Smart Air Pollution Monitoring and Filtration for Urban Areas

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***Abstract*—The rapid growth of urbanization and industrialization has significantly increased air pollution levels, creating an urgent need for an efficient and reliable monitoring and active remediation system to ensure a healthy urban environment. The air quality in dense urban areas is highly sensitive to variations in pollutant concentrations, such as particulate matter (PM2.5,PM10), carbon monoxide (CO), nitrogen oxides (NOx), and other toxic gases. Improper monitoring of these parameters can lead to severe public health crises, environmental degradation, and long-term climate impacts. This project presents the design and implementation of a Smart Air Pollution Monitoring and Filtration System for urban areas integrated with essential components such as a multi-gas sensor array, particulate matter sensor, active filtration unit, Internet of Things (IoT) communication module, and a standalone solar power management system for accurate real-time monitoring and proactive air remediation. The proposed system uses a combination of high-efficiency particulate air (HEPA) and activated carbon filters as the primary air scrubbing mechanism due to their proven ability to remove a broad spectrum of airborne pollutants. A dedicated microcontroller-based control unit is employed to continuously monitor local air quality parameters and maintain hazardous pollutant concentrations below critical limits. The gas sensors measure specific pollutant levels to prevent dangerous human exposure and detect sudden pollution spikes. The filtration unit is activated automatically based on real-time data to scrub the surrounding air when thresholds are exceeded. Additionally, the IoT module transmits the collected data to a cloud platform for remote logging, historical analysis, and public alerting. The developed prototype is energy-efficient, scalable, and suitable for high-traffic intersections, bus stops, and other urban hotspots. By integrating comprehensive environmental sensing with automated, localized filtration and real-time data transparency, the system significantly improves urban air quality monitoring resolution and direct respiratory protection. This project contributes to enhancing urban environmental resilience while promoting sustainable and health-conscious smart city development solutions.**

***Index Terms*—Urban Air Pollution, Internet of Things (IoT), Distributed Sensor Network, HEPA/Activated Carbon Filtration, Proactive Air Remediation, Real-time Monitoring, Public Health, Smart City.**

I. INTRODUCTION

The rapid growth of urbanization and vehicular traffic has severely degraded urban air quality, increasing the demand for efficient, reliable, and intelligent environmental monitoring systems. Since clean air is a fundamental requirement for public health, ensuring continuous environmental tracking and active remediation of localized pollution is essential. A Smart Air Pollution Monitoring and Filtration System is designed to enhance urban air quality, monitor environmental health, and provide automated physical remediation of hazardous pollutants in dense traffic zones. In this system, a solar-integrated battery bank serves as the primary energy source due to its sustainable nature, ensuring autonomous, continuous operation without reliance on the municipal grid. The local microclimate is managed by a continuous sensing loop, which monitors pollutant concentrations—such as Carbon Monoxide (CO), Carbon Dioxide (), Ammonia (), and particulate matter—to detect heavy exhaust, smog formation, and poor air quality conditions. The microcontroller acts as the central processing unit of the system. It receives real-time analog inputs from the multi-gas sensor array alongside meteorological data like temperature and humidity. Based on these inputs, the controller evaluates the local Air Quality Index (AQI) and regulates power flow to an active filtration unit, which consists of high-RPM DC exhaust fans and HEPA/Activated Carbon filters.The local digital display and IoT-connected cloud dashboard provide real-time information about current air quality status, ensuring public awareness and rapid data access for municipal authorities. The active filtration feature ensures that in the case of extreme pollution spikes, such as rush-hour traffic or localized smog events, the system can automatically initiate air scrubbing, thereby improving pedestrian safety.This intelligent monitoring and active control approach enhances respiratory health, improves street-level air quality, and reduces the delayed response typical of traditional, passive government monitoring stations. Overall, the Smart Air Pollution Monitoring and Filtration System integrates IoT telemetry, high-precision sensing technologies, and electromechanical filtration to deliver a proactive, efficient, and sustainable environmental solution for modern smart cities.

II. EXISTING SYSTEM

The conventional urban air quality management system operates using large, centralized Continuous Ambient Air Quality Monitoring (CAAQM) stations that supply environmental data to a main server, which in turn updates public health portals. The system includes industrial gas analyzers, particulate matter sensors, temperature and humidity sensors, a central data logging controller, and output components such as public web dashboards, mobile app alerts, and large electronic billboards.
The monitoring display shows the Air Quality Index (AQI) and specific pollutant levels to the public. When the pollution level becomes critically high, the system simply issues health advisories or triggers broad municipal warnings (like restricting traffic). There is no active filtration mechanism or immediate, localized air remediation capability in most conventional urban air monitoring designs.

III. PROPOSED SYSTEM

The proposed Smart Air Pollution Monitoring and Filtration System introduces an intelligent, decentralized IoT architecture to ensure continuous environmental tracking and proactive air remediation. Under normal operating conditions, the solar-integrated power supply drives the central microcontroller, which operates the multi-gas sensor array. The system continuously monitors key parameters such as overall Air Quality Index (AQI), Carbon Monoxide (CO), particulate matter (smoke), temperature, and humidity to ensure accurate environmental assessment. When the local pollutant concentration crosses a predefined hazardous threshold, or a sudden spike in toxic exhaust is detected, the microcontroller automatically activates an intelligent relay mechanism.

This mechanism seamlessly engages the active filtration unit, powering high-RPM DC exhaust fans equipped with HEPA and activated carbon filters, without requiring any manual human intervention. Upon activation of the filtration system, the node enters an active remediation mode in which it physically scrubs the immediate surrounding air to reduce toxicity, while maintaining essential reporting functions such as real-time IoT cloud data transmission and local public display warnings. The proposed system enhances public health safety by preventing prolonged exposure to toxic street-level exhaust and actively mitigating localized pollution hotspots.

By leveraging machine learning and real-time cloud analytics, this system revolutionizes urban environmental management, optimizing filtration performance, extending physical filter lifespan, and predicting future smog events. Its predictive and proactive approach enhances pedestrian safety and supports the broader adoption of sustainable smart city infrastructure by addressing critical localized air quality concerns, allowing municipalities to combat pollution precisely where it occurs.

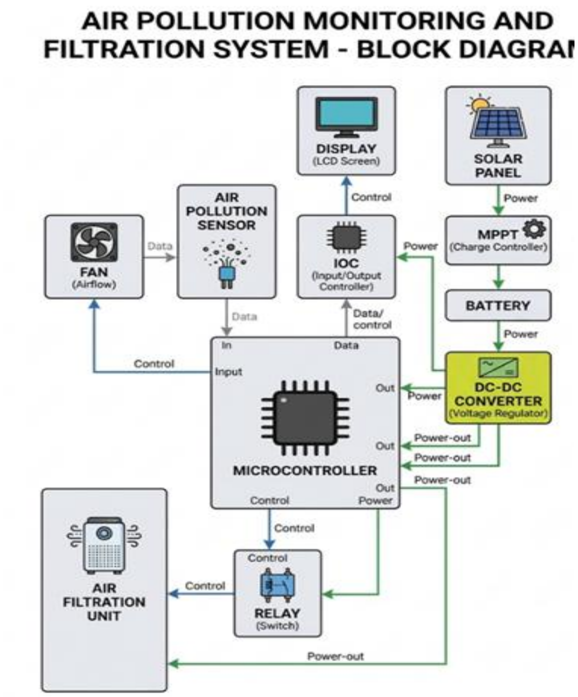

Fig.1 Block diagram of Proposed system

IV. METHODOLOGY

1.System Design and Architecture

The overall system architecture is designed based on a central microcontroller (such as an ESP32 or NodeMCU) that manages data acquisition from the environmental sensors and controls the active filtration unit. A solar power management system is integrated to ensure continuous, off-grid operation. The system's block diagram includes input sensors (gas, temperature, and humidity), automated processing logic, and output devices (digital relay, DC exhaust fan, IoT cloud dashboard, and local LCD display).

2.Power Management and Solar Integration

A solar-charged battery bank (Lithium-Ion or LiFePO4) is used as the primary energy source to ensure 24/7 autonomous operation without relying on the municipal grid. The integrated charge controller and power management system continuously monitor:

- Solar charging input voltage
- Battery voltage and discharging current
- State of Charge (SOC) This setup protects the battery from overcharging, deep discharge, and ensures the system remains online during city power outages.

3.Sensor Implementation

A multi-sensor array is integrated to ensure accurate environmental monitoring:

- Gas Sensors (MQ135, MQ7, MQ2): Continuously monitor levels of harmful gases including CO, CO2, and NH3 particulate smoke.
- DHT11 Sensor: Measures ambient temperature and relative humidity, which are critical variables for smog formation analysis. Sensor data is continuously fed to the microcontroller as analog signals for real-time digital conversion and decision-making.

4. Controller Programming and Control Strategy

The microcontroller acts as the central processing unit. It continuously executes the following logic:

- Receives and filters raw analog data from the sensor array.
- Calculates accurate Parts Per Million (PPM) and Air Quality Index (AQI) values.
- Evaluates live data against pre-programmed hazardous pollution safety thresholds.
- Regulates the digital relay to control the high-draw filtration fan.
- Transmits live telemetry data to the IoT cloud platform. A specific control algorithm is implemented to ensure the physical air filters are only activated when necessary, optimizing energy efficiency.

5. Active Filtration Operation

The active remediation unit (a 12V high-RPM DC exhaust fan paired with HEPA and Activated Carbon filters) is controlled automatically based on real-time AQI inputs. When the microcontroller detects a severe pollution spike (e.g., heavy traffic exhaust), it triggers the relay switch. This activates the fan, actively pulling contaminated street-level air through the filters to physically scrub toxic particulate matter and volatile organic compounds (VOCs) from the immediate environment.

6. Autonomous Failsafe Mechanism

The system is designed to maintain continuous monitoring and stable output during:

- Localized grid power failures
- Fluctuating sunlight and weather conditions
- Extended nighttime operation If the battery

management system detects a critically low State of Charge (SOC), the microcontroller automatically suspends the heavy-draw filtration fan to conserve energy, prioritizing continuous sensor data logging and emergency cloud transmission until the battery is recharged.

7. Display and Cloud Interface

To ensure data transparency, the system features a dual-interface approach that provides real-time information:

Local LCD Display: Shows live AQI levels, specific gas warnings, and system status to nearby pedestrians.

IoT Cloud Dashboard (e.g., ThingSpeak): Logs historical data and visualizes real-time pollution trends for municipal authorities. This dual setup vastly improves public environmental awareness while enabling remote, city-wide operational management.

8. System Process

The Smart Air Pollution Monitoring and Filtration System operates by coordinating the solar battery pack, central microcontroller, environmental sensors, and the active filtration exhaust fan to ensure autonomous, safe, and efficient air remediation. The overall system process is explained below:

Step 1: Power Initialization

When the system is deployed, the solar-charged battery pack supplies power to the network.

- The internal voltage regulators step down the battery voltage (12V) to the required logic levels (5V/3.3V) for the microcontroller, relay, and gas sensors.
- The microcontroller boots up, connects to the local Wi-Fi/GSM network, and initiates a brief sensor pre-heating phase to ensure accurate gas readings.

Step 2: Continuous Environmental Sensing (Data Acquisition)

The multi-sensor array continuously monitors the surrounding street-level environment for:

- Carbon Monoxide (CO) & Carbon Dioxide (CO_2)
- Ammonia (NH_3) & Volatile Organic Compounds (VOCs)
- Particulate Smoke
- Ambient Temperature & Relative Humidity
- The sensors feed raw analog voltage data directly to the microcontroller.

Step 3: Data Processing & Display

- The microcontroller executes calibration algorithms to convert the raw sensor voltages into precise Parts Per Million (PPM) and an overall Air Quality Index (AQI).
- The controller immediately updates the local LCD/Smart Display to show the live air quality level and safety warnings to nearby pedestrians.
- Data is simultaneously transmitted to the IoT cloud dashboard for remote municipal monitoring.

Step 4: Automated Filtration Control (Actuation)

- The microcontroller constantly compares the live AQI against pre-programmed hazardous safety thresholds.
- If the air quality drops below safe limits (e.g., during a traffic jam), the controller sends a signal to the digital relay.
- The relay switches ON, sending 12V power to the high-RPM DC exhaust fan, actively pulling the contaminated air through the HEPA and Activated Carbon filters.

Step 5: Power & System Health Monitoring (BMS Operation)

The integrated Battery Management System (BMS) and MPPT solar controller continuously monitor:

- Solar charging input
- Battery voltage and discharging current
- If any abnormal condition is detected (e.g., overheating fan motor or battery overvoltage), the controller temporarily halts the fan to protect the hardware.

Step 6: Auxiliary Alerts & Telemetry

The microcontroller manages emergency communications:

- Triggers localized visual warnings (LEDs or display alerts).
- Dispatches emergency SMS alerts via the GSM module to traffic authorities if pollution levels reach critical toxicity.

Step 7: Autonomous Backup & Failsafe Mode

- During prolonged periods of heavy cloud cover or sudden load fluctuations, the solar battery backup system ensures continuous operation.

- If the main battery voltage drops below a critical threshold (low State of Charge), the microcontroller automatically suspends the heavy power draw of the filtration fan. It enters a low-power mode, prioritizing continuous sensor monitoring and data logging to extend battery life until the sun recharges the system.

2.Feasibility Study

1. Technical Feasibility

- Uses readily available components such as ESP microcontrollers, MQ gas sensors, DC exhaust fans, and HEPA/Carbon filters.
- Microcontroller-based IoT control system is easy to program, calibrate, and integrate with cloud platforms.
- Proven sensor and physical filtration technologies ensure reliable and safe operation.
- System design is modular, autonomous, and highly scalable for dense urban deployment.

2.Economic Feasibility

- Components are cost-effective and widely available in the market compared to massive industrial monitoring stations.
- Low maintenance cost due to an automated design with very few moving parts.
- Energy-efficient, solar-powered architecture drastically reduces long-term operational costs.
- Suitable for both student prototype projects and expansive commercial smart city applications.

3.Operational Feasibility

- Fully automated operation that triggers the active filtration system based on real-time air quality thresholds.
- Automatic solar battery monitoring and overcharge protection to ensure continuous 24/7 uptime.

User-friendly local LCD displays and live cloud dashboards for easy public and administrative monitoring.

Minimal human intervention required, limited primarily to routine physical filter replacements.

4. Environmental Feasibility

- Actively reduces localized particulate matter (PM2.5), carbon monoxide, and toxic gases from urban traffic exhaust.
- Promotes eco-friendly sustainability by utilizing a solar energy harvesting system for 100% renewable operation.
- Engineered for low noise pollution by utilizing high-efficiency brushless DC exhaust fans.

System Design and Architecture

The overall system architecture is designed based on a central microcontroller (such as an ESP32 or NodeMCU) that manages continuous data acquisition from the environmental sensors and controls the power flow to the active filtration unit. A Solar Power and Battery Management System (BMS) is integrated to ensure autonomous off-grid operation, battery protection, and energy monitoring. The system's block diagram includes input sensors (multi-gas, temperature, and humidity), automated processing logic, and output devices (digital relay, DC exhaust fan with HEPA/Carbon filters, IoT cloud dashboard, and local LCD display).

Arduino UNO

Arduino/Genuine Uno is a microcontroller board based on the ATmega328P. It has 14 digital input/output pins (of which 6 can be used as PWM outputs), 6 analogue inputs, a 16 MHz quartz crystal, a USB connection, a power jack, an ICSP header and a reset button. It contains everything needed to support the microcontroller; simply connect it to a computer with a USB cable or power it with AC-to DC adapter or battery to get started. You can tinker with your UNO without worrying too much about doing something wrong, wors case scenario you can replace the chip for a few dollars and start over again.

Fig.3 Arduino UNO interface LCD display

They are used in a wide range of applications including: computer monitors, television, instrument panels, aircraft cockpit displays, signage, etc. They are common in consumer devices such as video players, gaming devices, clocks, watches, calculators, and telephones. LCDs have displaced cathode ray tube (CRT) displays in most applications.

Fig.5 Temperature Sensor MQ7 Gas Sensor

Technical Detail: Operates using a unique high/low-temperature cycling method. It heats up to 5V (high phase) to clean the sensor, then drops to 1.5V (low phase) to accurately detect Carbon Monoxide (CO).
Target Gases: Specifically calibrated for CO, which is heavily present in urban traffic exhaust.

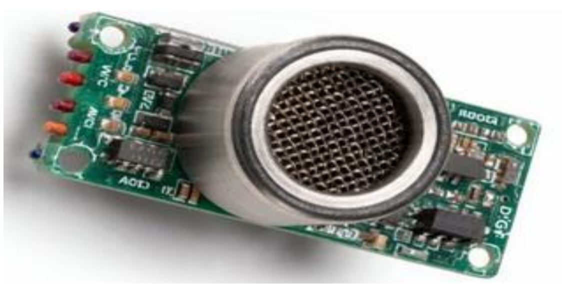

Fig 1.5 MQ7 Gas Sensor

DHT11 Temperature and Humidity Sensor
Technical Detail: Contains a resistive humidity-sensing component and an NTC thermistor for temperature measurement. It outputs a

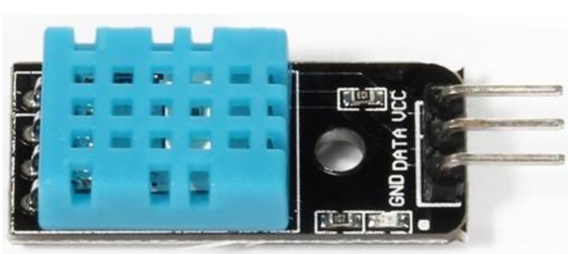

Fig 1.6 DHT11 Sensor

pre-calibrated digital signal directly to the microcontroller.
Why it is used: Smog formation is heavily dependent on high humidity and specific temperatures. This data is fed into the predictive machine learning models.

Thing speak
Thing Speak is an opensource API "Internet of Things" application and API to store and retrieve data from things using HTTP over the Internet or via a Local Area Network. With location tracking applications, and a social network of things with status updates in addition to storing and retrieving numeric and alphanumeric data, the Thing Speak API allows for numeric data processing such as time scaling, averaging, median, summing, and rounding. Each Thing Speak Channel supports data entries of up to 8 data fields, latitude, longitude, elevation and status. The channel fields support JSON, XML, and CSV formats for integration into applications. The primary element of Thing Speak activity is the channel, which contains data fields, location fields, and a status field.

V. DESIGN VALIDATION/PROTOTYPE TESTING

- Power System Validation: Verification of solar panel charging and battery discharging operation under various sunlight conditions.
- BMS Testing: Validation of the MPPT Charge Controller and Battery Management System (BMS) functionality.
- Voltage Stability: Measurement of output voltage and current stability feeding the ESP32 microcontroller and the 12V exhaust fan.
- Load Testing: Stress testing the active filtration system (running the fan continuously) to measure battery drain.
- Battery Accuracy: State of Charge (SoC) monitoring accuracy test to ensure the system reads battery levels correctly.
- Thermal Testing: Thermal performance testing of the 12V DC fan motor and relay module during continuous, high-speed operation.
- Safety Protection: Overcharge, over-discharge, short-circuit, and overcurrent protection testing for the solar battery pack

VI. HARDWARE SPECIFICATION

A Solar Battery Bank (Lithium-Ion / LiFePO4)
- 12V DC output
- 10Ah–20Ah capacity
- Rechargeable via integrated Solar Panel
- Provides the main power supply for the filtration fans and electronics

B Solar Charge Controller / Power Management
- Overvoltage and overcharge protection
- Undervoltage (deep discharge) protection
- Overcurrent and short-circuit protection
- Regulates raw solar input to safely charge the battery

C. Active Filtration Unit (DC Exhaust Fan)
- 10W–30W power rating
- 12V operating voltage
- High RPM and high static pressure for effective HEPA suction
- Low maintenance brushless DC motor

D. Digital Relay Module (Actuator)
- 3.3V / 5V logic input from the microcontroller
- Safely switches the 12V high-current load (exhaust fan)
- Automated ON/OFF switching based on real-time pollution thresholds

G. Environmental Sensor Array (MQ Series & DHT11)
- Monitors levels of, CO, and particulate smoke
- Measures ambient temperature and humidity
- Sends continuous analog data to the MCU for AQI calculation

H. IoT Communication Module Integrated Wi-Fi or external GSM (SIM800L) module
- Transmits real-time environmental data to the cloud dashboard (ThingSpeak)

I. Display Unit Ø 16x2 I2C LCD or Smart OLED display
- Shows real-time Air Quality Index (AQI), pollutant PPM, and battery level
- Displays localized emergency warnings for pedestrians

VII. RESULT AND DISCUSSION

A Stable Power Distribution

The voltage regulator and solar charge controller maintained a constant and stable output supply to the microcontroller, sensor array, and auxiliary components, ensuring uninterrupted 24/7 operation.

B Efficient Autonomous Energy Monitoring

The Battery Management System (BMS) accurately monitored the solar battery bank's voltage, temperature, and current. Overcharge and deep-discharge protections were successfully triggered during extreme weather and heavy-load test conditions, protecting the energy storage.

C Automated Filtration Performance

The environmental sensor array successfully detected abnormal localized pollution spikes (such as high CO and smoke levels). The microcontroller responded instantly by triggering the digital relay, activating the exhaust fan and filters to actively neutralize the hazardous air.

D Efficient Air Scrubbing Operation

The 12V DC exhaust fan demonstrated smooth, high-RPM operation upon activation. Suction through the HEPA and Activated Carbon filters was stable and consistent, effectively pulling in contaminated air without mechanical stalling or sudden fluctuations.

E Effective Off-Grid Performance

The solar energy system provided reliable backup power during prolonged active filtration cycles and overcast conditions, maintaining continuous sensor monitoring and data transmission without sudden power drops.

F Real-Time Display and Telemetry Monitoring

The local LCD display accurately reflected live Air Quality Index (AQI) levels and system status, allowing pedestrians to monitor the air health easily. Simultaneously, the IoT module pushed this data to the cloud dashboard without latency.

The experimental results demonstrate that the proposed smart monitoring and filtration system significantly enhances both the tracking and remediation of urban air pollution. The integration of

high-precision gas sensors with an automated, physical filtration response significantly reduces localized health risks, such as exposure to dense traffic exhaust and street-level smog.
The microcontroller plays a critical role in coordinating continuous inputs from the environmental sensors to maintain a safe local atmosphere. The use of a high-efficiency DC exhaust fan combined with HEPA and Carbon filters improves the physical purification process due to its targeted, on-demand activation and high suction capability.

The system shows excellent energy management and efficient power utilization through its standalone solar architecture. However, the purification performance may vary depending on ambient wind speed, overall environmental temperature, and how quickly the physical filters become saturated. Future improvements may include advanced Machine

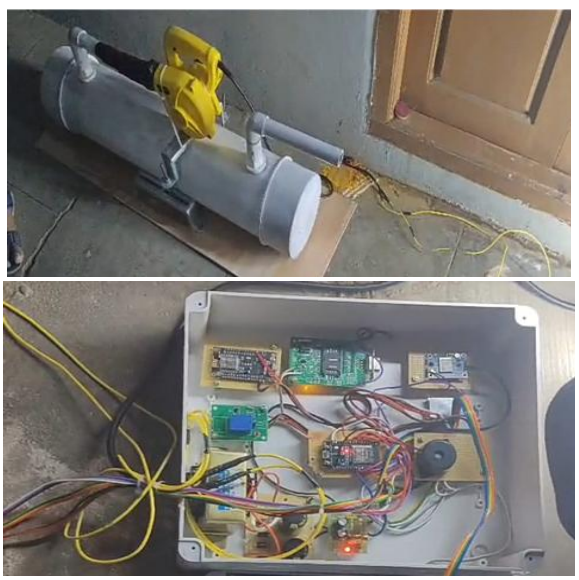

Fig 6 Smart Air Pollution Monitoring System

Learning algorithms for predictive smog modelling, expansion into a city-wide mesh network, and direct integration with municipal traffic control systems to reroute vehicles during high-pollution events.

VIII. CONCLUSION

The Smart Air Pollution Monitoring and Filtration System is a reliable and efficient solution designed to enhance the air quality, public health, and environmental safety of dense urban areas. The developed system integrates key components such as the solar battery bank, power management system, voltage regulators, microcontroller, multi-gas sensor array, active filtration exhaust fan, and monitoring displays to ensure continuous and autonomous operation.

The environmental sensor network continuously monitors specific gas concentrations, particulate matter, temperature, and humidity parameters to accurately detect hazardous pollution spikes and smog conditions. The microcontroller effectively manages inputs from these sensors to evaluate the real-time Air Quality Index (AQI) and automatically regulate the active filtration unit to physically scrub the air when thresholds are crossed. The solar charge controller and voltage regulators provide a stable, off-grid power supply to sensitive electronic components and the heavy-draw fans, improving overall system reliability. Furthermore, the local LCD and IoT cloud dashboard help the public and municipal authorities monitor live pollution levels, ensuring timely environmental warnings and preventing dangerous respiratory exposure.

Overall, the proposed system improves localized urban air quality, enhances proactive health safety, and provides real-time remote monitoring for better environmental control. It is cost-effective, modularly scalable, and highly suitable for modern smart city infrastructure. The implementation of this automated monitoring and filtration system contributes to sustainable urban living by actively mitigating harmful traffic exhaust and promoting the use of renewable solar energy.

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