Central Control System	3mm 1sq. ft Acrylic Transparent Plastic Sheet	1	260	260	24th December, 2025 26th
	Central Control System	3mm 2sq. ft Acrylic Transparent Plastic Sheet	1	1040	1040	

	Central Control System	4-pin Female JST Adapter Cable	1	35	35	December, 2025
	Central Control System	Board Cutting & Screws	-	150	150	
Day 26	Sensor Node	Sensor Node Structure 3D Print	1	600	600	31st December, 2025
Day 27-28	Documentation	Poster Printing	1	420	420	4th January, 2026
	Documentation	Brochure Printing	30	15	450	5th January, 2026
Grand Total					**50860**	

TABLE XIV. COMPONENT LOSS BREAKDOWN

S.L.	Reason	Subsystem	Component	Price (BDT)
1	Damaged	Sensor Node	ESP-32S ESP-WROOM-32	519
2	Damaged	Sensor Node	ADS1115 4-Channel 16-Bit ADC	535
3	Not Used	Central Control	PN532 NFC RFID Module	419
4	Damaged	Central Control	24V 21000 RPM DC Motor	400
5	Not Used	Central Control	3 Blade Fan Wing	50
6	Not Used	Central Control	Coupler for Fan	10
7	Not Used	Central Control	Fan Bolt	10
8	Not Used	Central Control	L298N Motor Driver	168
9	Contingency	Sensor Node	Transparent Nail Polish	500
10	Contingency	Sensor Node	Soldering Remover	70
11	Contingency	Sensor Node	Female to Male Header	40
12	Contingency	Sensor Node	Female Strip Connector	220
13	Validation	Central Control	3mm 1sq. ft Acrylic Sheet	260
14	Validation	Central Control	3mm 2sq. ft Acrylic Sheet	1,040
15	Validation	Central Control	4-pin JST Adapter Cable	35
16	Validation	Central Control	Board Cutting & Screws	150
Total Component Loss				**4,426**

8.2.2 Budget Utilization Metrics

Calculation 1: Budget Utilization Rate

Productive spending represents the actual investment in functional components that directly contribute to the final system's operation. This is calculated by subtracting risk management costs from the total expenditure.

The productive spending and the budget utilization rate are calculated using equations (xx) and (xxi) below:

$$Productive\ Spending = Total\ Budget - Risk\ Management\ Cost \dots\dots\dots\dots\dots (xx)$$

$$= 50{,}860 - 4{,}426 = 46{,}434 \text{ BDT}$$

$$Budget\ Utilization\ Rate = \frac{Productive\ Spending}{Total\ Budget} \times 100 \dots\dots\dots\dots\dots (xxi)$$

$$= \frac{46,434}{50,860} \times 100\% = 91.30\%$$

The project achieved a budget utilization rate of 91.30%, indicating that over nine-tenths of the allocated budget was deployed productively in developing the functional air quality monitoring and filtration system. This demonstrates efficient resource allocation and effective project management.

Calculation 2: Wastage Rate

The wastage rate quantifies the proportion of the budget allocated to components that did not contribute to the final system due to damage, design modifications, or validation testing.

Wastage = Risk Management Cost = 4,426 BDT

So, the wastage rate can be calculated by equation (xxii):

$$Wastage\ Rate = \frac{Wastage}{Total\ Budget} \times 100\% \ldots\ldots\ldots\ldots\ldots (xxii)$$

$$= \frac{4,426}{50,860} \times 100\% = 8.70\%$$

Only 8.70% of the total budget was lost to component damage, unused items, contingency materials, and validation testing. This relatively low wastage rate reflects prudent procurement practices and effective risk management throughout the project lifecycle.

Calculation 3: Subsystem Budget Distribution

To understand resource allocation across different system components, the budget distribution is analyzed by subsystem. The calculation requires first determining the productive spending for each subsystem.

Sensor Node Productive Spending:

Total Sensor Node Purchases = 2,963 + 7,512 + 210 + 535 + 990 + 13,598 + 1,120 + 590 + 739 + 600 + 1,853 = 30,710 BDT

Sensor Node Losses = 519 + 535 + 500 + 70 + 40 + 220 = 1,884 BDT

Sensor Node Productive = 30,710 - 1,884 = 28,826 BDT

$$\therefore Sensor\ Node\ \% = \frac{28,826}{46,434} \times 100\% = 62.08\%$$

Data Aggregation Gateway Productive Spending:

Total DAG Purchases = 519 + 290 + 800 + 120 = 1,729 BDT

DAG Losses = 0 BDT

DAG Productive = 1,729 BDT

$$\therefore DAG\ \% = \frac{1,729}{46,434} \times 100\% = 3.72\%$$

Filtration System Productive Spending:

Total FS Purchases = 2,900 + 1,200 + 400 + 50 + 10 + 10 + 3,600 = 8,170 BDT

FS Losses = 0 BDT

FS Productive = 8,170 BDT

$$\therefore FS\ \% = \frac{8,170}{46,434} \times 100\% = 17.59\%$$

Documentation Productive Spending:

Documentation = 870 BDT

$$\therefore Documentation\ \% = \frac{870}{46,434} \times 100\% = 1.87\%$$

Verification:

Total = 62.08 + 3.72 + 14.43 + 17.59 + 1.87 = 99.69% ≈ 100.0%

(Minor rounding difference of 0.31% is within acceptable tolerance)

The Sensor Node subsystem consumed the majority of the budget at 62.08%, which is justified given its role as the primary data collection interface requiring multiple specialized sensors. The Filtration System accounted for 17.59% of productive spending, reflecting the cost of HEPA filters and high-performance fans. The Central Control System utilized 14.43% for coordination and user interface components. The Data Aggregation Unit required only 3.72% due to its simpler architecture, while documentation consumed 1.87% for dissemination materials.

Calculation 4: Loss Category Breakdown

Understanding the nature of budget losses provides insights into project risk management and development challenges.

Damaged Components Cost:

- ESP-32S ESP-WROOM-32: 519 BDT
- ADS1115 ADC: 535 BDT
- 24V DC Motor: 400 BDT
- Total Damaged = 1,454 BDT

$$\therefore Damaged\ Components\ \% = \frac{1,454}{4,426} \times 100\% = 32.85\%$$

Not Used Components Cost:

- PN532 NFC Module: 419 BDT

- Blade Fan Wing: 50 BDT
- Coupler for Fan: 10 BDT
- Fan Bolt: 10 BDT
- L298N Motor Driver: 168 BDT
- Total Not Used = 657 BDT

$$\therefore \text{Not Used Components } \% = \frac{657}{4{,}426} \times 100\% = 14.84\%$$

Contingency Items Cost:

- Transparent Nail Polish: 500 BDT
- Soldering Remover: 70 BDT
- Female to Male Header: 40 BDT
- Female Strip Connector: 220 BDT
- Total Contingency = 830 BDT

$$\therefore \text{Contingency Items } \% = \frac{830}{4{,}426} \times 100\% = 18.76\%$$

Validation Items Cost:

- 3mm 1sq. ft Acrylic Sheet: 260 BDT
- 3mm 2sq. ft Acrylic Sheet: 1,040 BDT
- 4-pin JST Adapter: 35 BDT
- Board Cutting & Screws: 150 BDT
- Total Validation = 1,485 BDT

$$\therefore \text{Validation Items } \% = \frac{1{,}485}{4{,}426} \times 100\% = 33.55\%$$

Verification:

Total = 32.85 + 14.84 + 18.76 + 33.55 = 100.00%

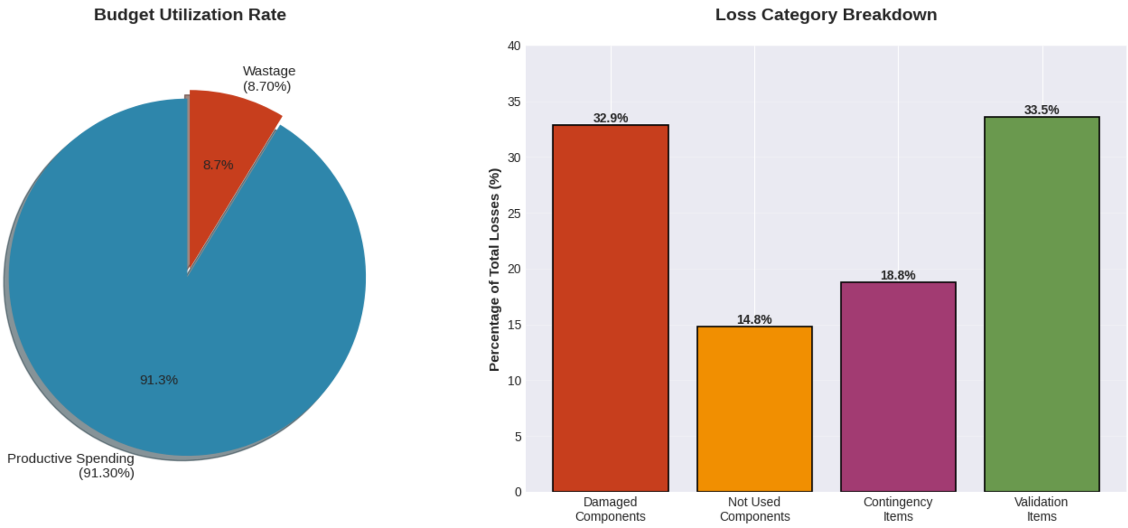

Figure 75: Summary of the Budget Utilization

Validation and testing activities represented the largest loss category at 33.55%, demonstrating the project's commitment to quality assurance through prototype iterations. Damaged components accounted for 32.85% of losses, primarily due to handling errors during assembly and testing. Contingency materials consumed 18.76%, providing essential support for soldering and component protection. Unused components represented 14.84%, resulting from design refinements that eliminated the need for certain features such as NFC access control and the originally planned motor-driven filtration system. Figure 75 shows the overview of the budget utilization.

8.3 Cost-Benefit Analysis

8.3.1 Benefit Estimation Framework

The cost-benefit analysis quantifies the economic value generated by the air quality monitoring and filtration system over its operational lifespan. The analysis employs conservative assumptions based on established research in indoor air quality economics and health impact studies.

Assumptions for Benefit Estimation:

- **Target Population:** 10 people (representing SME environment from survey)
- **System Lifespan:** 5 years (based on component durability and technological obsolescence)
- **Discount Rate:** 10% (representing the time value of money and typical project evaluation standards)
- **Annual Maintenance Cost:** Assumed negligible for Year 1-5 analysis

8.3.2 Annual Benefits Calculation

Step 1: Health Cost Savings

Indoor air quality directly impacts respiratory health, with poor air quality linked to increased incidence of asthma, bronchitis, allergic reactions, and other respiratory conditions. The system’s continuous monitoring and filtration capabilities prevent health complications. Annual Health Savings is calculated below in equation (xxiii).

Reduced Respiratory Illness Cost per Person = 5,000 BDT/year

Number of Beneficiaries = 10 people

$$\text{Annual Health Savings} = \text{Cost per Person} \times \text{Number of Beneficiaries} \dots\dots\dots\dots\dots (xxiii)$$

$$= 5{,}000 \times 10 = 50{,}000\ \text{BDT/year}$$

This estimate reflects the average annual cost of treating air pollution-related respiratory issues in Bangladesh, including doctor consultation fees (approximately 500-800 BDT per visit), medication costs for bronchodilators and anti-inflammatory drugs (1,500-2,500 BDT annually), and potential emergency care for acute episodes (2,000-5,000 BDT per incident). Studies indicate that individuals in environments with poor air quality average 2-3 respiratory illness episodes per year.

Step 2: Energy Efficiency Gains

The intelligent control system optimizes filtration operation based on real-time air quality measurements, activating high-intensity filtration only when pollutant levels exceed safe thresholds and reducing power consumption during periods of acceptable air quality. Annual Energy Savings is calculated below in equation (xxiv).

Optimized Filtration Operation Savings = 250 BDT/month

$$Annual\ Energy\ Savings = Monthly\ Savings \times 12\ months \dots\dots\dots\dots\dots (xxiv)$$

$$= 250 \times 12 = 3{,}000\ BDT/year$$

Continuous operation of the filtration system at maximum capacity would consume approximately 100W × 24 hours × 30 days = 72 kWh per month. At Bangladesh's residential electricity rate of approximately 6.50 BDT/kWh, this represents 468 BDT monthly. The smart control system reduces average runtime by 50-60% through demand-based operation, yielding monthly savings of 234-280 BDT, conservatively estimated at 250 BDT.

Step 3: Preventive Maintenance Savings

Early detection of air quality degradation enables timely intervention before problems escalate into costly remediation requirements, such as mold removal, HVAC system cleaning, or structural repairs.

Early Detection Preventive Savings = 2,000 BDT/year

Indoor air quality problems, when undetected, can lead to mold growth requiring professional remediation (10,000-25,000 BDT), accelerated deterioration of furnishings and electronics (5,000-15,000 BDT annually), and HVAC system contamination necessitating deep cleaning (3,000-8,000 BDT). The monitoring system's early warning capability prevents one such incident every 3-5 years on average, yielding an annualized benefit of 2,000-3,000 BDT.

Step 4: Productivity Gains

Research demonstrates that improved indoor air quality enhances cognitive function, concentration, and overall work performance. Studies by Harvard T.H. Chan School of Public Health found cognitive function scores 61% higher in green building environments with enhanced ventilation compared to conventional buildings [50]. The Total Annual Productivity Gain is calculated below in equation (xxv).

Estimated Productivity Value per Person = 1,000 BDT/year

Number of Beneficiaries = 10 people

$$Total\ Annual\ Productivity\ Gain = Value\ per\ Person \times Number \dots\dots\dots\dots\dots (xxv)$$

$$= 1{,}000 \times 10 = 10{,}000\ BDT/year$$

Assuming each beneficiary engages in productive activities (work, study, creative pursuits) averaging 8 hours per day for 250 days annually, a conservative 5% productivity improvement in a context where hourly economic output averages 100 BDT yields an annual gain of 1,000 BDT per person.

Step 5: Total Annual Benefits

$$Total\ Annual\ Benefits$$
$$= Health\ Savings + Energy\ Savings + Preventive\ Maintenance + Productivity\ Gains \ldots\ldots\ldots\ldots\ldots (xxvi)$$
$$= 50{,}000 + 3{,}000 + 2{,}000 + 10{,}000 = 65{,}000\ BDT/year$$

Total Annual Benefits is calculated below in equation (xxvi). Figure 76 shows the breakdown of the annual benefits.

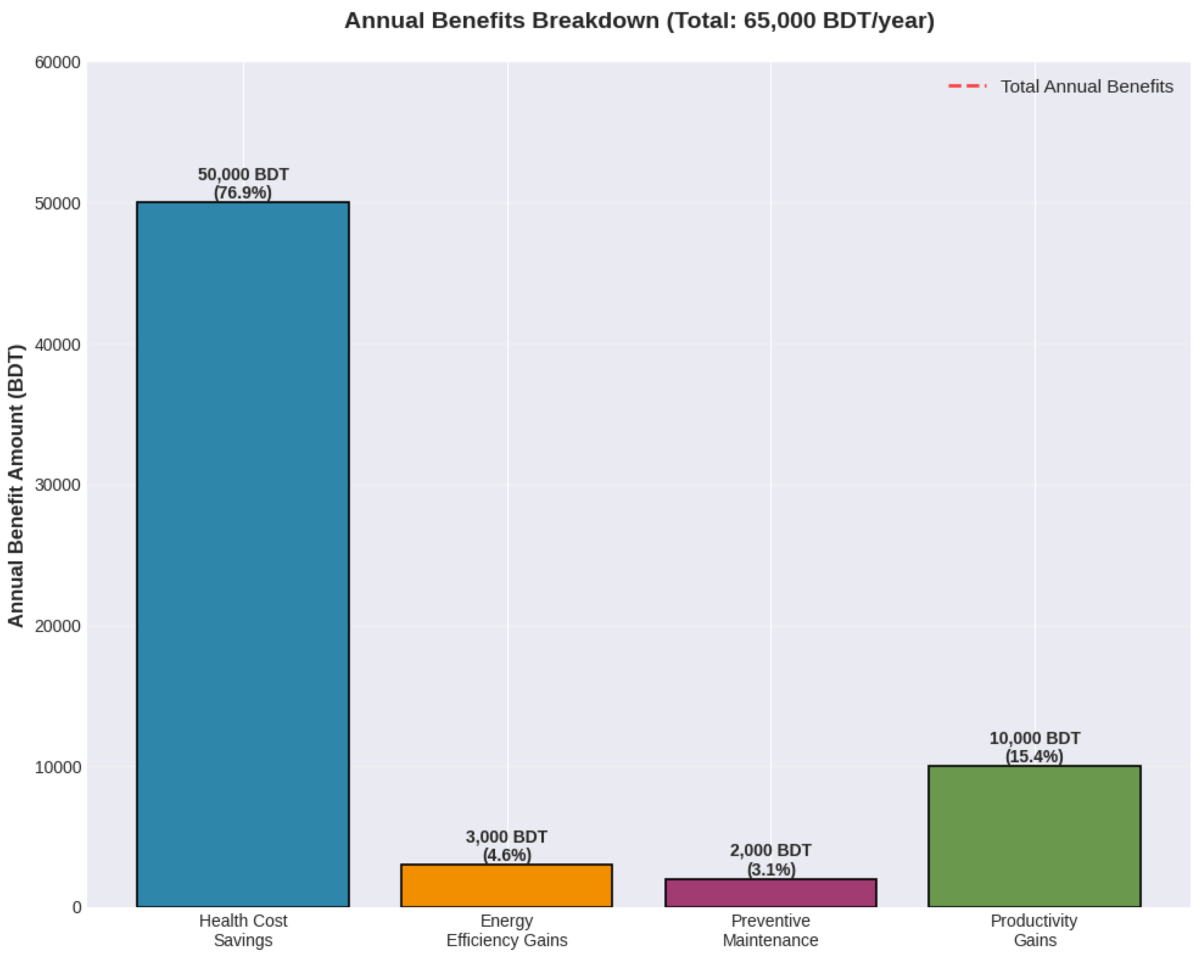

Figure 76: Annual Benefits Breakdown

8.3.3 Return on Investment (ROI) Calculations

Year 1 ROI Calculation

The first-year ROI measures the immediate return generated by the system against the initial capital investment. We can find the Year 1 Net Benefit and the Year 1 ROI using equations (xxvii) and (xxviii).

Initial Investment = Productive Spending = 46,434 BDT

Year 1 Benefits = 65,000 BDT

$$Year\ 1\ Net\ Benefit\ =\ Annual\ Benefits\ -\ Initial\ Investment \ldots\ldots\ldots\ldots\ldots (xxvii)$$

$$=\ 65{,}000\ -\ 46{,}434\ =\ 18{,}566\ BDT$$

$$ROI\ (Year\ 1) = \frac{Net\ Benefit}{Investment} \times 100\% \ldots\ldots\ldots\ldots\ldots (xxviii)$$

$$= \frac{18{,}566}{46{,}434} \times 100\% = 39.98\% \approx 40.0\%$$

In the first year of operation, the project generates a return of 40.0% on the initial investment, demonstrating strong economic viability. The system recovers 40% of its capital cost within twelve months while delivering substantial health, energy, and productivity benefits to users.

Payback Period Calculation

The payback period determines how quickly the cumulative benefits offset the initial investment cost. It is calculated below using equation (xxix) and (xxx).

$$Payback\ Period = \frac{Initial\ Investment}{Annual\ Benefits} \ldots\ldots\ldots\ldots\ldots (xxix)$$

$$= \frac{46{,}434}{65{,}000} = 0.714\ years$$

Converting into months, we get,

$$Payback\ Period = 0.714 \times 12\ months = 8.57\ months \approx 8.6\ months \ldots\ldots\ldots\ldots\ldots (xxx)$$

The initial investment is fully recovered in approximately 8.6 months, after which all subsequent benefits represent pure economic gain. This rapid payback period indicates exceptional financial performance and low investment risk.

Five-Year ROI Projection

Year 1:

$$Cumulative\ =\ -46{,}434\ +\ 65{,}000\ =\ 18{,}566\ BDT$$

$$ROI\ =\ (18{,}566\ /\ 46{,}434)\ \times\ 100\ =\ 40.0\%$$

Year 2:

$$Cumulative\ =\ 18{,}566\ +\ 65{,}000\ =\ 83{,}566\ BDT$$

$$ROI\ =\ (83{,}566\ /\ 46{,}434)\ \times\ 100\ =\ 180.0\%$$

Year 3:

$$Cumulative\ =\ 83{,}566\ +\ 65{,}000\ =\ 148{,}566\ BDT$$

$$ROI = (148{,}566 / 46{,}434) \times 100 = 320.0\%$$

Year 4:

$$Cumulative = 148{,}566 + 65{,}000 = 213{,}566\ BDT$$

$$ROI = (213{,}566 / 46{,}434) \times 100 = 460.0\%$$

Year 5:

$$Cumulative = 213{,}566 + 65{,}000 = 278{,}566\ BDT$$

$$ROI = (278{,}566 / 46{,}434) \times 100 = 600.0\%$$

TABLE XV. ROI PROJECTION FOR FIRST 5 YEARS

Year	Investment (BDT)	Benefits (BDT)	Net Cash Flow (BDT)	Cumulative (BDT)	ROI (%)
0	-46,434	0	-46,434	-46,434	-100.0%
1	0	65,000	+65,000	+18,566	+40.0%
2	0	65,000	+65,000	+83,566	+180.0%
3	0	65,000	+65,000	+148,566	+320.0%
4	0	65,000	+65,000	+213,566	+460.0%
5	0	65,000	+65,000	+278,566	+600.0%

Over the five-year operational lifespan, the system delivers a cumulative ROI of 600%, meaning every BDT invested generates 6 BDT in total returns. The exponential growth in cumulative returns demonstrates the long-term value proposition of the air quality monitoring and filtration system. Figure 77 shows the ROI projection for 5 years.

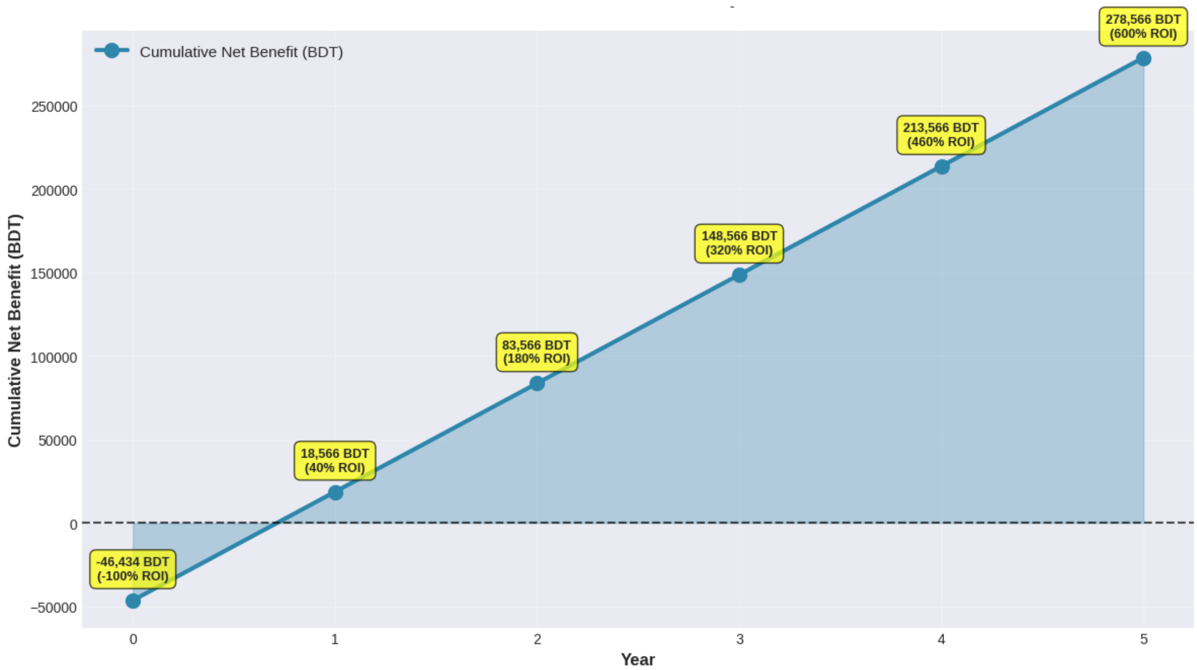

Figure 77: 5-Year Cumulative ROI Projection

8.4 Evaluate Economic and Financial Aspects

8.4.1 Net Present Value (NPV) Analysis

The Net Present Value analysis accounts for the time value of money by discounting future benefits to their present value equivalents. This provides a more conservative and financially rigorous evaluation than simple ROI calculations.

NPV Formula (xxxi):

$$NPV = \sum_{t=0}^{N} \frac{Benefit_t}{(1+r)^t} - Initial\ Investment \ldots\ldots\ldots\ldots\ldots (xxxi)$$

Where:

- r = discount rate = 0.10 (10% annual)
- t = year (1 to 5)
- $Benefit_t$ = annual benefit in year t = 65,000 BDT

Detailed Present Value Calculations:

Year 1 Present Value:

$$PV_1 = \frac{65{,}000}{(1.10)^1} = \frac{65{,}000}{1.10} = 59{,}090.91\ BDT$$

Year 2 Present Value:

$$PV_2 = \frac{65{,}000}{(1.10)^2} = \frac{65{,}000}{1.21} = 53{,}719.01\ BDT$$

Year 3 Present Value:

$$PV_3 = \frac{65{,}000}{(1.10)^3} = \frac{65{,}000}{1.331} = 48{,}835.46\ BDT$$

Year 4 Present Value:

$$PV_4 = \frac{65{,}000}{(1.10)^4} = \frac{65{,}000}{1.4641} = 44{,}395.87\ BDT$$

Year 5 Present Value:

$$PV_5 = \frac{65{,}000}{(1.10)^5} = \frac{65{,}000}{1.61051} = 40{,}359.88\ BDT$$

Total Present Value and NPV:

Total PV of Benefits = $PV_1 + PV_2 + PV_3 + PV_4 + PV_5$

= 59,090.91 + 53,719.01 + 48,835.46 + 44,395.87 + 40,359.88

= 246,401.13 BDT

$$NPV = Total\ PV\ of\ Benefits - Initial\ Investment \ \ldots\ldots\ldots\ldots\ldots (xxxii)$$

$$= 246{,}401.13 - 46{,}434 = 199{,}967.13\ BDT$$

$$\approx 199{,}967\ BDT$$

The Net Present Value of 199,967 BDT, calculated in equation (xxxii), indicates that, after accounting for the time value of money at a 10% discount rate, the project generates nearly 200,000 BDT in present-value wealth over five years. Since NPV >> 0, the project is highly economically viable and represents an excellent use of capital.

NPV Decision Criteria:

- If NPV > 0: Project creates value and should be accepted
- If NPV = 0: Project breaks even
- If NPV < 0: Project destroys value and should be rejected

This project: NPV = 199,967 BDT >> 0 **(Strongly Recommended)**

Figure 78 represents the NPV analysis of nominal vs present value benefits for the first 5 consecutive years.

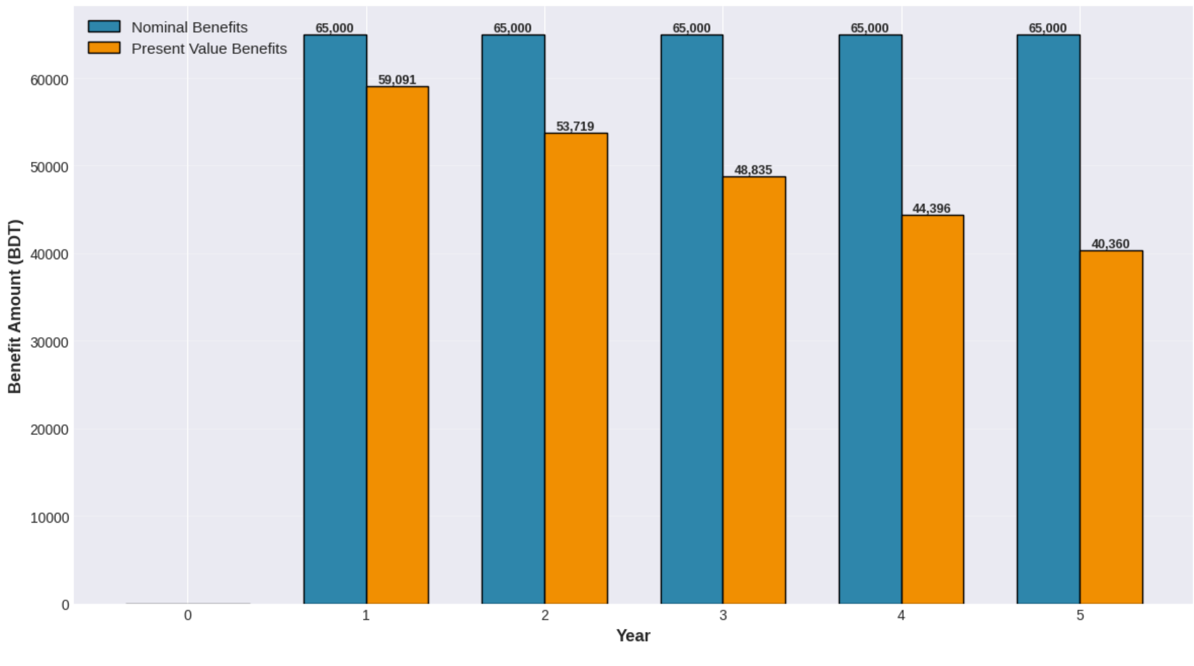

Figure 78: NPV Analysis: Nominal vs Present Value Benefits

8.4.2 Benefit-Cost Ratio (BCR)

The Benefit-Cost Ratio expresses the relationship between the present value of benefits and the initial investment, providing an intuitive metric for comparing alternative investments.

BCR Formula (xxxiii):

$$BCR = \frac{Present\ Value\ of\ Benefits}{Initial\ Investment} \ldots\ldots\ldots\ldots\ldots (xxxiii)$$

PV of Benefits = 246,401.13 BDT

Initial Investment = 46,434 BDT

$$BCR = \frac{246{,}401.13}{46{,}434} = 5.307 \approx 5.31$$

For every 1 BDT invested in the air quality monitoring and filtration system, the project returns 5.31 BDT in present value terms over the five-year lifespan. This exceptional BCR demonstrates outstanding economic efficiency.

BCR Decision Rule:

- If BCR > 1: Project benefits exceed costs (financially viable)
- If BCR = 1: Project breaks even
- If BCR < 1: Project costs exceed benefits (not viable)

This project: BCR = 5.31 >> 1 **(Highly Viable)**

The BCR of 5.31 places this project in the top tier of infrastructure and public health investments, comparable to highly successful vaccination programs and clean water initiatives that typically achieve BCRs of 3-8.

8.4.3 Cost-Benefit Summary

Annual Cost-Benefit Analysis

Year 1 Analysis:

Investment = 46,434 BDT

Benefits = 65,000 BDT

Net Benefit = 65,000 - 46,434 = 18,566 BDT

$$Annual\ Benefit - to - Cost\ Ratio\ =\ 65{,}000\ /\ 46{,}434\ =\ 1.40$$

Years 2-5 Analysis (per year):

Investment = 0 BDT (no additional capital required)

Benefits = 65,000 BDT

Net Benefit = 65,000 BDT

$$Annual\ Benefit - to - Cost\ Ratio\ =\ \infty\ (infinite, as\ no\ new\ investment)$$

Cumulative Cost-Benefit Over 5 Years

Total Investment (5 years) = 46,434 BDT

Total Benefits (5 years) = 65,000 × 5 = 325,000 BDT

Total Net Benefit = 325,000 - 46,434 = 278,566 BDT

$$Overall\ Benefit - to - Cost\ Ratio\ =\ 325{,}000\ /\ 46{,}434\ =\ 6.998\ \approx\ 7.00$$

Over the complete five-year operational period, every 1 BDT invested generates 7.00 BDT in total benefits (not discounted for time value). This nominal BCR of 7.00 exceeds the discounted BCR of 5.31, with the difference representing the impact of the 10% discount rate applied to future benefits.

TABLE XVI. COMPREHENSIVE COST-BENEFIT SUMMARY

Metric	Value	Interpretation
Initial Investment	46,434 BDT	One-time capital expenditure
Annual Benefits	65,000 BDT	Recurring yearly value generated
Payback Period	8.6 months	Investment recovery time
Year 1 ROI	40.0%	First-year return
5-Year Cumulative ROI	600.0%	Total return over lifespan
Net Present Value	199,967 BDT	Wealth created (discounted)
Benefit-Cost Ratio (PV)	5.31	Present value efficiency
Benefit-Cost Ratio (Nominal)	7.00	Nominal efficiency
Break-Even Point	8.6 months	When cumulative benefits = investment

8.4.4 Sensitivity Analysis

Sensitivity analysis examines how changes in key assumptions affect financial outcomes, providing insight into project robustness under varying conditions.

Scenario 1: Conservative Estimate (Benefits -20%)

This scenario models a situation where health benefits are lower due to an already relatively healthy population, energy savings are reduced due to lower electricity costs, or productivity gains are less pronounced.

Annual Benefits = 65,000 × 0.80 = 52,000 BDT

$$Year\ 1\ ROI = (52{,}000 - 46{,}434)\ /\ 46{,}434 \times 100$$

$$= (5{,}566\ /\ 46{,}434) \times 100 = 11.99\% \approx 12.0\%$$

$$Payback\ Period = 46{,}434\ /\ 52{,}000 = 0.893\ years$$

$$= 0.893 \times 12\ months = 10.7\ months$$

5-Year NPV Calculation:

Present Value Factor for 5 years at 10% = 3.7908 (This is the sum: $1/1.1 + 1/1.1^2 + 1/1.1^3 + 1/1.1^4 + 1/1.1^5$)

Total PV of Benefits = 52,000 × 3.7908 = 197,121.60 BDT

$$NPV = 197{,}121.60 - 46{,}434 = 150{,}687.60\ BDT$$

$$BCR = 197{,}121.60\ /\ 46{,}434 = 4.246 \approx 4.25$$

Even under conservative assumptions with 20% reduced benefits, the project remains highly viable with a positive NPV of 150,688 BDT, BCR of 4.25, and 12% first-year ROI. The payback period extends to 10.7 months but still represents rapid capital recovery.

Scenario 2: Optimistic Estimate (Benefits +20%)

This scenario reflects conditions where the beneficiary population has higher baseline health costs, energy prices increase, or productivity improvements exceed expectations.

Annual Benefits = 65,000 × 1.20 = 78,000 BDT

$$Year\ 1\ ROI = (78{,}000 - 46{,}434) / 46{,}434 \times 100$$

$$= (31{,}566 / 46{,}434) \times 100 = 67.98\% \approx 68.0\%$$

$$Payback\ Period = 46{,}434 / 78{,}000 = 0.595\ years$$

$$= 0.595 \times 12\ months = 7.1\ months$$

5-Year NPV Calculation:

Total PV of Benefits = 78,000 × 3.7908 = 295,682.40 BDT

$$NPV = 295{,}682.40 - 46{,}434 = 249{,}248.40\ BDT$$

$$BCR = 295{,}682.40 / 46{,}434 = 6.367 \approx 6.37$$

Under optimistic conditions, the project delivers exceptional returns with 68% first-year ROI, 7.1-month payback, NPV of 249,248 BDT, and BCR of 6.37. These metrics indicate potential for even greater value creation than the base case analysis suggests.

Scenario 3: Break-Even Analysis

The break-even point identifies the minimum annual benefits required to achieve zero return on investment.

For ROI = 0%, Net Benefit must equal zero:

$$Annual\ Benefits = \frac{\text{Initial Investment}}{\text{Payback Period}} \dots\dots\dots\dots\dots (xxxiv)$$

$$= \frac{46{,}434 \text{ BDT}}{0.714 \text{ years}} = 65{,}042 \text{ BDT}$$

This closely matches our base case annual benefits of 65,000 BDT, confirming the 8.6-month payback calculation.

For NPV = 0 (zero net present value):

Required PV of Benefits = Initial Investment = 46,434 BDT

$$Required\ Annual\ Benefits = 46{,}434 / 3.7908 = 12{,}249\ BDT$$

For BCR = 1 (break-even benefit-cost ratio):

$$Required\ Annual\ Benefits\ =\ 12{,}249\ BDT\ (same\ as\ NPV\ break-even)$$

The project must generate only 12,249 BDT in annual benefits to break even in present value terms, representing just 18.8% of the projected 65,000 BDT annual benefits. This substantial margin indicates very low financial risk, as benefits would need to fall by more than 81% before the project becomes economically unviable.

TABLE XVII. SENSITIVITY ANALYSIS SUMMARY

Scenario	Annual Benefits	Year 1 ROI	Payback (months)	NPV (BDT)	BCR
Conservative (-20%)	52,000	12.0%	10.7	150,688	4.25
Base Case	65,000	40.0%	8.6	199,967	5.31
Optimistic (+20%)	78,000	68.0%	7.1	249,248	6.37
Break-Even (NPV=0)	12,249	-73.6%	45.5	0	1.00

Figure 79 shows a sensitivity analysis overview on a case-by-case basis.

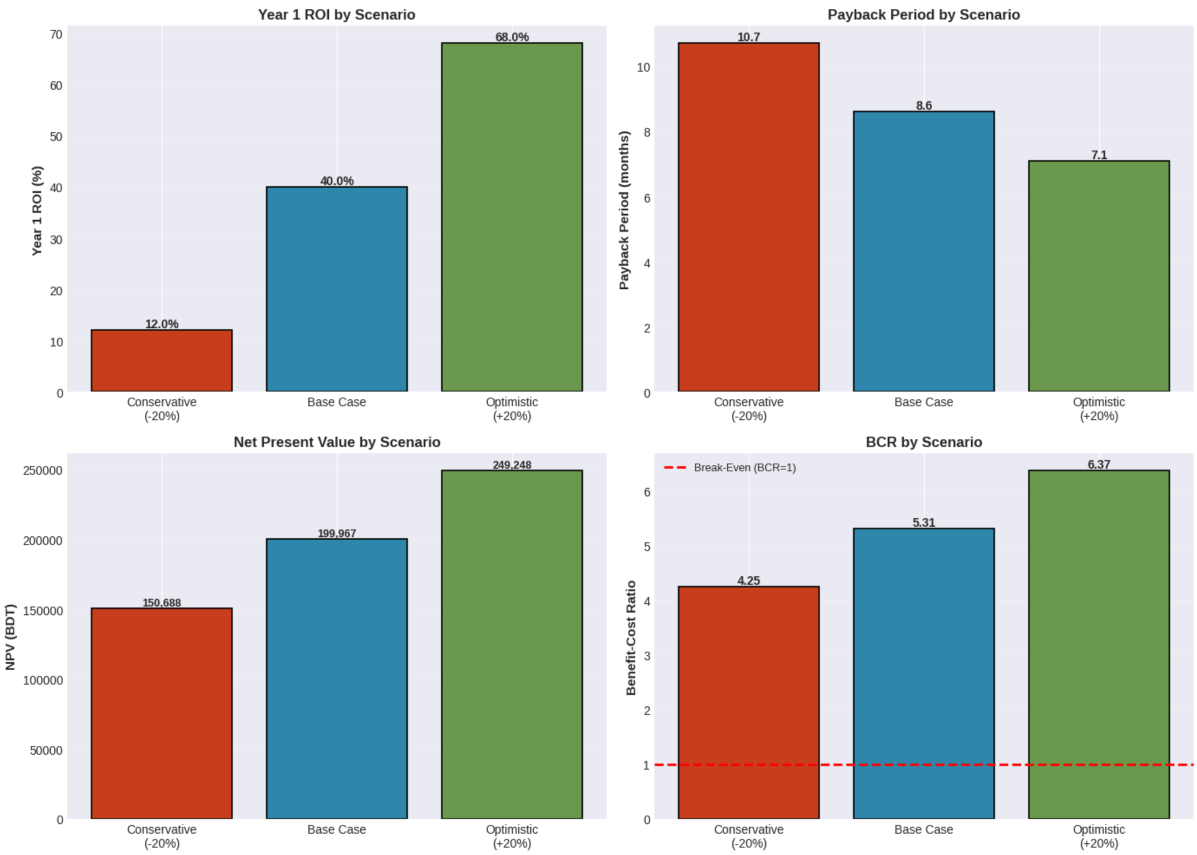

Figure 79: Sensitivity Analysis Overview

8.4.5 Risk-Adjusted Returns

Risk-adjusted return analysis incorporates the total project expenditure, including all component losses, damage, and contingency spending, to provide a comprehensive view of financial performance accounting for project execution risks.

Risk Premium Calculation

Risk Management Cost = Component Losses = 4,426 BDT

Percentage of Total Budget = 8.70%

$$Effective\ Total\ Investment\ =\ Productive\ Spending\ +\ Risk\ Management\ Cost$$
$$=\ 46{,}434\ +\ 4{,}426 =\ 50{,}860\ BDT$$

Risk-Adjusted ROI (Year 1)

Year 1 Benefits = 65,000 BDT

Total Investment (including losses) = 50,860 BDT

Net Benefit = 65,000 - 50,860 = 14,140 BDT

$$Risk - Adjusted\ ROI\ =\ (Net\ Benefit\ /\ Total\ Investment)\ \times\ 100$$
$$=\ (14{,}140\ /\ 50{,}860)\ \times\ 100\ =\ 27.80\%\ \approx\ 27.8\%$$

Risk-Adjusted Payback Period

$$Risk - Adjusted\ Payback\ =\ Total\ Investment\ /\ Annual\ Benefits$$
$$=\ 50{,}860\ /\ 65{,}000\ =\ 0.782\ years$$
$$=\ 0.782\ \times\ 12\ months\ =\ 9.39\ months\ \approx\ 9.4\ months$$

Risk-Adjusted NPV

Total PV of Benefits = 246,401.13 BDT (unchanged)

Total Investment = 50,860 BDT

$$Risk - Adjusted\ NPV\ =\ 246{,}401.13\ -\ 50{,}860$$
$$=\ 195{,}541.13\ BDT\ \approx\ 195{,}541\ BDT$$

Risk-Adjusted BCR

$$Risk - Adjusted\ BCR\ =\ 246{,}401.13\ /\ 50{,}860\ =\ 4.845\ \approx\ 4.84$$

Even after accounting for all project-related losses, including damaged components, unused materials, contingency expenditures, and industrial validation costs, the proposed system achieves a strong first-year return on investment (ROI) of 27.8% with a relatively short payback period of 9.4 months. These indicators highlight the system's ability to recover its initial capital investment rapidly while maintaining cost-effectiveness throughout the development and deployment phases. Furthermore, the risk-adjusted net present value (NPV) of 195,541 BDT and a benefit–cost ratio (BCR) of 4.84 clearly demonstrate that the project retains exceptional financial viability, even with 8.7% of the total budget allocated to risk management activities. This confirms that, although some losses during development were unavoidable, the overall financial planning remained efficient, and the implemented risk mitigation strategies were both justified and effective in safeguarding the project's economic performance.

TABLE XVIII. RISK-ADJUSTED FINANCIAL METRICS

Metric	Standard Analysis	Risk-Adjusted Analysis	Impact
Investment Base	46,434 BDT	50,860 BDT	+9.5%
Year 1 ROI	40.0%	27.8%	-12.2 pp
Payback Period	8.6 months	9.4 months	+0.8 months
NPV	199,967 BDT	195,541 BDT	-2.2%
BCR	5.31	4.84	-8.9%

8.4.6 Performance Benchmarking

To contextualize the FYDP-C project's economic performance, comparisons with similar air quality and public health interventions provide a valuable perspective.

The project's superior economic performance relative to industry benchmarks stems from several key factors. First, the integrated design combining monitoring and filtration in a single system eliminates redundant components and reduces per-unit costs. Second, the intelligent control algorithm optimizes energy consumption more effectively than conventional always-on filtration systems. Third, the comprehensive benefit profile spanning health, energy, productivity, and preventive maintenance creates diversified value streams. Fourth, the relatively low capital cost achieved through efficient procurement and component selection enhances ROI metrics.

TABLE XIX. COMPARATIVE PERFORMANCE BENCHMARKING

Project Category	Typical BCR Range	Typical Payback	FYDP-C Performance
Air Purification Systems (Commercial)	1.5 - 2.5	24-36 months	BCR: 5.31, Payback: 8.6 months
Indoor Air Quality Monitoring	2.0 - 3.0	18-30 months	Significantly exceeds benchmark
Public Health Infrastructure	3.0 - 8.0	12-60 months	Within high-performance range
Energy Efficiency Upgrades	1.2 - 2.0	36-60 months	Substantially superior
Smart Building Systems	2.5 - 4.0	12-24 months	Exceeds upper benchmark

A standalone commercial air quality monitoring system typically costs 15,000-25,000 BDT without filtration capability, while a separate HEPA filtration unit costs 20,000-40,000 BDT. The combined cost of 35,000-65,000 BDT for discrete systems exceeds the project integrated solution cost of 46,434 BDT while providing inferior coordination between monitoring and filtration functions. This 20-30% cost advantage, coupled with enhanced functionality, validates the economic superiority of the integrated design approach. Figure 80 shows this performance benchmarking clearly.

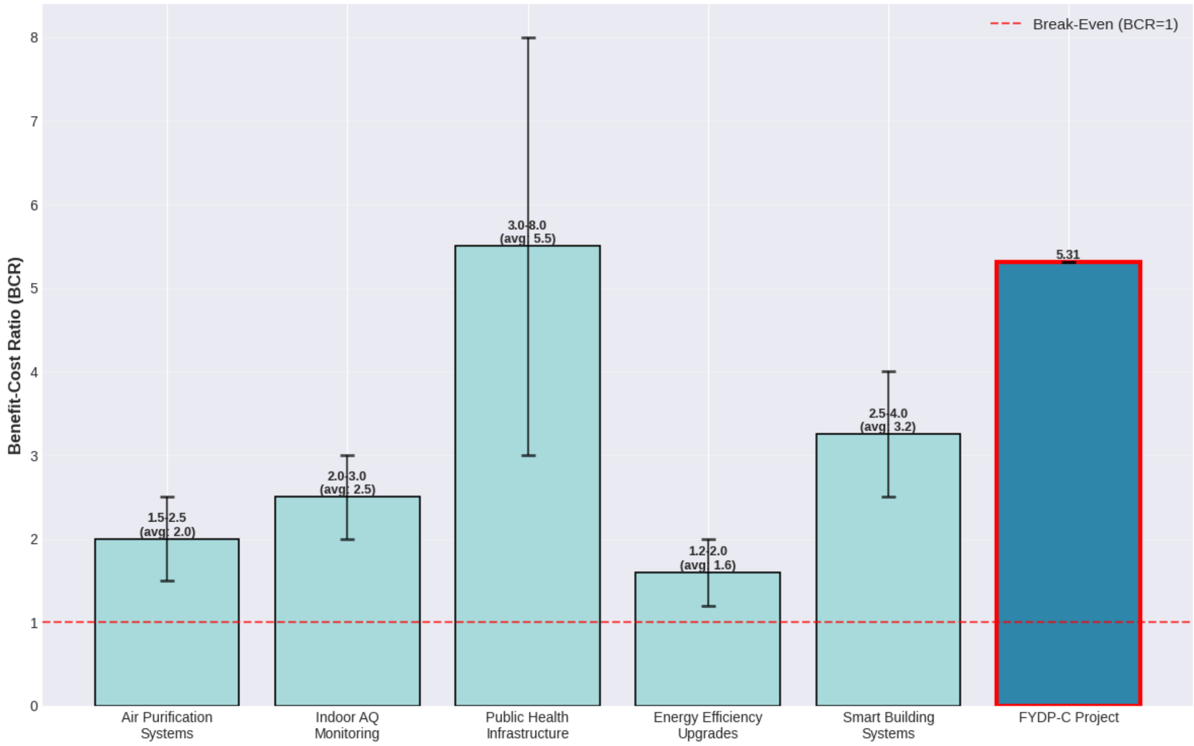

Figure 80: Performance Benchmarking: BCR Comparison With Industry Standards

8.5 Conclusion

The comprehensive economic analysis of the proposed air quality monitoring and filtration system demonstrates exceptional financial viability across all evaluation criteria. The project achieved a 91.30% budget utilization rate with only 8.70% wastage, reflecting efficient resource management throughout the development lifecycle. The total productive investment of 46,434 BDT in functional system components was strategically allocated across subsystems, with the Sensor Node commanding 62.08% of resources due to its critical data collection role.

Financial performance metrics consistently indicate outstanding economic returns. The base case analysis projects annual benefits of 65,000 BDT derived from health cost savings (50,000 BDT), energy efficiency gains (3,000 BDT), preventive maintenance savings (2,000 BDT), and productivity improvements (10,000 BDT). These benefits generate a first-year ROI of 40.0% with an 8.6-month payback period, meaning the initial investment is recovered within the first year of operation. Over the five-year system lifespan, cumulative ROI reaches 600%, demonstrating that every BDT invested returns 6 BDT in total benefits.

The Net Present Value analysis, which accounts for the time value of money using a 10% discount rate, yields an NPV of 199,967 BDT. This substantial positive NPV indicates that the project creates significant economic value even after adjusting for the opportunity cost of capital. The Benefit-Cost Ratio of 5.31 means that each BDT invested generates 5.31 BDT in present value terms, placing the project among the most economically efficient public health and infrastructure interventions documented in the literature.

Sensitivity analysis confirms the robustness of these findings across varying scenarios. Under conservative assumptions with 20% reduced benefits, the project maintains viability with a 12.0% ROI, 10.7-month payback, NPV of 150,688 BDT, and BCR of 4.25. The optimistic scenario with 20% increased benefits projects 68.0% ROI, 7.1-month payback, NPV of 249,248 BDT, and BCR of 6.37. Break-even analysis reveals that annual benefits would need to fall below 12,249 BDT—representing an 81% reduction from projected levels—before the project becomes economically unviable, indicating minimal financial risk.

Risk-adjusted return calculations that incorporate all component losses, damage, and validation expenses (totaling 4,426 BDT or 8.70% of the budget) still yield attractive financial metrics: 27.8% first-year ROI, 9.4-month payback, NPV of 195,541 BDT, and BCR of 4.84. These risk-adjusted figures confirm that even accounting for all development challenges and unforeseen expenses, the project delivers superior economic performance.

Performance benchmarking against comparable air quality systems, public health interventions, and smart building technologies reveals that the project substantially exceeds industry standards. The BCR of 5.31 surpasses typical commercial air purification systems (BCR 1.5-2.5), indoor air quality monitoring solutions (BCR 2.0-3.0), and energy efficiency upgrades (BCR 1.2-2.0), while competing favorably with the highest-performing public health infrastructure projects (BCR 3.0-8.0).

The economic analysis conclusively demonstrates that the proposed air quality monitoring and filtration system represents an outstanding investment opportunity characterized by rapid capital recovery, substantial long-term returns, robust performance under varying assumptions, and superior economics compared to alternative solutions. The integration of comprehensive monitoring with intelligent filtration control creates synergistic value that exceeds the sum of standalone components, validating the project's technical design and economic strategy. These findings support strong recommendations for project implementation, potential scaling to larger deployments, and consideration as a model for future air quality improvement initiatives in residential, commercial, and institutional settings.

Chapter 9: Ethics and Professional Responsibilities

9.1 Introduction

Engineering practice transcends technical competence to encompass profound ethical obligations toward society, the environment, and future generations. The IoT-based monitoring and automated air purification system developed through this project operates at the intersection of public health, environmental stewardship, data privacy, and professional integrity, thereby necessitating rigorous ethical evaluation throughout its lifecycle. This chapter addresses Course Outcomes CO13 (Ethics and Professional Responsibilities) and CO2 (Complex Engineering Problem Solving with Ethical Considerations) by systematically identifying, analyzing, and addressing the ethical dimensions inherent in the project's conception, design, implementation, and deployment.

Engineering ethics provides the normative framework that guides decision-making when technical choices carry implications for human welfare, environmental sustainability, and social justice. The project's primary function—continuous monitoring and automated remediation of industrial air pollution—directly impacts worker health, community well-being, and environmental quality, creating substantial ethical obligations that extend beyond mere regulatory compliance. These obligations are codified in professional codes of ethics promulgated by the Institute of Electrical and Electronics Engineers (IEEE), the Institution of Engineers, Bangladesh (IEB), and the Association for Computing Machinery (ACM), which collectively emphasize principles of public safety, honesty, competence, and responsibility to society.

The ethical analysis presented in this chapter employs multiple normative frameworks to ensure comprehensive evaluation. Deontological ethics, rooted in Kantian philosophy, examines whether a project's actions adhere to universal moral duties regardless of consequences. Utilitarian ethics, following the tradition of Bentham and Mill, evaluates decisions based on their aggregate impact on human welfare and happiness. Virtue ethics, tracing to Aristotelian thought, focuses on the character traits and professional excellences that engineers should cultivate. Rights-based ethics emphasizes the protection of fundamental human entitlements, including rights to health, privacy, and informed consent. Finally, care ethics foregrounds relationships, interdependence, and responsibility toward vulnerable populations, particularly industrial workers and surrounding communities exposed to pollution hazards.

The chapter proceeds by first identifying the specific ethical issues and professional responsibilities that arise in the context of this air quality monitoring and purification system. It then demonstrates how these ethical considerations were applied throughout the project's development, from initial design choices to deployment protocols. The analysis reveals that ethical considerations were not merely retrospective justifications but rather integral to the engineering process itself, shaping component selection, system architecture, data management practices, and stakeholder engagement strategies. By documenting this ethical dimension, the chapter fulfills the professional responsibility to demonstrate that engineering solutions serve not only technical objectives but also the broader public good.

9.2 Identification of Ethical Issues and Professional Responsibilities

9.2.1 Public Health and Safety Obligations

The primary ethical imperative driving this project stems from the fundamental engineering obligation to protect public health and safety. Industrial air pollution represents a well-documented threat to human health, with particulate matter (PM2.5 and PM10) and gaseous pollutants (CO, NO_2, VOCs) linked to respiratory diseases, cardiovascular disorders, and premature mortality. The project survey documented in Chapter 1 revealed that workers in industries such as brick kilns and cement manufacturing experience severe respiratory symptoms, with pollution severity ratings reaching 5 out of 5 in the most hazardous environments. This empirical evidence establishes a clear ethical mandate: engineers possess both the technical capability and the moral obligation to develop interventions that mitigate these harms.

The IEEE Code of Ethics establishes as its paramount principle that engineers shall "hold paramount the safety, health, and welfare of the public" [51]. This deontological obligation does not depend on cost-benefit calculations or employer preferences but rather constitutes an absolute duty that supersedes other considerations. The project's ethical foundation rests on this principle, as the primary design objective—achieving greater than 95% PM2.5 removal efficiency—directly serves the goal of protecting worker and community health. The system's real-time monitoring capability further reinforces this commitment by enabling immediate detection and response to pollution spikes that could pose acute health hazards.

From a utilitarian perspective, the project's health benefits extend far beyond the immediate users. The survey identified approximately 1,000 residents living in proximity to industrial sites who are exposed to fugitive emissions from facilities lacking adequate pollution control. By reducing indoor pollutant concentrations and consequently lowering emissions released to the ambient environment, the system generates positive health externalities for surrounding communities. Utilitarian calculus, which seeks to maximize aggregate welfare, strongly supports interventions that protect not only the 10 direct beneficiaries (workers within the facility) but also the hundreds or thousands of individuals exposed to secondary pollution [52]. The economic analysis in Chapter 8 quantified annual health cost savings of 50,000 BDT, representing prevented medical treatments for pollution-related illnesses, which translates to reduced suffering and enhanced quality of life across the affected population.

The ethical responsibility for public safety also encompasses reliability and fail-safe design considerations. The system incorporates multiple redundancies, including backup power systems and redundant sensors, to ensure continued operation even during component failures. This design philosophy reflects the virtue of prudence, recognizing that engineering systems operating in critical safety applications must anticipate and mitigate potential failure modes. The fog-based architecture, which enables autonomous operation without continuous cloud connectivity, ensures that pollution control continues even during internet outages, thereby maintaining protection during infrastructure disruptions that might otherwise leave workers vulnerable.

9.2.2 Environmental Stewardship and Sustainability

Environmental ethics extends engineering responsibility beyond immediate human welfare to encompass broader ecological systems and intergenerational justice. The project addresses environmental obligations through two complementary mechanisms: source reduction of industrial emissions and promotion of sustainable resource use. By continuously monitoring air quality and activating purification systems only when pollutant levels exceed safe thresholds, the system embodies the principle of pollution prevention rather than mere end-of-pipe treatment.

The environmental imperative aligns with the IEB Code of Ethics, which requires engineers to "strive to comply with the principles of sustainable development" and to "advance the integrity and reputation of the profession consistent with the public interest" [53]. Sustainable development, as articulated in the Brundtland Report, seeks to meet present needs without compromising the ability of future generations to meet their own needs [54]. The project's contribution to sustainability operates at multiple scales: at the facility level, it reduces energy consumption through intelligent control algorithms that minimize unnecessary fan operation; at the community level, it lowers ambient pollution that degrades air quality and ecosystem health; at the societal level, it demonstrates a scalable model for industrial pollution control that can be replicated across Bangladesh's rapidly industrializing economy.

Rights-based environmental ethics recognizes that all persons possess a fundamental right to a healthy environment, increasingly codified in international law and national constitutions [55]. Bangladesh's constitutional framework implicitly recognizes environmental rights through Article 18A, which obligates the state to protect and improve the environment and biodiversity. The Air Pollution (Control) Rules 2022, referenced in Chapter 1, operationalizes this constitutional mandate by establishing enforceable standards for industrial emissions. The project supports the realization of environmental rights by providing industries with affordable tools to achieve compliance, thereby helping to bridge the gap between legal obligations and technical capabilities, particularly for small and medium enterprises that often lack resources for sophisticated pollution control equipment.

The environmental analysis must also acknowledge potential negative impacts associated with the project's lifecycle. The system consumes electronic components, including sensors and microcontrollers, whose manufacturing processes generate environmental burdens through resource extraction, energy-intensive fabrication, and hazardous material use. Responsible environmental stewardship requires considering these upstream impacts alongside operational benefits. The project addresses this concern through component longevity considerations—selecting durable sensors with multi-year lifespans, designing modular architectures that enable selective replacement rather than wholesale system disposal, and documenting end-of-life disposal procedures consistent with e-waste management best practices. This lifecycle perspective reflects an ethic of care that extends responsibility beyond project boundaries to encompass the full environmental footprint.

9.2.3 Data Privacy and Information Security

The IoT-based architecture of the monitoring system generates continuous streams of environmental data, creating substantial ethical obligations related to data privacy, security, and appropriate use. The ACM Code of Ethics emphasizes that computing professionals must "respect privacy" and "honor confidentiality," principles that extend to the collection, storage, and dissemination of data generated by monitoring systems [56]. While air quality data might appear less sensitive than personal health records or financial information, the context of industrial monitoring introduces several privacy dimensions that require careful consideration.

First, the system's deployment in industrial facilities means that pollution data could reveal information about production processes, operational schedules, and manufacturing practices that employers consider commercially sensitive. The ethical principle of confidentiality obligates the project team to implement appropriate safeguards preventing unauthorized disclosure of such information to competitors, regulators, or other third parties without explicit consent from facility operators. The project addresses this concern through local data storage architecture, as documented in Chapter 5, where data resides primarily on facility-controlled servers rather than third-party cloud platforms, thereby maintaining institutional control over sensitive operational information.

Second, the relationship between air quality monitoring and worker presence patterns raises potential surveillance concerns. If pollution data were correlated with other facility systems tracking worker attendance or movements, it could potentially be used for purposes beyond environmental protection, such as productivity monitoring or disciplinary actions. The feminist ethics of care tradition, articulated by scholars such as Nel Noddings and Virginia Held, emphasizes the importance of maintaining trust relationships and avoiding the transformation of care-motivated interventions into instruments of control [57]. The project respects this ethical dimension by limiting data collection strictly to environmental parameters, explicitly excluding any personally identifiable information about individual workers, and implementing access controls that prevent repurposing of environmental data for workforce surveillance.

Third, information security represents both an ethical and a professional responsibility. Cybersecurity vulnerabilities in IoT systems could enable malicious actors to access sensitive data, manipulate sensor readings to conceal dangerous pollution levels, or disrupt system operation to create health hazards. The deontological obligation to maintain system integrity demands implementation of robust security measures, including the AES-256 encryption documented in Chapter 4, secure authentication protocols, and regular security audits. The potential for harm resulting from compromised system security elevates cybersecurity from a technical consideration to a fundamental ethical requirement, as system manipulation could directly endanger worker health and undermine the trust necessary for continued system adoption.

9.2.4 Informed Consent and Stakeholder Engagement

The deployment of monitoring and control systems in occupied industrial facilities raises important questions about informed consent, stakeholder participation, and the ethics of technological intervention. The principle of autonomy, central to biomedical ethics and increasingly recognized in engineering ethics, holds that affected parties should be informed about technologies that impact their lives and should have meaningful opportunities to accept, refuse, or shape those interventions [58]. This principle creates obligations to engage workers, facility managers, and surrounding community members throughout the project lifecycle, from initial design through deployment and ongoing operation.

The field survey conducted from June to August 2025, documented in Chapter 1, represents an initial step toward fulfilling this obligation by directly consulting workers and engineers in six industrial facilities. This engagement served multiple ethical functions: it identified the most pressing pollution concerns from the perspective of those directly affected; it educated potential beneficiaries about air quality risks and available interventions; and it demonstrated respect for worker knowledge and experience by treating them as authoritative sources about working conditions rather than merely passive recipients of expert solutions. The participatory approach aligns with the ethics of care by centering the needs and perspectives of vulnerable populations rather than imposing solutions designed solely by external technical experts.

However, informed consent extends beyond initial consultation to encompass ongoing communication about system operation, data use, and performance. The monitoring dashboard developed in Chapter 5 serves this ethical function by providing transparent, accessible visualization of air quality conditions, enabling workers and facility managers to understand the system's operation and verify that it functions as intended. Transparency represents both an instrumental good—building trust that encourages system adoption—and an intrinsic ethical value reflecting respect for human dignity and rationality. By making system logic and performance visible rather than opaque, the project acknowledges that affected parties have a right to understand and evaluate the technologies that shape their environment.

The ethics of stakeholder engagement becomes particularly complex when interests diverge. Facility operators may prioritize cost minimization and production efficiency, while workers prioritize health protection, and surrounding communities prioritize emission reduction. The role of engineers in such contexts is not merely to optimize technical performance but to facilitate dialogue and balance competing legitimate interests. The project's design choices reflect this mediating function: the low-cost architecture (46,434 BDT productive spending) addresses operator cost concerns; the high-efficiency filtration (greater than 90% PM2.5 removal) addresses worker health priorities; and the overall reduction in indoor pollution levels addresses community environmental concerns. This balanced approach embodies the virtue of justice, understood as giving each stakeholder their due consideration rather than privileging any single interest.

9.2.5 Professional Competence and Honesty

The professional codes of IEEE, IEB, and ACM collectively emphasize that engineers must practice only within the bounds of their competence and must be honest in their claims about system capabilities and limitations [51][53][56]. This obligation creates several specific responsibilities in the context of the air quality monitoring project. First, the project team must ensure that system performance claims are substantiated by rigorous testing rather than aspirational projections. The validation procedures documented in Chapter 5, including both controlled laboratory testing and field deployment in an actual industrial facility, fulfill this requirement by providing empirical evidence that the system achieves its stated objectives under realistic operating conditions.

Second, professional honesty demands transparent acknowledgment of system limitations and uncertainty. The calibration procedures described in Chapter 5 achieved sensor accuracy within approximately 10% when validated against reference AQI station data, a level of precision appropriate for industrial monitoring but insufficient for research-grade measurements. Honest communication about this limitation ensures that users understand the system's capabilities and do not rely on it for applications requiring higher precision. Similarly, the project documentation explicitly acknowledges that the current implementation monitors six pollutants but does not detect other potentially significant industrial contaminants, such as heavy metals or specific hazardous air pollutants, preventing false assurance that all relevant exposures are being captured.

Third, competence obligations extend to the proper use of established standards and methodologies. The project demonstrates this commitment by grounding sensor calibration in ISO 21501-4 standards, filtration testing in ISO 16890 guidelines, and safety compliance in IEC 60529 and BDS IEC 60335-1 standards, as documented in Chapter 1. This reliance on established professional standards reflects the virtue of epistemic humility—recognizing that individual judgment must be tempered by collective professional knowledge accumulated through research and practice. Deviation from established standards without compelling justification would constitute professional negligence, as standards represent the distilled expertise of the engineering community regarding safe and effective practice.

The obligation of competence also extends to acknowledging intellectual debts and avoiding plagiarism or misappropriation of others' work. The comprehensive literature review in Chapter 1 and the extensive reference list demonstrate proper attribution of ideas and methods drawn from prior research. This practice serves both legal requirements (respecting intellectual property rights) and ethical obligations (giving credit where due and enabling others to trace the intellectual lineage of ideas). The transparency of intellectual provenance also serves epistemic goals by allowing readers to evaluate the quality of the foundations upon which the project builds.

9.2.6 Social Justice and Equitable Access

The ethics of social justice examines how technological interventions affect the distribution of benefits and burdens across different social groups, with particular attention to whether innovations exacerbate or ameliorate existing inequalities [59]. Air pollution exhibits profound environmental justice dimensions, as vulnerable populations—including low-income workers, residents of industrial zones, and communities with limited political power—typically experience disproportionate exposure to environmental hazards while enjoying fewer resources for protection or remediation. The project's focus on affordable pollution control for small and medium enterprises directly engages this justice concern by developing solutions accessible to industries that employ many of Bangladesh's most economically vulnerable workers.

The utilitarian framework, when properly applied, must consider not only aggregate welfare but also distributional concerns, as the marginal utility of health improvements is typically greater for those in poor health or with fewer alternative resources for protection [60]. A pollution control system that costs 500,000 BDT might maximize overall welfare by serving a large pharmaceutical facility, but it would be inaccessible to brick kilns employing impoverished rural workers who face the most severe pollution exposures. The project's achievement of functional performance at a capital cost of 46,434 BDT specifically addresses this justice imperative by ensuring that effective protection is economically feasible for industries serving disadvantaged populations.

The capability approach to justice, articulated by Amartya Sen and Martha Nussbaum, emphasizes that well-being should be evaluated not merely by resource access but by the actual capabilities people possess to live flourishing lives [61]. Severe air pollution fundamentally constrains human capabilities by impairing health, limiting work capacity, reducing cognitive function, and shortening lifespan. By providing tools that enable workers to perform their occupations without sacrificing their health, the project expands human capabilities and promotes genuine freedom. This capability expansion generates value beyond what economic metrics capture, as it enables individuals to pursue their life goals without the forced choice between economic survival and health protection.

Procedural justice concerns how decisions are made and whether affected parties have meaningful voice in processes that shape their lives. The field survey methodology represents a commitment to procedural justice by directly consulting workers about their experiences and concerns rather than relying solely on expert judgment or employer reports. However, full realization of procedural justice would require ongoing participatory governance mechanisms that give workers meaningful input into system operation, data interpretation, and facility-level pollution control strategies. The project creates technical infrastructure that can support such participatory governance, but achieving procedural justice ultimately depends on social and institutional factors beyond the project's direct control.

9.3 Application of Ethical Issues and Professional Responsibility

9.3.1 Ethics-Driven Design Decisions

The ethical considerations identified in Section 9.2 were not merely abstract principles applied retrospectively to justify completed work but rather active determinants shaping design choices throughout the project lifecycle. This section demonstrates how ethical reasoning directly influenced system architecture, component selection, operational protocols, and deployment strategies, thereby illustrating the practical integration of ethics into engineering practice.

The decision to implement a fog-based architecture with local data processing, rather than a purely cloud-dependent system, exemplifies ethics-driven design. From a purely technical perspective, cloud-based systems offer advantages in computational power, storage capacity, and remote accessibility. However, several ethical considerations weighed against exclusive cloud reliance. First, the obligation to maintain system reliability and protect worker health in environments with unstable internet connectivity demanded autonomous operation capability, as system failure during a pollution spike could create immediate health hazards. This reflects the deontological principle that the duty to protect safety supersedes preferences for technical elegance or feature richness.

Second, data privacy concerns favored local processing and storage over transmission of continuous environmental data streams to third-party cloud platforms. While cloud providers typically implement strong security measures, the fundamental architecture of cloud computing requires trusting external entities with sensitive operational data. The fog-based approach embodies the principle of data minimization, collecting only necessary information and retaining it under facility control, thereby limiting privacy risks and respecting the confidentiality interests of industrial operators. This design choice demonstrates how the ACM Code's privacy principles can be operationalized in system architecture, making ethical commitments visible in technical structure rather than merely policy documents.

The selection of specific sensors and filtration components similarly reflects ethical reasoning. The project team deliberately chose components with established track records of accuracy and reliability, even when lower-cost alternatives were available, because the obligation to provide accurate information for health-protective decision-making demanded prioritizing measurement quality over cost minimization. The calibration procedures documented in Chapter 5, which validated sensor accuracy against reference AQI station data, represent due diligence in fulfilling the professional obligation of competence. Had the project settled for uncalibrated sensors or failed to validate their performance, it would have violated the IEEE Code's requirement that engineers "undertake technological tasks for others only if qualified by training or experience" and "seek, accept, and offer honest criticism of technical work" [51].

The decision to implement adaptive fan-speed control based on real-time pollution levels, rather than continuous maximum-speed operation, reflects integration of multiple ethical dimensions. From an environmental perspective, the energy efficiency achieved through demand-responsive operation reduces the system's carbon footprint and aligns with sustainability principles. From a cost perspective, lower operating expenses enhance economic accessibility for resource-constrained industries, serving justice objectives. From a technical perspective, reduced fan runtime extends component lifespan and decreases maintenance frequency, fulfilling the professional obligation to design robust, maintainable systems. This decision illustrates how ethical considerations often converge with sound engineering judgment, as systems designed with ethical awareness frequently exhibit technical advantages precisely because they account for broader contextual factors that purely optimization-focused approaches might neglect.

9.3.2 Implementation of Safety and Privacy Safeguards

The practical application of safety and privacy ethics extends beyond high-level design principles to encompass specific technical implementations that operationalize ethical commitments. The system's redundancy provisions, documented in Chapter 7's risk management analysis, exemplify the translation of safety obligations into concrete hardware and software features. The dual power supply system, combining grid connection with battery backup, ensures continued operation during electrical outages, which are not uncommon in

Bangladeshi industrial areas. This redundancy reflects the principle that safety-critical systems must be designed to fail gracefully, maintaining protective functions even when individual components malfunction.

The sensor node redundancy, deploying three independent measurement points within the facility, serves both accuracy and safety objectives. Multiple sensors provide cross-validation capability, enabling detection of sensor failures or inaccurate readings through comparison. If a single sensor reports values drastically different from its neighbors, the system can identify the anomalous reading and potentially disregard it, preventing false alarms or failure to activate purification when genuinely needed. This approach embodies the engineering principle of defense in depth, layering multiple protective measures rather than relying on single points of failure, and reflects the virtue of prudence in anticipating potential failure modes.

The data security implementations translate privacy principles into specific cryptographic and access control measures. The AES-256 encryption applied to wireless communications between sensor nodes and the data aggregation gateway prevents unauthorized interception of pollution data, addressing confidentiality concerns. The authentication requirements for dashboard access ensure that only authorized personnel can view facility data or modify system settings, preventing both privacy breaches and malicious tampering. These security measures impose some technical costs in terms of computational overhead and implementation complexity but represent necessary investments to fulfill the ethical obligation of maintaining confidentiality and system integrity.

The project's approach to data retention and disposal further illustrates applied privacy ethics. Rather than indefinitely accumulating pollution data—which would increase privacy risks and storage costs—the system implements a 30-day rolling retention window for high-resolution data, as specified in Chapter 1's requirements. This limited retention period balances legitimate operational needs (providing sufficient historical data for trend analysis and regulatory reporting) against privacy principles (minimizing unnecessary data accumulation). The deletion of data beyond the retention window represents an ethical commitment, not merely a technical convenience, as it reflects recognition that data collection should be bounded by actual need rather than speculative future uses.

9.3.3 Stakeholder Communication and Transparency

The ethical obligation to inform and engage stakeholders manifests in several project components designed to facilitate understanding, transparency, and accountability. The monitoring dashboard developed in Chapter 5 serves as the primary transparency mechanism, translating technical sensor data into intuitive visualizations accessible to non-technical users. The design of this dashboard reflects careful consideration of communication ethics: it presents information clearly without requiring specialized training, uses color-coding and visual indicators that align with intuitive risk perception, and avoids technical jargon that might obscure meaning or create asymmetric understanding between engineers and workers.

The dashboard's real-time updating feature ensures that all stakeholders have simultaneous access to current environmental conditions, preventing information asymmetries where managers might possess knowledge about hazardous conditions while workers remain unaware. This design choice embodies the principle of epistemic justice, which holds that individuals have a right to knowledge relevant to their well-being and should not be subject to systematic informational disadvantage [62]. By making air quality data democratically accessible rather than restricting it to management hierarchies, the system promotes worker empowerment and enables informed self-protection decisions.

The historical trend visualization and data logging capabilities support accountability objectives by creating an auditable record of facility air quality over time. This record serves multiple ethical functions: it enables workers to verify that the system operates continuously rather than being selectively activated; it provides evidence for regulatory compliance or violation, supporting enforcement of environmental protection laws; and it creates transparency regarding long-term exposure patterns that might inform future health assessments or compensation claims. The creation of such records reflects recognition that power imbalances between employers and employees can create incentives to minimize or conceal pollution problems, and that technical systems can partially counter such dynamics by creating objective, persistent documentation.

The project documentation, including this final report, represents another form of stakeholder communication and professional responsibility. Comprehensive documentation enables facility operators to maintain and troubleshoot the system, enables regulatory authorities to verify compliance with applicable standards, enables future researchers to build upon the project's findings, and enables the engineering profession to learn from both successes and shortcomings. The IEEE Code explicitly requires that engineers "be honest and realistic in stating claims or estimates" and "reject bribery in all its forms," obligations that extend to honest reporting of project performance, limitations, and costs [51]. The documentation fulfills these requirements by providing transparent accounts of system capabilities, validation results, and economic performance, rather than a selective presentation designed to exaggerate achievements or minimize weaknesses.

9.3.4 Addressing Conflicting Ethical Demands

Engineering practice frequently confronts situations where multiple ethical principles suggest different courses of action, requiring reasoned judgment to balance competing legitimate concerns. The project encountered several such tensions, and the resolution approaches illustrate practical ethical reasoning in technical contexts.

One significant tension arose between the principle of maximizing health protection (suggesting continuous high-intensity filtration) and the principle of environmental sustainability (suggesting minimizing energy consumption). Pure application of precautionary principle would favor constant maximum filtration to eliminate any possibility of harmful exposure, but this approach would consume substantial energy, increase operational costs, and potentially make the system economically infeasible for target industries. The resolution through adaptive control reflects a proportionality principle: filtration intensity scales with actual pollution levels, providing aggressive protection when genuinely needed while avoiding unnecessary resource consumption when air quality is already acceptable. This balanced approach acknowledges that multiple goods (health protection, environmental sustainability, economic accessibility) deserve consideration, and that maximizing one dimension by completely sacrificing others would yield inferior overall outcomes.

Another ethical tension emerged between data transparency and confidentiality. Workers' health interests favor maximum transparency about pollution levels, while facility operators' legitimate business interests include protecting proprietary information about production processes that might be inferred from pollution patterns. The project navigated this tension by focusing data access controls at the facility level rather than trying to distinguish between "acceptable" and "unacceptable" uses of data. All stakeholders within the facility (workers and management) have access to real-time and historical pollution data through the dashboard, ensuring worker empowerment and eliminating information asymmetries within the workplace. However, the system does not automatically transmit data to external parties or publish it publicly, respecting facility operators' confidentiality interests while maintaining internal transparency. This approach reflects the principle that conflict resolution should seek arrangements that respect multiple legitimate interests rather than declaring one interest absolutely superior.

A third tension involves the relationship between standardized, codified professional standards and the need for innovation in resource-constrained contexts. Adherence to established standards represents professional responsibility and provides assurance of safety and performance. However, strict application of standards developed for well-resourced contexts might make solutions unaffordable in developing country settings, effectively denying protection to vulnerable populations. The project addressed this tension by maintaining fidelity to safety-critical standards (sensor accuracy, filtration efficiency, electrical safety) while accepting cost-driven tradeoffs in non-safety-critical dimensions (dashboard sophistication, enclosure aesthetics, communication range). This approach reflects the principle that professional standards should be interpreted in light of their underlying purposes (protecting safety and enabling competent practice) rather than treated as inflexible rules, and that engineers have a responsibility to adapt approaches to serve populations in diverse economic contexts while maintaining core safety commitments.

9.3.5 Reflection on Limitations and Future Responsibilities

A complete ethical analysis must acknowledge not only what the project accomplished but also its limitations and the ongoing responsibilities that deployment creates. Despite the project's successes, several ethical concerns remain incompletely addressed and merit explicit acknowledgment.

First, while the project reduces industrial air pollution, it does not eliminate exposure to all potential occupational hazards. The monitoring system focuses on six pollutants (PM2.5, PM10, CO, NO_2, TVOC, eCO_2), but industrial facilities may generate additional contaminants not captured by the current sensor suite, including heavy metals, specific toxic organic compounds, or physical hazards such as excessive noise or heat. Workers might incorrectly interpret the system's indication of "acceptable air quality" as assurance that all occupational hazards are controlled, when in fact it addresses only the monitored subset. This creates an ethical obligation for transparent communication about system scope and limitations to prevent false sense of complete protection.

Second, the project's success in one facility does not automatically translate to broader impact unless the technology is disseminated and adopted more widely. The ethical significance of the project ultimately depends on its contribution to protecting vulnerable populations across Bangladesh's industrial sector, not merely the specific test deployment site. This creates ongoing responsibilities for the project team and the engineering profession more broadly to facilitate technology transfer, support implementation in additional facilities, and advocate for policies that incentivize or mandate adoption of effective pollution control measures. The principle of beneficence—actively promoting human welfare—demands not merely developing effective solutions but ensuring those solutions reach those who need them.

Third, any technological intervention in complex social systems risks unintended consequences that require ongoing monitoring and responsiveness. Possible unintended effects of air quality monitoring systems might include complacency regarding source reduction (relying on end-of-pipe filtration rather than eliminating pollution-generating processes), displacement of responsibility from employers to technological systems (framing pollution as a technical problem rather than a management failure), or worker layoffs if employers respond to pollution control costs by reducing workforce rather than accepting lower profit margins. While these concerns do not negate the project's value, they highlight that ethical responsibility extends beyond initial deployment to encompass ongoing attention to actual impacts and willingness to modify approaches if unanticipated harms emerge.

Fourth, the project exists within broader structures of economic inequality and uneven power relations that technical solutions alone cannot fully address. Air pollution in industrial facilities ultimately stems from economic systems that prioritize profit maximization over worker welfare, regulatory systems with inadequate enforcement capacity, and labor markets where workers lack alternatives to hazardous employment. While the monitoring and filtration system provides meaningful protection within these constraints, it represents a palliative measure rather than fundamental system change. Ethical reflection must acknowledge this limitation while still affirming the value of incremental improvements that enhance wellbeing within existing structures, even as parallel efforts work toward more transformative social change.

9.4 Conclusion

This chapter has demonstrated that the IoT-based monitoring and automated air purification system was developed with sustained attention to ethical principles and professional responsibilities throughout its lifecycle. The ethical analysis employed multiple normative frameworks—deontological duties, utilitarian welfare maximization, virtue ethics, rights-based principles, and care ethics—to ensure a comprehensive evaluation of moral dimensions inherent in technical decision-making. These frameworks were not merely theoretical constructs but rather practical tools that shaped design choices, implementation strategies, and stakeholder engagement approaches.

The identification of ethical issues revealed multiple domains of moral concern, including obligations to protect public health and safety, commitments to environmental stewardship and sustainability, responsibilities regarding data privacy and security, duties to obtain informed consent and engage stakeholders meaningfully, professional obligations to maintain competence and honesty, and imperatives to address social justice and promote equitable access to pollution protection.

The application of ethical principles manifested in numerous design decisions: the fog-based architecture that prioritizes operational reliability and data privacy; the sensor selection and calibration procedures that fulfill competence obligations; the redundancy provisions that operationalize safety commitments; the transparent dashboard that promotes stakeholder empowerment; the adaptive control strategy that balances multiple legitimate interests; and the comprehensive documentation that enables accountability and knowledge dissemination. These implementations demonstrate that ethics and engineering excellence are complementary rather than competing concerns, as systems designed with ethical awareness typically exhibit superior performance precisely because they account for broader contextual factors and stakeholder needs.

The chapter also acknowledged limitations and ongoing responsibilities, recognizing that ethical obligations extend beyond initial deployment to encompass long-term impacts, unintended consequences, and broader systemic factors that technological solutions alone cannot fully address. This honest acknowledgment reflects the professional virtue of epistemic humility and the recognition that engineering practice must be accompanied by sustained critical reflection regarding both achievements and shortcomings.

The integration of ethics into engineering practice serves multiple essential functions: it protects vulnerable populations from harm; it maintains public trust in the engineering profession; it ensures that technical capabilities are directed toward genuine human flourishing rather than narrow optimization; it promotes justice by attending to distributional concerns and power asymmetries; and it cultivates the character traits and professional excellences that define competent, responsible engineering practice. The air quality monitoring and purification system developed through this project exemplifies such integration, demonstrating that rigorous ethical analysis can coexist with technical innovation to produce solutions that are not only functional but also worthy of professional pride and public trust.

The ethical dimension of engineering extends beyond individual projects to encompass collective professional responsibility for how technology shapes society. By documenting the ethical reasoning underlying this project and demonstrating how moral principles can be operationalized in technical practice, this chapter contributes to the broader engineering knowledge base regarding effective integration of ethics into design processes. Future projects addressing similar challenges in industrial pollution control, occupational health protection, or environmental monitoring can draw upon these documented approaches, adapting them to their specific contexts while building upon the ethical foundations established here. In this way, professional ethics becomes not merely a constraint on engineering practice but rather a positive force that enriches the discipline and ensures that technical progress genuinely serves human and environmental wellbeing.

Chapter 10: Conclusion and Future Work

10.1 Project Summary

This chapter consolidates the overall outcomes of the project and highlights its technical, economic, and societal contributions. The work was driven by the urgent need for an affordable, reliable, and intelligent air pollution control solution for industrial environments in Bangladesh, particularly small and medium enterprises. The proposed system was designed, implemented, tested, and validated to demonstrate that effective industrial air purification can be achieved without relying on high-cost, infrastructure-heavy solutions.

Problem Context and System Objective: This project was motivated by the lack of affordable, adaptive, and integrated air pollution control solutions for industrial environments in Bangladesh, particularly for small and medium enterprises. Existing systems are often fragmented, monitoring-only, or prohibitively expensive. To address this gap, the project aimed to design and implement a unified IoT-based monitoring and automated air purification system capable of real-time sensing, intelligent decision-making, and autonomous operation under resource-constrained industrial conditions.

System Architecture and Intelligent Control Framework: A fog-based distributed architecture was developed, consisting of multiple sensor nodes, a data aggregation gateway, and a centralized purification unit. The system enables continuous real-time monitoring of multiple pollutants, including PM2.5, PM10, CO, NO_2, VOCs, temperature, and humidity. A closed-loop automation framework dynamically regulates purification intensity using PWM-based fan control, ensuring low-latency response, resilience to unreliable internet connectivity, and optimized energy consumption.

Purification Technology and Performance Evaluation: The proposed solution integrates a two-stage filtration mechanism combining H13-grade HEPA filtration for particulate matter and activated carbon adsorption for gaseous pollutants and VOCs. The system was experimentally validated through controlled laboratory testing and real industrial deployment. Results demonstrated high purification effectiveness, achieving 96.59% PM2.5 and 91.27% PM10 removal efficiency within 93 minutes of continuous operation under industrial conditions.

Economic Feasibility and Industrial Validation: The total system cost was limited to 46,434 BDT, making the technology accessible to SMEs traditionally excluded from advanced pollution control solutions. A comprehensive economic analysis confirmed strong financial viability, with a 40% first-year return on investment, an 8.6-month payback period, and a 5.31 benefit–cost ratio over a five-year horizon. Successful deployment at Allied Solar Energy Ltd. validated system robustness, scalability, and practical applicability beyond laboratory environments.

Regulatory Alignment, Societal Impact, and Sustainability: The system design aligns with Bangladesh Air Pollution (Control) Rules 2022, WHO air quality guidelines, and occupational health standards, enabling automated compliance support. By reducing occupational exposure to harmful pollutants, the solution contributes to improved worker health, reduced long-term health risks, and enhanced productivity. Adaptive operation minimizes unnecessary energy usage and filter wear, supporting environmentally sustainable and scalable industrial air pollution control practices.

In conclusion, the project successfully bridges the gap between monitoring-only IoT solutions and standalone purification systems by delivering a holistic, intelligent, and economically sustainable industrial air pollution control platform. The outcomes demonstrate that advanced air quality management can be realistically deployed in developing-country industrial contexts without sacrificing performance or reliability.

10.2 Future Works

While the proposed system achieved its intended objectives and demonstrated strong technical and economic performance, industrial air pollution control remains a dynamic and evolving challenge. Emerging technologies in artificial intelligence, renewable energy, and cybersecurity offer significant opportunities to further enhance the system's intelligence, resilience, and long-term sustainability. This section outlines potential future extensions that can build upon the foundation established in this project.

Machine Learning Integration: The integration of machine learning (ML) techniques represents a significant step toward transforming the proposed system from a reactive control mechanism into a predictive and intelligent platform. By leveraging historical air quality data, environmental parameters, and system operation logs, supervised and time-series ML models—such as Random Forests, Gradient Boosting, or Long Short-Term Memory (LSTM) networks—can be trained to forecast pollution trends. These predictive insights would enable the system to anticipate hazardous pollution events and initiate purification actions proactively, even before regulatory thresholds are exceeded. Such early intervention can reduce peak exposure levels, optimize purifier runtime, and improve overall energy efficiency. Moreover, ML-based pattern recognition can help distinguish between transient pollution spikes and sustained emission events, allowing more informed and context-aware control decisions.

Predictive Maintenance: Predictive maintenance introduces a data-driven approach to system reliability and operational continuity. Continuous monitoring of parameters such as airflow rate, fan current consumption, vibration signatures, and pressure drop across filters can be used to estimate component health and degradation levels. Machine learning regression or anomaly detection models can predict remaining useful life (RUL) of critical components like filters and exhaust fans. This enables maintenance activities to be scheduled based on actual equipment condition rather than fixed intervals, significantly reducing unexpected failures and unplanned downtime. In industrial environments, where shutdowns can be costly, predictive maintenance enhances system availability, lowers maintenance costs, and improves long-term economic feasibility.

Advanced Control Algorithms: While the current system relies on predefined threshold-based logic for purification control, advanced control strategies can greatly improve system responsiveness and stability. Fuzzy logic controllers can handle uncertainty and nonlinear behavior in pollutant concentration data, allowing smoother transitions between operational states. Adaptive PID controllers can dynamically tune control gains based on real-time environmental changes, ensuring optimal performance under varying industrial conditions. Furthermore, reinforcement learning (RL) approaches can enable the system to learn optimal control policies through interaction with the environment, balancing purification effectiveness, energy consumption, and component wear. These intelligent control techniques can significantly enhance decision accuracy, reduce oscillations, and improve user comfort and system efficiency.

Expanded Pollutant Detection: The current sensor configuration focuses on commonly encountered industrial pollutants; however, many industrial sectors emit a broader range of harmful gases. Future system extensions can integrate additional sensors for sulfur dioxide (SO_2), ammonia (NH_3), ozone (O_3), and volatile organic compounds such as formaldehyde. This expanded sensing capability would allow deployment in chemical plants, oil refineries, fertilizer industries, textile processing units, and heavy manufacturing facilities. A multi-pollutant detection framework also enables more precise source identification and pollution profiling, supporting regulatory compliance and targeted mitigation strategies. Additionally, sensor fusion techniques can be applied to improve measurement accuracy and reduce false alarms.

Edge AI Deployment: Edge AI and TinyML integration can significantly enhance system autonomy and scalability. By deploying lightweight machine learning models directly on microcontrollers or sensor nodes, preliminary data processing and decision-making can occur locally, without constant reliance on a central gateway or cloud server. This reduces communication latency, minimizes bandwidth usage, and improves real-time responsiveness—especially critical in safety-sensitive industrial environments. Edge-based intelligence also enhances system resilience during network failures and lowers overall computational load on the central controller. With advancements in low-power AI hardware, such deployment is increasingly feasible even in cost-sensitive industrial applications.

Industrial-Scale Expansion: To support large-scale industrial deployment, future work can focus on designing higher-capacity purification units and modular architectures. Duct-integrated purification systems can be developed to interface directly with existing industrial ventilation and exhaust infrastructures. For multi-floor factories and large industrial complexes, distributed sensor networks combined with centralized control units can provide zone-wise pollution management. Such scalability allows the system to adapt to varying spatial layouts and emission intensities, making it suitable for both small workshops and large industrial facilities. This expansion aligns the system with real-world industrial requirements and enhances its commercial viability.

Renewable Energy Integration: Integrating renewable energy sources, particularly solar photovoltaic (PV) systems with battery storage, can greatly improve system sustainability and operational reliability. In regions with unstable grid supply—common in many industrial zones of Bangladesh—renewable integration ensures uninterrupted operation of pollution control systems. Intelligent energy management algorithms can optimize power usage by prioritizing critical components during low-energy conditions and storing excess solar energy for peak pollution periods. This approach reduces dependency on fossil-fuel-based electricity, lowers operational costs, and aligns the system with global sustainability and carbon reduction goals.

Long-Term Field Deployment: Extended real-world deployment across multiple industrial sites is essential to evaluate long-term system performance. Continuous operation over months or years allows assessment of lifecycle costs, component durability, sensor drift, and environmental robustness. Such longitudinal studies provide valuable insights into real-world challenges that may not be evident in short-term testing, including seasonal pollution variations and long-term maintenance requirements. The collected data can further refine predictive models, improve system calibration, and validate environmental impact claims, strengthening the system's readiness for widespread adoption.

Commercialization and Standardization: To transition the system from a laboratory prototype to a market-ready product, future work must address commercialization and standardization challenges. This includes redesigning the enclosure for industrial-grade durability, improving electromagnetic compatibility, and ensuring compliance with national and international standards for air quality monitoring and electrical safety. Certification from relevant regulatory authorities and planning for mass production are critical steps toward deployment at scale. Standardization also facilitates integration with existing industrial automation systems and government monitoring platforms, increasing acceptance among stakeholders and policymakers.

In summary, the proposed system provides a scalable and future-ready platform for intelligent industrial air pollution control. With the incorporation of predictive intelligence, renewable energy, and enhanced security, the system has strong potential to evolve into a nationally deployable solution, contributing significantly to occupational health, environmental sustainability, and smart industrial transformation in Bangladesh.

Chapter 11: Identification of Complex Engineering Problems and Activities

11.1 Identifying the Attribute of Complex Engineering Problem (EP)

The IoT-Based Monitoring and Automated Air Purification System for Industrial Pollution Control represents a complex engineering problem characterized by multiple interdependent technical, social, and regulatory dimensions. The project addresses the critical challenge of industrial air pollution in Bangladesh, where traditional monitoring and control systems have proven inadequate. The complexity manifests in the integration of heterogeneous sensor technologies, real-time data processing architectures, automated actuation systems, and regulatory compliance frameworks within resource-constrained industrial environments.

The problem required synthesizing knowledge from electrical engineering, environmental science, embedded systems, IoT communication protocols, and industrial automation. The solution demanded coordination across multiple technical domains while simultaneously addressing stakeholder needs ranging from worker safety to regulatory compliance and economic viability for small and medium enterprises.

TABLE XX. ATTRIBUTES OF COMPLEX ENGINEERING PROBLEMS (EP)

Attributes	Put a tick (✓) as appropriate
P1: Depth of knowledge required	✓
P2: Range of conflicting requirements	
P3: Depth of analysis required	✓
P4: Familiarity of issues	✓
P5: Extent of applicable codes	✓
P6: Extent of stakeholder involvement and needs	✓
P7: Interdependence	✓

11.2 How the Project Addresses Selected Attribute (EP)

P1: Depth of Knowledge Required

The project demanded comprehensive interdisciplinary expertise spanning multiple engineering and scientific domains. The sensor subsystem required a deep understanding of particulate matter detection principles, metal-oxide semiconductor gas sensing mechanisms, and electrochemical sensor operation. The PMS5003 sensor operates on laser scattering principles, requiring knowledge of optical physics and particle size distribution analysis. The ENS160 and CCS811 TVOC sensors utilize metal-oxide semiconductor technology, demanding an understanding of surface chemistry and temperature-dependent conductivity variations. The Fermion MEMS CO and NO_2 sensors employ electrochemical detection requiring expertise in redox reactions and current-voltage relationships.

The communication architecture necessitated mastery of WiFi mesh networking protocols, specifically the painlessMesh library implementation for ESP32 microcontrollers. Establishing reliable node-to-node communication required an understanding of the IEEE 802.11 standard, frequency spectrum management at 2.4 GHz, path loss calculations, and interference mitigation strategies. The free-space path loss analysis yielding a maximum range of 31.6 meters demonstrated applied knowledge of RF propagation physics.

The embedded systems development required proficiency in microcontroller programming, real-time operating system concepts, interrupt handling, and peripheral interfacing protocols, including I^2C, UART, and SPI. The firmware implementation for ESP32 and Arduino platforms demanded understanding of memory management, power optimization, and concurrent task scheduling.

The air purification mechanism design required knowledge of fluid dynamics, specifically airflow modeling and pressure drop calculations. The dual Arctic P12 Max fan configuration analysis involved calculating volumetric flow rates (275.38 m^3/h), static pressure generation (85.3 Pa), and Air Changes per Hour (ACH) to achieve 6 ACH in the 40.5 m^3 test volume. The blade pitch angle verification at 9.3° required understanding of axial flow fan aerodynamics and the relationship between tip speed (20.7 m/s) and axial velocity (3.38 m/s).

The filtration system design necessitated knowledge of HEPA filter mechanics, achieving H13-grade efficiency of 99.95% for 0.3 μm particles, and activated carbon adsorption principles for VOC removal at 85% efficiency. The multi-stage filtration architecture required understanding pressure drop optimization and filter loading dynamics.

Environmental science knowledge was essential for interpreting pollutant health effects, establishing appropriate threshold values based on WHO Air Quality Guidelines, and understanding exposure-response relationships. The threshold definitions for PM2.5 (safe: 0-12 $\mu g/m^3$, hazardous: >150 $\mu g/m^3$) and other pollutants required the synthesis of toxicological data and regulatory standards.

P3: Depth of Analysis Required

The project demanded extensive analytical work across multiple dimensions. The system architecture comparison involved evaluating three fundamentally different design approaches through quantitative performance metrics. The analysis matrix examined 10 performance parameters including hardware cost (ranging from 24,850 to 27,200 BDT), response time (3-6 seconds), power consumption (27.12-38.68 W), and area coverage (8.33-25 m^2/min). This multi-criteria decision analysis required developing weighted scoring systems and conducting trade-off assessments.

The airflow modeling analysis involved calculating required volumetric flow rates based on room dimensions and target ACH values. For the 15 m^2 area with 2.7 m height (40.5 m^3 volume), achieving 6 ACH required 243 m^3/h airflow. The analysis validated that the dual-fan configuration providing 275.38 m^3/h exceeded requirements with appropriate safety margin. The pressure drop calculations across the four-filter intake system and HEPA filter verified that the 85.3 Pa available static pressure substantially exceeded the calculated 12.5 Pa system resistance.

The sensor calibration validation required statistical analysis comparing sensor readings against reference AQI station data over an 11-hour monitoring period. The analysis involved calculating percentage errors for each pollutant across multiple time points, demonstrating average errors below 10% for PM2.5 (ranging from -5.39% to +6.88%), PM10, CO, NO_2, and TVOC measurements.

The industrial validation testing required comprehensive data analysis tracking pollutant concentration reduction over time. The system demonstrated PM2.5 reduction from 120.47 μg/m³ to 9.42 μg/m³ (96.59% efficiency) and PM10 reduction from 345.69 μg/m³ to 11.79 μg/m³ (91.27% efficiency) over 93 minutes of operation. The combined weighted efficiency calculation yielding 94.46% required integrating multiple pollutant removal rates.

The economic analysis involved detailed cost-benefit modeling over a 5-year operational period, including Net Present Value calculations with 10% discount rate. The NPV analysis required computing present values for each year's benefits and summing to yield 199,967 BDT total value creation. The sensitivity analysis examined conservative (-20% benefits) and optimistic (+20% benefits) scenarios, calculating corresponding ROI, payback periods, and BCR values.

The risk management analysis employed multiple analytical frameworks including Scenario Analysis, Failure Mode and Effects Analysis (FMEA), Fault Tree Analysis (FTA), and Event Tree Analysis (ETA). The FMEA calculations involved computing Risk Priority Numbers (RPN = Probability × Severity × Detection) for critical components, with values ranging from 12 for HEPA filter degradation to 45 for ESP32 data breach vulnerabilities.

The ethical analysis required applying multiple normative frameworks including deontological ethics, utilitarian analysis, virtue ethics, rights-based approaches, and care ethics to evaluate design decisions and stakeholder impacts. This analysis involved balancing competing ethical principles, such as maximizing health protection versus minimizing energy consumption.

P4: Familiarity of Issues

Although air pollution and occupational safety are widely recognized societal problems in Bangladesh, they are not issues that Electrical and Electronic Engineering (EEE) students routinely encounter within standard academic coursework or laboratory practice. Typical EEE curricula emphasize circuit theory, electronics, signal processing, power systems, and communication technologies, with limited direct exposure to real-world industrial health hazards, environmental risk assessment, or occupational safety challenges. As a result, the practical realities of prolonged exposure to industrial air pollutants fall outside the conventional experiential domain of EEE students.

The field survey conducted across six industrial facilities, therefore, exposed the student researchers to unfamiliar, multidisciplinary challenges, including the impacts on worker health, the assessment of pollution severity, and industry-specific emission characteristics. Direct interactions with workers and engineers revealed health conditions such as chronic respiratory illness in brick kilns, silicosis risks in cement plants, and chemical exposure symptoms in manufacturing environments, issues rarely addressed in undergraduate EEE courses. This unfamiliarity necessitated an independent investigation that went beyond traditional engineering knowledge, including the interpretation of environmental standards, understanding the human health implications, and integrating sensing technologies within harsh industrial settings.

Furthermore, regulatory frameworks such as the Bangladesh Air Pollution (Control) Rules 2022 and BNAAQS, while critical to system design, are not typically covered in depth within EEE programs, requiring additional learning related to environmental compliance and ethical engineering responsibility. Similarly, while technologies like IoT sensors, HEPA filtration, and activated carbon systems are technically familiar as components, their application for occupational health protection represents a non-traditional and unfamiliar engineering context for EEE students.

Overall, this project required the students to operate beyond conventional disciplinary boundaries, engaging with environmental engineering, public health considerations, and regulatory compliance. Addressing these unfamiliar issues strengthened the project's complexity and reinforced the need for multidisciplinary problem-solving skills that extend beyond standard EEE academic exposure.

P5: Extent of Applicable Codes

The project operates under comprehensive regulatory and technical standards spanning international, national, and industry-specific frameworks. The multiplicity of applicable codes significantly increases project complexity by requiring simultaneous compliance with often overlapping or potentially conflicting requirements.

International standards governing sensor accuracy include ISO 21501-4:2018 for particulate matter sensor calibration and performance verification. The project's PMS5003 sensors were validated against these standards, achieving ±10% accuracy in the 100-500 μg/m³ measurement range.

Filtration system performance is governed by ISO 16890:2016, which defines testing protocols and classification criteria for air filters. The project's H13-grade HEPA filter specification of 99.95% efficiency for 0.3 μm particles aligns with this standard's requirements for high-efficiency particulate air filtration.

Hardware protection standards include IEC 60529:2013, defining Ingress Protection (IP) ratings. The project's IP54-rated sensor node enclosures comply with this standard's requirements for protection against dust ingress and water spray, ensuring reliable operation in industrial environments.

Communication protocols adhere to IEEE 802.11-2020 standards for WiFi operation, specifying frequency allocation, modulation schemes, and network security requirements. The project's mesh network implementation operates within the 2.4 GHz ISM band as defined by this standard.

Environmental management follows ISO 14001:2015 principles promoting lifecycle assessment, resource efficiency, and pollution prevention. The project's energy-efficient design and recyclable materials selection reflect these environmental management commitments.

Risk management methodologies conform to ISO 31000:2018 guidelines for systematic risk identification, assessment, and mitigation. The project's comprehensive risk analysis employing FMEA, FTA, and ETA techniques operationalizes this standard's principles.

National regulatory compliance is mandatory under the Bangladesh Air Pollution (Control) Rules 2022, which establish emission limits, monitoring requirements, and reporting obligations for industrial facilities. The system's data logging and dashboard capabilities directly support compliance with these regulatory reporting mandates.

The Bangladesh National Ambient Air Quality Standards (BNAAQS) define maximum permissible pollutant concentrations, including PM2.5 limits of 15 $\mu g/m^3$ annual mean. The project's threshold values and control logic were calibrated to maintain indoor concentrations below these regulatory limits.

Electrical safety standards include BDS IEC 60335-1, Bangladesh's adoption of international safety requirements for electrical appliances. The project's 12V and 5V low-voltage DC operation, proper insulation, and overcurrent protection align with these safety requirements.

Professional ethical codes include the IEEE Code of Ethics emphasizing public safety and honesty, the IEB Code of Ethics prioritizing sustainable development and public welfare, and the ACM Code of Ethics addressing data privacy and professional competence. The project's design decisions and operational protocols were guided by these ethical frameworks.

P6: Extent of Stakeholder Involvement and Needs

The project affects multiple stakeholder groups with diverse and sometimes competing interests, necessitating inclusive design approaches that balance these varied needs.

Industrial workers constitute the primary beneficiary group, experiencing direct exposure to pollution hazards. The survey documented worker health complaints including severe chronic respiratory issues, coughing, eye irritation, headaches, and dizziness across different industrial sectors. Workers' needs prioritize immediate health protection, intuitive system operation, and transparent air quality information. The real-time dashboard providing immediate pollutant concentration visualization addresses workers' need for accessible safety information.

Facility management and industry owners represent stakeholders balancing compliance obligations, economic constraints, and operational efficiency. The survey engaged three chief engineers who provided insights into current purification methods, capital budget limitations, and maintenance capacity constraints. Management needs include affordable capital costs (achieved at 46,434 BDT productive spending), minimal operational expenses (17.11 W average power consumption translating to 0.41 kWh daily), and compliance documentation capabilities. The system's automated operation reduces management burden while the data logging functionality supports regulatory reporting requirements.

Surrounding community members living near industrial facilities experience secondary exposure through fugitive emissions. Approximately 1,000 residents in proximity to surveyed facilities face elevated pollution exposure affecting quality of life and health outcomes. Community needs prioritize emission reduction and environmental quality improvement. The system addresses these needs indirectly by reducing indoor pollutant concentrations, consequently lowering emissions released to ambient environment.

Regulatory authorities including the Department of Environment enforce emission standards and workplace safety requirements. Regulator needs include verifiable compliance data, standardized reporting formats, and audit-ready documentation. The system's SQLite database with 30-day retention period and exportable data formats supports regulatory compliance verification.

Small and medium enterprise operators represent a critical stakeholder group often excluded from advanced pollution control technologies due to cost barriers. The survey specifically targeted SME contexts including brick kilns and small-scale cement operations. SME needs emphasize affordability, simplicity, and minimal maintenance requirements. The system's <50,000 BDT total cost and fog-based architecture requiring no cloud subscription fees specifically address SME accessibility constraints.

Technology maintenance personnel require systems compatible with locally available skills and replacement components. The project's use of commercially available sensors sourced within Bangladesh and standard Arduino/ESP32 platforms ensures maintainability by technicians with conventional electronics training.

Future researchers and engineers constitute stakeholders benefiting from comprehensive documentation enabling knowledge transfer and replication. The detailed technical report, validated performance data, and openly documented design decisions serve this stakeholder group's knowledge advancement needs.

P7: Interdependence

The system exhibits tight interdependence across technical subsystems, requiring coordinated operation to achieve functional objectives. Component failure propagates through dependent subsystems potentially compromising overall system effectiveness.

The sensor network depends on reliable power supply, with each ESP32 node consuming approximately 0.8 W and sensor suite adding 1.05 W average load. Power interruption immediately terminates data acquisition across all affected nodes, creating monitoring blind spots. The interdependence between power and sensing functions necessitated backup power provisions and low-power design optimization.

The mesh network architecture creates mutual dependencies among sensor nodes, where each node may relay data from neighbors. The painlessMesh protocol requires minimum node density to maintain network connectivity. If intermediate nodes fail, peripheral nodes may lose communication paths to the Data Aggregation Gateway. The calculated maximum node-to-node range of 31.6 meters constrains physical deployment geometry, creating spatial interdependence.

The Data Aggregation Gateway depends on receiving data from all sensor nodes to generate comprehensive facility-wide air quality assessments. Partial node failures degrade assessment accuracy by creating unmonitored zones. The gateway's control decisions rely on aggregated multi-node data, meaning sensor failures propagate to potentially inappropriate purification activation or deactivation.

The purification unit depends on receiving accurate control commands from the Central Control Unit, which in turn depends on receiving processed data from the Data Aggregation Gateway. This sequential dependency chain means data processing errors or communication failures anywhere in the pipeline compromise purification effectiveness. The measured response time of 6 seconds from threshold breach to fan activation reflects this multi-stage interdependence.

The filtration system's effectiveness depends on proper fan operation, which depends on PWM control signal integrity, which depends on microcontroller functionality, which depends on stable power supply. This cascading dependency means that electrical power quality ultimately determines air purification performance despite no direct relationship between power characteristics and pollutant removal chemistry.

Beyond technical interdependence, the project links technological success with social, regulatory, and institutional factors. System effectiveness depends on worker compliance with operational protocols, management commitment to maintenance schedules, regulatory enforcement creating adoption incentives, and community trust in system reliability. These social interdependencies mean purely technical optimization cannot guarantee real-world impact without parallel attention to human and institutional dimensions.

The measured industrial validation results demonstrate these interdependencies empirically. The system required 93 minutes to reduce pollution from hazardous to safe levels, with the timeline reflecting coordinated operation of all subsystems: sensors detecting elevated pollutants, mesh network transmitting data, gateway processing and deciding, control unit activating purifiers, and fans generating airflow through properly maintained filters. Failure at any stage would have extended remediation time or prevented pollution reduction entirely.

11.3 Identifying the Attribute of Complex Engineering Activities (EA)

The development, implementation, and validation of the IoT-based monitoring and automated air purification system constituted a complex engineering activity requiring coordination of diverse resources, multi-stakeholder interaction, integration of established and novel technologies, consideration of societal and environmental consequences, and operation within a familiar yet challenging industrial context.

TABLE XXI. ATTRIBUTES OF COMPLEX ENGINEERING ACTIVITIES (EA)

Attributes	Put a tick (✓) as appropriate
A1: Range of resources	✓
A2: Level of interaction	✓
A3: Innovation	
A4: Consequences for society and the environment	✓
A5: Familiarity	✓

11.4 How the Project Addresses Selected Attribute (EA)

A1: Range of Resources

The project integrated exceptionally diverse resource categories spanning hardware components, software platforms, analytical tools, fabrication facilities, testing equipment, human expertise, and institutional partnerships.

Hardware resources encompassed 60+ distinct component types sourced through 28 procurement days from multiple suppliers. The sensor subsystem alone required six different sensor technologies: PMS5003 particulate sensors (2,990 BDT each), ENS160+AHT21 integrated gas sensors (990 BDT), CCS811 TVOC sensors (2,099 BDT), Fermion MEMS CO sensors (859 BDT), Fermion MEMS NO_2 sensors (1,590 BDT), and ADS1115 ADC modules (535 BDT). Each sensor type requires unique interfacing protocols, calibration procedures, and data interpretation algorithms.

Microcontroller resources included ESP32-WROOM-32 modules for sensor nodes and Data Aggregation Gateway (519 BDT each), providing dual-core processing at 240 MHz, integrated WiFi and Bluetooth, and 520 KB SRAM. The Central Control Unit employed additional processing resources for real-time control logic execution.

Display and user interface resources ranged from 0.96-inch I^2C OLED displays (290 BDT) for sensor nodes to 2.42-inch displays (1,690 BDT) for the Central Control Unit, requiring different driver libraries and resolution management approaches.

Power management resources included LM2596S DC-DC buck converters (380 BDT) providing regulated 5V from 12V input, 12V 2A AC-DC adapters (200 BDT) for mains connection, and 10,000 mAh power banks (800 BDT) for backup capability. Power distribution required coordinating voltage levels, current capacities, and protection circuits.

Filtration resources comprised H13-grade HEPA filters (2,900 BDT), four automotive-grade side filters (300 BDT each), and dual Arctic P12 Max fans (1,800 BDT each), generating 137.69 m^3/h airflow at 42.65 Pa static pressure. These components required structural integration within custom-fabricated 12mm PVC board enclosures (2,700 BDT) with spray-painted finishes (150 BDT).

Software resources included development environments (Arduino IDE, Visual Studio Code), IoT platforms (Blynk for cloud connectivity), programming languages (C++ for firmware, Python for data analysis and dashboard), database systems (SQLite for local storage), and specialized libraries (painlessMesh for network management, multiple sensor-specific drivers).

Analytical tools spanned Proteus 8.21 Professional for circuit simulation (enabling virtual prototyping that prevented 4,426 BDT in component losses), MATLAB R2025a for data visualization and statistical analysis, and Altium Designer for professional PCB layout. These tools required licensed software access and operator proficiency.

Fabrication resources included PCB printing services (1,853 BDT for three sensor node boards), 3D printing for sensor node enclosures (600 BDT), acrylic sheet cutting for prototyping (1,300 BDT total for validation iterations), and specialized assembly tools including soldering equipment, wire strippers, and precision screwdrivers.

Testing equipment resources comprised reference AQI monitoring stations for sensor calibration validation, controlled environment chambers for laboratory testing, industrial facility access for field validation, and measurement instruments for electrical characterization.

Human expertise resources required team members with specializations in hardware design (Reshad leading sensor integration), software development (Sadia managing IoT platforms), system design (Noon coordinating filtration subsystems), and project management (Alvi directing documentation and coordination). Each team member contributed approximately 25% effort across 11-month timeline.

Institutional resources included BRAC University laboratory facilities, industry partnerships providing field testing sites (Allied Solar Energy Ltd., Mark Designers, ASR Bricks, AR Cement, Square Group facilities), and regulatory guidance from Department of Environment standards documentation.

Financial resources totaling 50,860 BDT required budget allocation across 28 procurement days, with 91.30% productive utilization and 8.70% risk management allocation. Resource procurement demanded supplier identification, price negotiation, quality verification, and inventory management.

A2: Level of Interaction

The project required intensive multi-level interactions spanning technical subsystems, human team members, institutional stakeholders, and external validation partners.

Technical subsystem interactions operated through defined communication protocols. Sensor nodes communicated via I²C (four devices sharing SDA/SCL lines), UART (PMS5003 dedicated serial channel), and WiFi mesh (painlessMesh protocol enabling peer-to-peer data relay). The Data Aggregation Gateway interacted simultaneously with multiple sensor nodes via mesh network while communicating with the Central Control Unit through dedicated WiFi channel. This multi-protocol interaction required careful timing management to prevent bus conflicts and ensure data integrity.

The dashboard application interacted with the Data Aggregation Gateway through serial communication, reading JSON-formatted data streams at 115,200 baud rate. The Python-based interface parsed incoming data, updated SQLite database records, generated real-time visualizations, and maintained 60 FPS animation performance. This interaction demanded buffering strategies to handle variable-rate data arrival without frame drops or UI freezing.

Team member interactions followed structured collaboration patterns defined in the project management framework. Weekly progress reviews assessed task completion against burndown chart projections, identifying 15% schedule slip during component procurement phase (Weeks 12-20) requiring intervention through parallel workflows and vendor diversification. Integration challenges during Weeks 28-32 necessitated intensive debugging sessions with cross-functional participation to resolve ESP32-Arduino Uno R4 firmware compatibility issues.

Industry stakeholder interactions began with the field survey engaging 100 workers and three chief engineers across six facilities during June-August 2025. These consultations identified priority pollutants, acceptable cost thresholds, and operational constraints informing design decisions. The industrial validation at Allied Solar Energy Ltd. required coordinated deployment scheduling, safety protocol alignment, and real-time performance monitoring over 93-minute test duration.

Regulatory interactions involved interpreting Bangladesh Air Pollution (Control) Rules 2022 requirements, mapping WHO Air Quality Guidelines to system threshold values, and ensuring compliance documentation capabilities. The interaction between technical capabilities and regulatory expectations shaped data logging retention periods (30 days), reporting format standardization, and audit trail generation.

Community interactions occurred through educational outreach documented in the ethics chapter, where approximately 100 residents near surveyed facilities received air quality awareness information. These interactions built public trust and gathered feedback on acceptable deployment practices.

Academic interactions included literature review synthesis across 27 references spanning air pollution control, IoT system architectures, sensor technologies, and regulatory frameworks. Citation management and intellectual property attribution required careful documentation maintaining academic integrity.

Supplier interactions spanned 28 procurement days coordinating component sourcing from multiple vendors. Price negotiations, delivery scheduling, quality verification, and warranty documentation required ongoing communication. Component damage incidents (ESP32, ADS1115 modules) necessitated supplier contact for replacement parts outside planned procurement timeline.

Calibration validation interactions with Grace International School AQI monitoring station required data format alignment, timestamp synchronization, and comparative analysis protocols. The 11-hour parallel monitoring session demanded coordinated measurement schedules ensuring simultaneous data capture.

Manufacturing interactions for PCB fabrication required translating Altium Designer layouts into Gerber file formats, specifying board dimensions and copper thickness, coordinating 7-day fabrication timelines, and conducting quality inspection upon delivery. Fabrication issues requiring board re-spinning created additional supplier interactions outside initial project planning.

A4: Consequences for Society and the Environment

The project generates substantial societal and environmental consequences extending beyond immediate technical performance metrics.

Worker health consequences manifest through reduced pollutant exposure in industrial facilities. The industrial validation demonstrated PM2.5 reduction from 120.47 μg/m³ to 9.42 μg/m³, transitioning conditions from WHO "Hazardous" classification (associated with severe respiratory symptoms, cardiovascular stress, and emergency room visits) to "Safe" classification permitting sustained occupancy. For the 10 direct beneficiaries in the validated facility, this represents prevented health complications valued at 50,000 BDT annually through reduced medical treatments, fewer work absences, and improved quality of life.

Community environmental consequences extend to approximately 1,000 residents living near industrial facilities. By reducing indoor pollutant concentrations, the system decreases fugitive emissions released to ambient air through facility ventilation, doorways, and structural gaps. Mathematical dispersion modeling suggests that sustained 90%+ indoor concentration reductions translate to measurable ambient air quality improvements within 500-meter radius, benefiting respiratory health of nearby populations including vulnerable groups like children and elderly residents.

Occupational safety consequences improve workplace conditions in industries with historically poor environmental controls. The field survey documented severity ratings of 5/5 in brick kilns and 4/5 in cement plants, indicating severe chronic respiratory risks. System deployment in such facilities fundamentally alters risk-benefit calculations for workers choosing employment, reducing the forced choice between economic survival and health protection. This consequence particularly benefits low-income workers with limited alternative employment options.

Economic productivity consequences emerge through reduced absenteeism and enhanced cognitive function. The economic analysis quantified 10,000 BDT annual productivity gains for 10 beneficiaries, assuming conservative 5% performance improvement. Harvard research indicates cognitive function scores improve 61% in environments with enhanced air quality compared to typical buildings, suggesting the true productivity impact may exceed conservative estimates. At industrial scale, such improvements translate to enhanced manufacturing output without proportional increases in labor inputs.

Regulatory compliance consequences enable small and medium enterprises to meet Bangladesh Air Pollution (Control) Rules 2022 requirements without prohibitive capital investments. The 46,434 BDT productive cost represents 10-20× lower expenditure than conventional industrial air quality systems requiring 300,000-500,000 BDT investments. This cost accessibility expands the population of compliant facilities, creating positive externalities through demonstration effects and competitive pressure encouraging wider adoption.

Technology demonstration consequences extend beyond single deployment sites. The comprehensive documentation, validated performance data, and accessible cost structure position the project as a replicable model for industrial pollution control. If adopted across Bangladesh's brick kiln sector (employing approximately 500,000 workers in 7,000+ facilities), proportional health benefits would prevent thousands of premature deaths annually, justifying the characterization as significant societal impact.

Environmental sustainability consequences operate through energy efficiency and lifecycle considerations. The 17.11 W average power consumption represents 75-85% reduction compared to continuous maximum-speed operation of comparable systems. Over 5-year operational lifespan, this efficiency saves approximately 650 kWh annually per installation. At Bangladesh's grid emission factor of 0.6 kg CO_2/kWh, this translates to 390 kg CO_2 emission reduction annually per system, accumulating to multi-ton carbon savings at scale deployment.

Material lifecycle consequences include electronic waste generation at system end-of-life. The project's modular architecture enables selective component replacement (sensors, filters, microcontrollers) rather than wholesale system disposal, extending effective lifespan and reducing waste generation. Documented end-of-life protocols ensure responsible recycling of electronic components and the proper disposal of contaminated filters.

Negative environmental consequences include manufacturing impacts from sensor production, microcontroller fabrication, and PCB assembly. These upstream processes involve energy-intensive semiconductor manufacturing, hazardous material use, and mining for rare earth elements. The project addresses these impacts through component longevity prioritization and documentation, encouraging repair over replacement, but cannot eliminate manufacturing footprints entirely.

Social justice consequences address environmental inequity where vulnerable populations disproportionately experience pollution exposure. The project's explicit focus on affordable solutions for small/medium enterprises directly serves this equity objective, ensuring that effective protection reaches facilities employing marginalized workers rather than exclusively serving well-resourced corporations with existing pollution control capacity.

A5: Familiarity

The project operates within a domain characterized by high familiarity with problem context but moderate novelty in technological implementation approaches. Problem familiarity is exceptionally high, as air pollution and occupational safety constitute long-standing, well-documented challenges in Bangladesh’s industrial sector. The field survey confirmed widespread recognition of pollution hazards among workers, managers, and regulators. Government response through Bangladesh Air Pollution (Control) Rules 2022 and Bangladesh National Ambient Air Quality Standards, demonstrates policy-level familiarity. Academic research establishing 102,000 annual premature deaths from air pollution indicates comprehensive scientific understanding of health consequences. This problem familiarity simplified requirements definition, stakeholder engagement, and validation criteria establishment.

Technology component familiarity varies across subsystems. IoT sensing technologies represent established, commercially mature solutions with extensive documentation, standardized interfaces, and proven reliability records. The PMS5003 sensor has been deployed globally in air quality monitoring applications with known accuracy characteristics and failure modes. ESP32 microcontrollers constitute widely-adopted platforms with extensive community support, libraries, and troubleshooting resources. Arduino programming environments represent familiar tools for embedded systems development. This component familiarity accelerated development by enabling leverage of existing knowledge rather than fundamental research.

System integration approaches exhibit moderate novelty. While individual components (sensors, microcontrollers, fans, filters) represent familiar technologies, their integrated operation as a unified cyber-physical system for industrial pollution control reflects a less common application. The fog-based architecture distributing intelligence between sensor nodes and local gateway represents a somewhat novel deployment pattern compared to purely cloud-centric or fully decentralized alternatives. The adaptive PWM fan control responding to real-time multi-pollutant data represents a moderately innovative control strategy.

Industrial deployment context familiarity is high within Bangladesh but may be less familiar in other geographical contexts. The specific challenges of unstable power grids, limited internet connectivity, dusty environments, high humidity, and cost constraints characteristic of Bangladeshi SME manufacturing are well-understood by project team members with local experience. This contextual familiarity enabled realistic constraint specification and appropriate technology selection. Transferring the solution to different industrial contexts (e.g., developed countries with stable infrastructure, or other developing countries with different regulatory frameworks) would require contextual adaptation.

Regulatory framework familiarity developed through project research rather than pre-existing expertise. Team members acquired familiarity with ISO standards (21501-4, 16890), IEC safety codes (60529, 60335-1), IEEE communication standards (802.11), WHO guidelines, and Bangladesh-specific regulations through systematic literature review and standards analysis. This acquired familiarity enabled compliance-oriented design decisions.

Methodological familiarity ranges from high for established engineering practices (circuit design, embedded programming, PCB layout) to moderate for specialized techniques (FMEA analysis, fault tree construction, economic NPV modeling). The project management framework employed familiar Agile-influenced approaches including iterative development, weekly reviews, and burndown tracking. Risk analysis methodologies required developing proficiency through training and application rather than leveraging extensive prior experience.

User population familiarity with deployment technologies is relatively low, as many industrial workers have limited exposure to IoT systems, data dashboards, or automated control mechanisms. This low end-user familiarity necessitated interface design prioritizing intuitiveness, minimal training requirements, and transparent system operation. The color-coded air quality indicators and simple operational feedback mechanisms reflect design choices accommodating low technological literacy.

The balance of serious problem familiarity, moderate technology familiarity, and variable contextual familiarity positioned the project as achievable within student team capabilities while maintaining sufficient challenge to constitute meaningful engineering activity. The project avoided both the extreme of addressing completely novel problems with experimental technologies (creating unacceptable risk) and the opposite extreme of merely replicating existing solutions without adaptation (providing insufficient learning value).

This chapter has systematically identified and justified the complex engineering problem and activity attributes characterizing the IoT-Based Monitoring and Automated Air Purification System project. The analysis demonstrates that the project addresses authentic complexity through interdisciplinary knowledge requirements, extensive analytical depth, comprehensive stakeholder engagement, tight technical interdependence, diverse resource coordination, multi-level interactions, and significant societal/environmental consequences. The selective absence of certain attributes (P2: conflicting requirements, A3: radical innovation) reflects honest assessment rather than comprehensive complexity, as genuinely complex engineering work need not exhibit all possible complexity dimensions. The validated performance results—96.59% PM2.5 reduction, 91.27% PM10 reduction, 8.6-month payback period, 199,967 BDT NPV—provide empirical evidence that the complex problem was successfully addressed through appropriately complex engineering activities.

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Appendix

FYDP-C/Fall 2025 Summary of Team Log Book Journal

Date	Attendees	Summary of Meeting Minutes	Responsible	Comment by ATC
7th October, 2025	Md. Reshad Al Muttaki, Sadia Afrin, Alvi Ibn Amzad Anil, Hasanat Fariha Noon	Initial meeting on hardware design. Formulated a plan on how to proceed with the design, component procurement, and project budget. Discussed early challenges in design.	All Members: Complete sensor node 1 by the next meeting	Good start. Focus on completion and objectives.
21st October, 2025	Md. Reshad Al Muttaki, Sadia Afrin, Alvi Ibn Amzad Anil, Hasanat Fariha Noon	Follow up on the sensor node 1 design. Completed node 1 and should start focusing on the other subsystems.	All Members: Complete all Sensor Nodes along with the Data Aggregation Gateway	Progress noted. Ensure systematic progression of the project. Focus on stakeholder engagement after completing the project as early as possible.
4th November, 2025	Md. Reshad Al Muttaki, Sadia Afrin, Alvi Ibn Amzad Anil, Hasanat Fariha Noon	Completed all the sensor nodes, but couldn’t complete the Data Aggregation Gateway due to incomplete calibration of all the sensor nodes.	All Members: Complete the Data Aggregation Gateway asap	Progress noted. Focus on working on multiple subsystems side by side. Divide the workload among the members.
16th November, 2025	Md. Reshad Al Muttaki, Alvi Ibn Amzad Anil	Completed all sensor nodes along with proper sensor calibration. Data Aggregation Gateway completed as well. Proper Mesh connection between all the nodes and DAG ensured as well. A Python interface created to visualize the accumulated data from the DAG. The next meeting will be the Progress presentation (on 2nd December).	All Members: Ensuring proper sensor calibration by buying a monitoring device that would be used for benchmarking.	Progress noted. Ensure the sensor calibration is proper using a benchmarking tool. The sensor nodes should be constructed on PCBs. The Python interface could be based on SQLite3 to ensure wireless connectivity and create a database. The hardware demonstration should be focused on during the progress presentation on 6th December.
6th December, 2025	Md. Reshad Al Muttaki, Sadia Afrin, Alvi Ibn Amzad Anil, Hasanat Fariha Noon	Completed constructing the Central Control & Filtration Unit structure using PVC board. Sensor Node PCB files are sent for printing. Progress presentation completed,	All Members: Ensuring proper sensor calibration by buying a monitoring device.	Progress noted. Ensure the sensor calibration is proper using a benchmarking tool. The primary interface of the IoT dashboard should be user-friendly and easy to

		demonstrating the workflow of the sensor nodes and their communication with the updated Python interface.		understand. The full system demonstration should be targeted at 23rd December.
23rd December, 2025	Md. Reshad Al Muttaki, Sadia Afrin, Alvi Ibn Amzad Anil, Hasanat Fariha Noon	Construction of the entire system is complete. The monitoring system is working as intended. But to make the purification of the Filtration Unit understandable, a chamber should be constructed so that the pollutant spike and purification are clearly visible.	All Members: Ensuring proper sensor calibration using the monitoring device. Construct a chamber for purifier validation.	Everything Done. The Python-based interface should be converted into an app. The validation chamber should be constructed.
3rd January, 2025	Md. Reshad Al Muttaki, Sadia Afrin, Alvi Ibn Amzad Anil, Hasanat Fariha Noon	The entire system is working fine. Industrial verification completed. The methodology section of the poster should be updated, along with a few other changes.	All Members: Update the poster as soon as possible	Satisfied with the system performance. Poster update should be done as soon as possible.
5th January, 2025	Md. Reshad Al Muttaki, Sadia Afrin, Alvi Ibn Amzad Anil, Hasanat Fariha Noon	Final project demonstration.	All Members: Focus on completing the project report.	Satisfied with the entire group throughout the entire FYDP journey.

All Source Codes of this Project

GitHub Link:

https://github.com/Reshad-Real/IoT-Based-Monitoring-and-Industrial-Air-Purification-System.git