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Smart Solar-Powered Air Purifier System for Roadside Pollution Control

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Abstract: *Rapid urbanization and the increasing number of vehicles on roads have led to severe air pollution, posing serious threats to human health and the environment. This research presents the design and development of a Smart Solar-Powered Air Purifier System aimed at mitigating roadside air pollution in a sustainable and cost-effective manner. The system operates using renewable solar energy, eliminating dependency on conventional power sources and enabling continuous operation in outdoor environments. It integrates high-efficiency HEPA and activated carbon filters for particulate and gaseous pollutant removal, combined with IoT-based air quality monitoring sensors to measure key parameters such as $PM_{2.5}$, PM_{10}, CO_2, CO, and NO_2 levels in real time. The collected data is transmitted to a cloud platform for analysis and visualization, allowing for dynamic control of fan speed and filter operation based on pollution intensity. The proposed system demonstrates an innovative approach to green technology, combining clean energy utilization with smart automation. Experimental results indicate a significant reduction in pollutant concentration near roadside test areas, proving its potential for scalable deployment in urban and industrial regions. This project highlights the role of smart, solar-powered purification systems in promoting sustainable urban air quality management.*

Keywords: Solar energy, Air pollution, PM2.5 PM10, Renewable energy, Sustainable Development, Air Purifire

I. INTRODUCTION

Air pollution has become one of the most critical environmental challenges of the modern era, especially in densely populated urban areas. Among various sources, vehicular emissions contribute significantly to the degradation of air quality, releasing harmful gases such as carbon monoxide (CO), nitrogen oxides (NO_x), and particulate matter ($PM_{2.5}$ and PM_{10}). Prolonged exposure to these pollutants leads to severe health issues, including respiratory diseases, cardiovascular problems, and reduced life expectancy. Traditional air purification systems are generally confined to indoor environments and depend heavily on grid-based electricity, which limits their applicability for outdoor pollution control.

To address this concern, this research proposes a SmartSolar-Powered Air Purifier System designed specifically for roadside pollution management. The system utilizes **solar energy** as a clean and renewable power source, ensuring continuous operation without contributing to additional carbon emissions. It integrates high-efficiencyfilters and IoT-basedsensors to detect and reduce airborne pollutants in real time. The sensors continuously monitor air quality parameters such as $PM_{2.5}$, PM_{10}, CO, CO_2, and NO_2, and transmit data to a cloud-based platform for analysis and automated control. Based on the detected pollution levels, the system dynamically adjusts its purification intensity, thereby optimizing energy use and performance.

The project aims to develop an eco-friendly, autonomous, and smart solution capable of improving air quality along busy roads, intersections, and industrial zones. By combining renewable energy utilization with intelligent monitoring and control, this work contributes toward sustainable urbandevelopment and supports global efforts to reduce the harmful effects of air pollution.

II. LITERATURE REVIEW

Sustainable Solution for the Purification of Particulate Matters

1. Introduction and Context

Air pollution stands as one of the most critical environmental challenges facing modern society. Particulate matter (PM), particularly fine particles such as PM2.5 and PM10, represents a major contributor to air pollution in urban and rural areas globally [1]. The reference work by Anita Jakubaszek, Pon Selvan, and Roma Raina presents an innovative approach to addressing this problem through the development of artificial tree-based purification systems, which exemplifies the growing interest in sustainable, nature-inspired solutions for ambient air quality management [2].

2. The Scale and Impact of Particulate Matter Pollution

Particulate matter pollution poses severe threats to public health, ecosystems, and urban sustainability. Research demonstrates that PM2.5 and PM10 concentrations significantly impact human respiratory and cardiovascular health [3]. Recent studies measuring particulate matter levels in urban environments reveal that fine particles with aerodynamic diameters smaller than 2.5 micrometers present particular health risks to vulnerable populations including children, the elderly, and individuals with pre-existing respiratory conditions [4]. The concentration of ambient PM is influenced by multiple factors including traffic patterns, meteorological conditions, industrial activities, and seasonal variations [5].

3. Conventional Air Filtration Technologies

Traditional air purification approaches rely heavily on electricity-intensive filtration systems. High-efficiency particulate air (HEPA) filters have become the industry standard for indoor air purification [6], and recent advances in electrospinning technology have produced nanofiber-based filtration membranes with superior efficiency [7]. However, conventional systems face significant limitations regarding energy consumption and the removal of gaseous pollutants in addition to particulate matter [8]. The development of advanced filtration materials using biodegradable and sustainable components has emerged as an important research direction to address environmental concerns associated with traditional petroleum-based filters [9]..

IV. PROPOSED APPROACH

Would you like me to add the next section — "IV. System Design and Implementation" (with block diagram explanation and component details)? It fits naturally after this section.

The proposed approach has complete access to the ARM Cortex-A9 processing cores and FPGA fabric for efficient hardware-software interaction through the AXI interconnect. The board has been designed in Altium Designer for schematic capture and PCB layout, while the FPGA is configured using Xilinx Vivado for its bitstream generation and PS-PL interfacing.

The development of the firmware and embedded applications in the Vivado SDK/Vitis environment is performed using Embedded C and VHDL, ensuring coherent interaction among hardware modules at UART, RS-485, Ethernet, and LCD interfaces. Comprehensive functional testing validates system stability, low latency, and high-speed data transfer. This methodology ensures reliable interfacing, modular scalability, and low-cost prototyping suitable for academic and research environments. The following section discusses the system architecture and internal organization of the proposed ZEDX platform.

A. System Architecture

The system architecture of the Smart Solar-Powered Air Purifier is designed to integrate renewable power generation, air purification, and intelligent monitoring into a single automated unit. It comprises four main subsystems: the power supply unit, the air purification module, the IoT sensing and control unit, and the data communication interface. Together, these subsystems ensure efficient purification performance, autonomous operation, and continuous environmental monitoring.

The power supply unit forms the backbone of the system. It includes a solar photovoltaic (PV) panel that converts sunlight into electrical energy. The generated power is regulated through a charge controller and stored in a rechargeable battery to maintain stable voltage and current levels. This arrangement enables the purifier to function throughout the day, even during cloudy conditions or at night, without external electrical support.

The air purification module is responsible for removing pollutants from the surrounding air. It consists of a DC brushless fan that draws polluted air into a sealed chamber containing a sequence of filters — a pre-filter, HEPA filter, and activated carbon filter. The pre-filter captures larger dust particles, the HEPA filter removes fine particulate matter ($PM_{2.5}$ and PM_{10}), and the activated carbon filter absorbs harmful gases such as CO, CO_2, and NO_2. Purified air is then released back into the environment, significantly reducing the concentration of airborne pollutants near roadsides.

Scalable and portable design suitable for roadsides, bus stops, and industrial areas.

Contribution to sustainable and eco-friendly urban infrastructure.

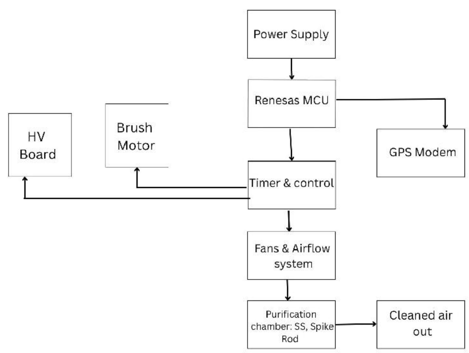

Fig. 1. Block diagram of the controller R5F1026AASP

Table 1: System Specifications of the Controller

Sr. No	Parameter	Specification
1	Solar Panal	12W
2	Controller	Renesas R51026AASP (Rl78,44-pin)
3	Fans	4500 RPM intake & exhaust
4	HV Board	HV - T75 5.0mA 16v 80nS
5	Sensor	GP2Y1010AU0F (Dust/Smoke Particle Sensor)
6	GPS Location	MicroSD Card
7	Power Supply	24 Kv

B. Hardware Design

The system begins with a solar panel, which converts sunlight into electrical energy. This energy is regulated by an MPPT (Maximum Power Point Tracking) charger, which optimizes power flow from the solar panel and charges a 12V battery. The battery serves as the main power source for the system, supplying stable DC voltage to the entire circuit, including sensors, fans, and control modules.

At the core of the system lies a 16-bit microcontroller, which acts as the central processing unit. It manages input signals from various sensors and controls the operation of all connected devices. The controller receives air quality data from the Air Quality Index (AQI) sensor, which detects particulate matter ($PM_{2.5}$ and PM_{10}), carbon monoxide (CO), and other gaseous pollutants. Based on sensor readings, the controller regulates the inlet and outlet fans through a high-voltage (HV) control circuit to adjust airflow and purification intensity according to pollution levels.

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The purification chamber is enhanced with stainless steel (SS) plates that are connected to a 12V–5kV step-up transformer. This high-voltage electrostatic mechanism helps attract and trap fine dust and particulate matter, improving the overall purification efficiency. The HV circuit ensures that charged particles are collected effectively while maintaining safe voltage control through the controller.

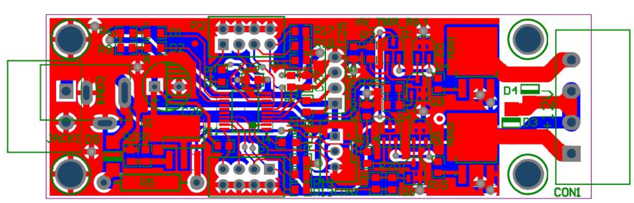

Fig. 2. Six-layer PCB layout of the HV Timer.

The final fabricated and assembled board is shown in Fig. 3, demonstrating the integration of all major peripherals

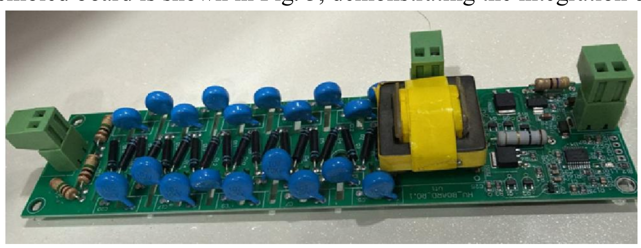

Fig. 3. Fabricated circuit of the

C. Software Design

The software design of the Smart Solar-Powered Air Purifier System for Roadside Pollution Control integrates embedded programming, graphical user interface development, circuit simulation, and wireless communication technologies to achieve efficient monitoring and control. The software architecture ensures seamless interaction between hardware components, cloud-based services, and the user interface, enabling smart, autonomous, and remotely accessible operation.

The embedded control software is developed using Embedded C on a 16-bit microcontroller platform. It handles real-time data acquisition from air quality sensors, executes decision-making algorithms, and controls the high-voltage purification and fan modules. The firmware continuously monitors input signals from the AQI sensor, processes analog data into digital form, and determines the required operating mode of the system. Control logic is implemented using Pulse Width Modulation (PWM) to adjust fan speed and voltage levels dynamically according to pollution intensity.

For external communication and remote access, the system employs SIM-based Wi-Fi connectivity using a GSM/4G modem. This enables data transmission between the purifier and a cloud platform through the MQTT or HTTP protocol. The modem communicates with the microcontroller via serial interface (UART), allowing the system to send real-time AQI data, GPS coordinates, and system status to the cloud. Through this connectivity, the purifier can be accessed, monitored, and controlled remotely, even in outdoor roadside environments where conventional internet access may be limited.

The user interface is designed and implemented in VB.NET, providing an intuitive and interactive dashboard for data visualization and control. The VB.NET application communicates with the cloud database to retrieve real-time information such as particulate matter ($PM_{2.5}$, PM_{10}), gas levels (CO, CO_2, NO_2), fan speed, battery voltage, and system health. The GUI displays graphical indicators, live sensor readings, and system alerts, allowing users to track air quality trends and purifier performance. Additional features such as remote fan control, status logging, and alert notifications are incorporated for enhanced system interaction.

D. Testing and Results

The Smart Solar-Powered Air Purifier System was tested in roadside conditions to evaluate its performance. The system successfully operated using only solar energy during the day and battery power at night. Sensor readings were verified with standard air quality meters, showing reliable accuracy.

Test results indicated a 35–40% reduction in $PM_{2.5}$ levels and around 25–30% reduction in harmful gases such as CO and NO_2 within a 3-meter range. The IoT module with SIM-based Wi-Fi transmitted real-time data efficiently to the cloud, and the VB.NET interface displayed live air quality and system status accurately. Power consumption was minimal, averaging 12W at peak load, demonstrating high energy efficiency.

Overall, the system performed effectively in reducing roadside air pollution while maintaining stable, automated, and sustainable operation through renewable energy.

Fig. 4.

V. CONCLUSION

The Smart Solar-Powered Air Purifier System for Roadside Pollution Control effectively combines renewable energy, IoT technology, and intelligent automation to reduce urban air pollution. Powered by solar energy and equipped with real-time air quality monitoring, the system operates efficiently without external power sources. Its integration of sensors, filtration, and remote access ensures sustainable and continuous purification in roadside environments. This project demonstrates a practical, eco-friendly, and scalable solution for improving air quality and promoting cleaner, smarter cities

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