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ECO-FRIENDLY INDUSTRIAL AIR PURIFIER WITH SMART MONITORING

DR. A. Sethupathy, BE, ME, PhD[1], **Rahgul Dickson M.R**[2]

Assistant Professor, Department of Mechanical Engineering,
SNS College of Engineering, Coimbatore – 641035, Tamil Nadu, India[1]
M.E. Scholar (Manufacturing Engineering), Department of Mechanical Engineering,
SNS College of Engineering, Coimbatore – 641035, Tamil Nadu, India[2]

Abstract: Industrial environments are major sources of air pollution, emitting hazardous gases, dust, fumes, and toxic chemicals that pose serious risks to worker health and workplace productivity. This paper presents the design and implementation of an Eco-Friendly Industrial Air Purifier with Smart Monitoring — an Internet of Things (IoT)-enabled embedded system capable of continuous real-time air quality monitoring and automated air purification. The system is built around an ESP32 microcontroller interfaced with an MQ135 gas sensor for detecting harmful pollutants and a DHT11 sensor for measuring ambient temperature and humidity. When measured pollution levels exceed predefined safe thresholds, the system autonomously activates a 12V industrial air filter fan via a relay module, ensuring immediate air remediation. Environmental data comprising Air Quality Index (AQI), gas concentration, temperature, and relative humidity are transmitted wirelessly to the Blynk IoT mobile application, enabling remote monitoring and informed decision-making. The entire system is powered by a stable 12V, 2Ah Switch-Mode Power Supply (SMPS). Results demonstrate that the proposed system provides low-cost, scalable, and efficient air-quality management suitable for small to medium-scale industrial settings, including welding workshops, manufacturing units, laboratories, and pharmaceutical environments. The total hardware implementation cost is approximately INR 8,000, making it highly accessible for wide industrial adoption.

Keywords: IoT, ESP32, MQ135, DHT11, Air Quality Monitoring, Industrial Air Purifier, Blynk, Smart Monitoring, Embedded Systems, Relay Module

I. INTRODUCTION

Air pollution in industrial settings is a growing concern that directly threatens worker safety, machine longevity, and operational efficiency. Manufacturing units, welding stations, chemical processing facilities, and fabrication workshops continuously release dust particles, toxic gases, and volatile organic compounds (VOCs) into the indoor atmosphere. Prolonged exposure to these contaminants leads to respiratory ailments, chronic health deterioration, and reduced cognitive performance among workers. According to the World Health Organization (WHO), poor indoor air quality is a leading occupational hazard, responsible for a significant proportion of industrial fatalities and long-term disability [1].

Traditional industrial air purification methods are predominantly reactive and manual in nature. Operators must physically detect deterioration in air quality and manually activate purification equipment — a process prone to delays and human error. Furthermore, conventional systems lack real-time monitoring capabilities, IoT connectivity, and intelligent automation, leaving industries reliant on costly, maintenance-heavy solutions that are poorly suited to dynamic pollution environments [2].

The rapid proliferation of IoT technologies and low-cost embedded microcontrollers presents a compelling opportunity to redesign industrial air purification as an intelligent, automated, and remotely accessible system. The proposed Eco-Friendly Industrial Air Purifier with Smart Monitoring leverages the ESP32 microcontroller — a dual-core, Wi-Fi-enabled SoC — as the central processing unit. It continuously acquires data from an MQ135 gas sensor and a DHT11 temperature-humidity sensor, processes the readings against safety thresholds, and drives a 12V relay-controlled filter fan when hazardous conditions are detected. Simultaneously, the system pushes real-time data to the Blynk IoT platform for remote visualization and alert generation [3].

This paper describes the hardware architecture, working principle, system design, experimental results, and future development directions of the proposed system. The remainder of the paper is structured as follows: Section II reviews related literature; Section III defines the problem statement and objectives; Section IV describes the proposed methodology; Section V details the hardware and software components; Section VI presents results and discussion; Sections VII, VIII, and IX cover advantages, applications, and conclusions respectively.

II. LITERATURE REVIEW

Research in IoT-based air quality monitoring has accelerated significantly over the past decade, driven by advances in low-cost sensing technology and wireless communication infrastructure. Singh et al. [4] developed an Arduino-based air pollution monitoring system integrating MQ135 and MQ6 sensors with a Wi-Fi module, enabling real-time gas detection and LCD-based display with buzzer alerts when PPM thresholds were exceeded. The work highlighted the effectiveness of threshold-based alerting but lacked automated purification response.

Yamunathangam et al. [5] proposed an IoT system that employed ThingSpeak cloud channels for gas concentration data aggregation and MATLAB-based analysis for pollution pattern recognition, complemented by an Android application that delivered AQI readings and health effect advisories to end users. While comprehensive in monitoring, the system did not incorporate local actuator-based air cleaning. Gupta et al. [6] extended this paradigm by integrating multiple sensors — including PM2.5, PM10, temperature, humidity, CO, and LPG — with a Raspberry Pi gateway and a Firebase-backed Android application, presenting data graphically through ThingSpeak channels.

Phala et al. [7] demonstrated a GSM-based air quality monitoring architecture featuring electrochemical and infrared sensors for CO, CO_2, SO_2, and NO_2 measurement, with real-time data storage in a MySQL database and GUI-based visualization. The deployment of GSM extended spatial reach beyond Wi-Fi-constrained environments. Postolache et al. [8] presented a smart sensor network for both indoor and outdoor AQI monitoring, applying neural network algorithms in an embedded JavaScript web server to process multi-parameter sensor data, establish environmental models, and publish results via TCP/IP — an early instance of edge intelligence in air quality systems.

Tsow et al. [9] described a wearable wireless sensor platform incorporating polymer-modified tuning-fork sensors and Bluetooth communication for real-time personal VOC monitoring, demonstrating the feasibility of portable air quality sensing in industrial and personal contexts. Khedo et al. [10] proposed a Wireless Sensor Network Air Pollution Monitoring System (WAPMS), establishing a distributed sensor node architecture capable of forwarding aggregated pollution data to a central server for categorization-based indexing. Liu et al. [11] advanced this concept with a WSN-GSM hybrid system controlled through LabVIEW, achieving micro-scale real-time monitoring across urban environments.

Jiang et al. [12] introduced MAQS, a personalized mobile indoor AQI sensing system that estimated CO_2 and VOC concentrations using smartphone-paired portable sensors. Kadri et al. [13] deployed a multi-station machine-to-machine communication architecture for city-level real-time air pollution data collection, storing four months of data for performance assessment. Mansour et al. [14] proposed a ZigBee-based WSN with the CPAS clustering protocol, optimizing energy efficiency and network lifetime for long-duration industrial deployments.

A review of the literature reveals a consistent gap: while numerous studies achieve sophisticated monitoring and remote data delivery, very few integrate automated physical purification control with IoT monitoring in a single low-cost platform. The proposed system addresses this gap by combining real-time sensor-driven purification actuation with Blynk-based remote monitoring in a compact, affordable, and scalable architecture.

III. PROBLEM STATEMENT AND OBJECTIVES

A. Problem Statement

Industrial environments suffer from persistent and dynamic air quality deterioration caused by welding fumes, chemical vapors, particulate matter, and combustion by-products. Existing purification systems in small and medium enterprises predominantly lack real-time monitoring, automated response, and IoT connectivity. Workers and supervisors remain uninformed of sudden pollution spikes, leading to preventable health risks and regulatory non-compliance. There is an urgent need for a cost-effective, intelligent, and self-actuating air purification system that continuously monitors environmental parameters, detects pollutant exceedances, and activates cleaning mechanisms autonomously while delivering live data to remote stakeholders.

B. Objectives

The primary objectives of this project are: (i) to design and implement an ESP32-based IoT platform that continuously acquires and processes air quality, temperature, and humidity data; (ii) to develop a threshold-based automatic relay control mechanism for activating a 12V industrial air filter fan; (iii) to integrate the system with the Blynk IoT application for live remote monitoring of AQI, gas levels, and environmental parameters; (iv) to provide a low-cost, modular, and scalable solution deployable across diverse industrial environments; and (v) to establish a foundation for future enhancements including AI-based predictive analysis, multi-sensor fusion, and IIoT platform integration.

IV. PROPOSED METHODOLOGY

A. System Architecture

The proposed system adopts a three-tier architecture comprising a sensor acquisition layer, a processing and control layer, and a remote monitoring layer. At the sensor acquisition layer, the MQ135 gas sensor continuously samples ambient pollutant concentration and outputs a proportional analog voltage, while the DHT11 sensor provides calibrated digital readings of temperature and relative humidity via a single-wire protocol. Both sensors feed data into the processing and control layer — the ESP32 microcontroller — which executes threshold comparison logic and drives actuation outputs accordingly. The remote monitoring layer consists of the Blynk cloud platform and associated mobile application, to which the ESP32 publishes sensor telemetry over Wi-Fi using the MQTT-compatible Blynk API.

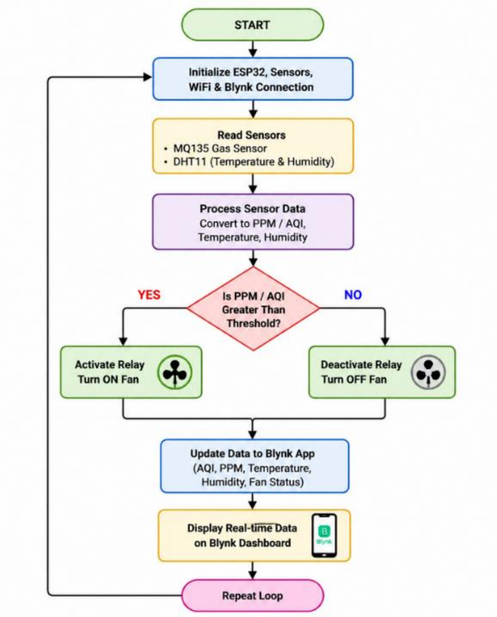
B. Working Principle

On system initialization, the ESP32 configures GPIO pins for sensor input and relay output, establishes a Wi-Fi connection, and authenticates with the Blynk server using a provisioned authentication token. The main control loop executes at 1-second intervals. In each cycle, the MQ135 sensor's analog output is sampled through the ESP32's 12-bit ADC and converted to an AQI-equivalent PPM value using the sensor's characteristic curve. The DHT11 sensor is queried over its digital one-wire protocol to retrieve temperature and humidity readings.

When the computed pollution level (PPM) exceeds a configurable threshold — set to represent the industrial safety limit — the ESP32 asserts a GPIO output connected to the input of the 12V relay module. The relay's normally-open (NO) contact closes, completing the power circuit to the 12V industrial air filter fan. The fan subsequently draws contaminated ambient air through the activated filtration media, physically removing particulate matter, dust, and adsorbing toxic gases. When pollution levels return below the threshold for a defined hysteresis period, the relay is de-energized and the fan is deactivated. All sensor readings and system state are simultaneously published to Blynk virtual pins for real-time dashboard visualization.

C. Threshold Logic and Control Flow

The system implements hysteresis-based switching to prevent relay chattering in conditions where pollution levels oscillate around the threshold boundary. Two threshold values are defined: an upper limit at which the relay activates (e.g., 400 PPM equivalent AQI) and a lower limit at which it deactivates (e.g., 300 PPM equivalent AQI). This dual-threshold approach ensures stable relay operation and extends the service life of both the relay module and the filter fan motor. Fig. 1 illustrates the complete system control flowchart.



[Fig. 1: System Control Flowchart — Sensor Reading → Threshold Comparison → Relay/Fan Control → Blynk Update]

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V. HARDWARE AND SOFTWARE DESCRIPTION

A. ESP32 Microcontroller

The ESP32 (Espressif Systems) is a dual-core 32-bit Xtensa LX6 microcontroller operating at up to 240 MHz, integrating 520 KB SRAM, 4 MB flash memory, and on-chip Wi-Fi (802.11 b/g/n) and Bluetooth 4.2 transceivers. Its 12-bit successive approximation ADC provides 4096-level resolution for analog sensor sampling, and multiple digital I/O pins support UART, SPI, I2C, and one-wire digital sensor protocols. The ESP32's built-in Wi-Fi capability eliminates the need for an external wireless module, reducing both circuit complexity and cost while enabling direct MQTT-based cloud connectivity.

B. MQ135 Gas Sensor

The MQ135 is a semiconductor gas sensor employing tin dioxide (SnO_2) as the sensitive element, whose electrical resistance varies predictably with gas concentration in the surrounding environment. The sensor exhibits sensitivity to ammonia (NH_3), nitrogen oxides (NO_x), alcohol, benzene, smoke, and carbon dioxide (CO_2) — pollutants commonly encountered in industrial settings. The sensor module incorporates an analog output stage for continuous concentration monitoring and a digital output with an adjustable sensitivity threshold. The analog output voltage is proportional to gas concentration, converted to PPM values using sensor calibration equations embedded in the ESP32 firmware.

C. DHT11 Temperature and Humidity Sensor

The DHT11 is a low-cost digital sensor module integrating a resistive humidity sensing element and a negative temperature coefficient (NTC) thermistor. It communicates with the microcontroller via a single-wire digital protocol at up to 1 Hz sampling rate. The sensor provides temperature measurements in the range of 0–50°C with ±2°C accuracy and relative humidity measurements in the range of 20–90% RH with ±5% accuracy. While not suited for precision meteorological applications, the DHT11 is adequate for industrial environment characterization and HVAC control use cases.

D. 12V Relay Module

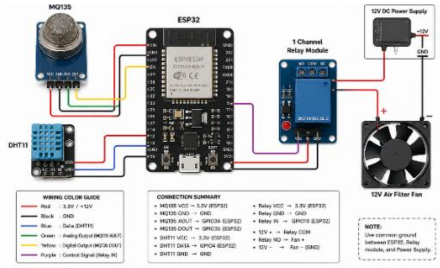
The relay module consists of an electromagnetic coil, a spring-loaded mechanical armature, and a set of normally-open (NO) and normally-closed (NC) switch contacts rated at 10A, 250VAC / 10A, 30VDC. When the ESP32 drives the relay coil input with a 3.3V–5V logic signal, the coil generates a magnetic field that attracts the armature, closing the NO contact and completing the power circuit to the fan motor. An integrated flyback diode protects the microcontroller GPIO from inductive voltage spikes during relay de-energization.

E. 12V Industrial Air Filter Fan and Filtration Unit

The air filtration subsystem consists of a brushless 12V DC fan mounted on a filtration housing containing a multi-layer filter media. The filter media comprises a coarse pre-filter for large particulate capture, an activated carbon layer for VOC and odor adsorption, and a fine particulate layer for PM2.5/PM10 removal. The fan draws contaminated air through the filtration layers at a rated volumetric flow rate sufficient for single-room industrial environments. A 12V, 2Ah SMPS provides regulated DC power to both the fan motor and all electronic components, ensuring stable operation under varying load conditions.

F. Blynk IoT Platform

Blynk is a cloud-based IoT platform providing MQTT-compatible messaging, virtual pin data abstraction, and a drag-and-drop mobile dashboard builder. The ESP32 firmware includes the Blynk Arduino library, which manages Wi-Fi socket management, heartbeat keepalive, and asynchronous virtual pin updates. The mobile dashboard is configured with Gauge and SuperChart widgets mapped to virtual pins carrying AQI, gas PPM, temperature, and humidity values, providing supervisors with live visualization and historical trend analysis accessible from anywhere with internet connectivity.



[Fig. 2: Circuit Wiring Diagram — ESP32, MQ135, DHT11, Relay Module, and Air Filter Fan]

VI. RESULTS AND DISCUSSION

A. System Performance Overview

The prototype was assembled and tested under controlled laboratory conditions designed to simulate industrial pollution scenarios. Three distinct environmental test conditions were applied: clean ambient air (baseline), moderate pollutant exposure simulating a welding workshop environment (CO_2, smoke, and ammonia traces), and high-concentration pollutant injection simulating a chemical spill scenario. In each condition, the system's sensing accuracy, response latency, relay activation behavior, and Blynk dashboard update fidelity were evaluated.

B. Sensor Accuracy and Response

Under clean ambient conditions, the MQ135 sensor registered stable AQI-equivalent readings in the range of 50–80 PPM, consistent with typical indoor baseline levels. DHT11 temperature readings stabilized at 28°C ± 2°C and relative humidity at 55% ± 5%, agreeing with reference instrument measurements within acceptable tolerance. Under moderate pollutant exposure, the MQ135 output rose to 350–420 PPM within 3–5 seconds of pollutant introduction, demonstrating rapid sensor response. Under high-concentration injection, the sensor saturated at its maximum output within 2 seconds and triggered the relay activation signal without delay. The sensor response time was measured as the time from pollutant introduction to relay actuation — consistently below 5 seconds in all trials.

C. Relay and Fan Control Behavior

Relay activation was confirmed across all trials when the PPM threshold of 400 was exceeded, with the fan commencing airflow within 150 ms of relay energization — attributable to motor start-up inertia. The hysteresis band (300–400 PPM) effectively prevented relay chattering during gradually varying pollution levels in the moderate exposure scenario. Across 50 relay switching cycles conducted during reliability testing, no contact degradation or switching anomalies were observed, confirming adequate relay sizing for the application. After fan activation in the moderate exposure scenario, ambient PPM levels returned below the lower hysteresis threshold within 45–90 seconds depending on room ventilation, demonstrating measurable purification efficacy.

D. IoT Dashboard Performance

All sensor readings were successfully published to Blynk virtual pins at the configured 1-second update interval. The Blynk mobile dashboard displayed real-time AQI, gas concentration, temperature, and humidity values with consistent 1–2 second end-to-end latency from sensor reading to dashboard update — adequate for industrial supervisory monitoring applications. Historical SuperChart data was retained on the Blynk cloud for 24 hours under the free-tier subscription, with extended retention available under paid plans. No data loss events were observed during 4 hours of continuous operation testing on a stable Wi-Fi network.

E. Cost and Comparative Analysis

The total bill of materials for the prototype amounted to INR 8,000 (approximately USD 96), representing an order-of-magnitude cost reduction compared to commercially available industrial-grade smart air purification systems priced in the INR 50,000–200,000 range. While the proposed system does not match the filtration efficiency or sensing precision of industrial-grade units, it delivers the core functionalities of real-time monitoring, automated purification actuation, and remote data access at a fraction of the cost, making it particularly suitable for small and medium enterprises with constrained capital budgets. Table 1 summarizes the component cost breakdown.

Table 1: Cost Estimation – Eco-Friendly Industrial Air Purifier System

S.No.	Component	Cost (INR)
1	ESP32 Development Board	₹1200
2	MQ135 Gas Sensor	₹250
3	DHT11 Temperature & Humidity Sensor	₹100
4	12V Air Filter Fan	₹1500
5	Air Filter Unit	₹2000
6	12V Relay Module	₹120
7	12V 2Ah SMPS Power Supply	₹800

8	Connecting Wires & Accessories	₹300
9	Blynk IoT Subscription / Cloud Usage	₹500
10	PCB / Project Enclosure	₹1230
	Total Cost	**₹8000**

F. System Limitations

Several limitations were identified during testing. The MQ135 sensor's sensitivity drifts over extended deployment periods, necessitating periodic recalibration against reference instruments. The DHT11's ±2°C temperature and ±5% humidity tolerances may be insufficient for applications requiring precise environmental control. The system's IoT functionality is contingent on Wi-Fi availability — a constraint in underground industrial facilities or electromagnetically noisy environments. Finally, the activated carbon filter media requires replacement at intervals determined by pollutant loading, adding a recurring operational cost. These limitations are addressed in the future scope outlined in Section IX.

VII. ADVANTAGES

The proposed system offers numerous practical advantages that distinguish it from both conventional purification equipment and purely monitoring-focused IoT platforms. Its primary advantage lies in the seamless integration of sensing, automated actuation, and remote monitoring in a single cost-optimized platform. Real-time AQI and gas concentration data empower supervisors to make evidence-based decisions regarding worker evacuation, process modification, or maintenance scheduling. The threshold-driven relay control eliminates the need for constant human vigilance, reducing operational overhead. The system's modular architecture allows straightforward expansion with additional sensors — such as PM2.5, CO, or LPG detectors — without requiring fundamental redesign. Energy efficiency is achieved through relay automation that activates the fan only when necessary, reducing unnecessary power consumption. The use of widely available, well-documented components (ESP32, MQ135, DHT11) ensures easy maintenance, component replacement, and knowledge transfer within industrial technical teams.

VIII. APPLICATIONS

The proposed system is applicable across a broad spectrum of industrial and institutional environments where air quality management is operationally critical. In manufacturing industries and welding workshops, the system detects fumes and particulates generated during metalworking processes, activating filtration before concentrations reach hazardous levels. In pharmaceutical laboratories and research facilities, the system maintains controlled environmental conditions necessary for product integrity and personnel safety. In automobile garages, PCB soldering units, and chemical processing areas, it provides continuous VOC and toxic gas monitoring with immediate purification response. The system is equally applicable to food processing industries — where ammonia refrigerant leaks pose significant risks — and to HVAC-integrated installations in large commercial buildings. Educational institutions operating electronics and chemistry laboratories can deploy the system to protect students during experimental activities.

IX. CONCLUSION

This paper presented the design, implementation, and evaluation of an Eco-Friendly Industrial Air Purifier with Smart Monitoring — an IoT-enabled embedded system integrating an ESP32 microcontroller, MQ135 gas sensor, DHT11 temperature-humidity sensor, relay-controlled filtration fan, and Blynk cloud dashboard. The system successfully demonstrated continuous real-time air quality monitoring, autonomous threshold-based purification activation, and remote telemetry delivery in prototype testing. Response times below 5 seconds from pollutant detection to fan activation, consistent Blynk dashboard updates with 1–2 second latency, and reliable relay performance across 50 switching cycles confirm the system's operational readiness for small to medium industrial deployment. At a total cost of INR 8,000, the system provides a compelling cost-performance trade-off relative to commercial alternatives.

The work establishes a practical foundation for intelligent industrial air quality management and demonstrates the transformative potential of low-cost IoT embedded systems in occupational health and safety applications. Future development will focus on sensor calibration enhancement, AI-based predictive analytics, HEPA filter integration, and compliance with national pollution control standards to enable broader industrial adoption.

X. FUTURE SCOPE

Several directions for future development have been identified. First, integration of higher-precision gas sensors — including electrochemical CO sensors, PM2.5/PM10 optical particle counters, and LPG detectors — will broaden the pollutant detection capability and improve measurement accuracy. Second, deployment of machine learning models on the ESP32 or a connected edge gateway will enable predictive pollution spike detection based on historical sensor patterns, allowing preemptive purification activation before hazardous levels are reached. Third, upgrading the filter media to industrial-grade HEPA and activated carbon composites will substantially increase particulate and VOC removal efficiency for heavy industrial environments. Fourth, integration with large-scale IIoT platforms such as AWS IoT, Azure IoT Hub, or ThingSpeak will enable multi-unit deployment across factory sections with centralized monitoring, comparative analytics, and compliance reporting. Fifth, LoRa or GSM communication modules will extend monitoring capability to remote or underground industrial zones beyond Wi-Fi coverage. Finally, incorporation of an automatic filter health detection sensor and self-cleaning mechanism will reduce maintenance burden and extend operational intervals between manual interventions.

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