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Smart Air Purification Powered by Footstep Energy Generation

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Abstract: *Air pollution and increasing energy demand have become significant challenges in modern urban environments, necessitating sustainable and energy-efficient solutions. This paper presents a Smart Air Purification System Powered by Footstep Energy Generation, which integrates renewable energy harvesting with intelligent environmental monitoring. The proposed system employs piezoelectric sensors embedded beneath pedestrian walkways to convert mechanical energy generated from human footsteps into electrical energy. The harvested energy is rectified, regulated, and stored in a rechargeable energy storage unit to power the entire system without relying solely on conventional electricity. An MQ135 air quality sensor continuously monitors the concentration of harmful gases and pollutants, while a microcontroller processes the sensor data and automatically controls a DC fan equipped with an activated carbon filter for air purification. LED indicators provide real-time visual feedback regarding air quality conditions. The integration of energy harvesting, automated air quality monitoring, and purification into a single platform enhances energy efficiency, reduces environmental impact, and supports sustainable smart city infrastructure. Experimental implementation demonstrates the feasibility of utilizing low-power renewable energy generated from human movement to operate an intelligent air purification system effectively. The proposed model offers a cost-effective, eco-friendly, and scalable solution suitable for deployment in high-footfall public locations such as railway stations, shopping malls, airports, educational institutions, and metro stations.*

Keywords: *Footstep Energy Generation, Piezoelectric Energy Harvesting, Smart Air Purification, MQ135 Gas Sensor, Air Quality Monitoring, Renewable Energy, Arduino, IoT, Energy Harvesting, Smart Cities.*

I. INTRODUCTION

Rapid urbanization and industrial growth have led to a significant increase in air pollution and energy consumption, creating serious environmental and public health concerns. Conventional air purification systems rely heavily on grid electricity, contributing to higher energy demand and operational costs. At the same time, a considerable amount of mechanical energy generated from human movement in crowded public places remains unused. Converting this wasted kinetic energy into useful electrical energy offers a promising approach to developing sustainable and self-powered environmental monitoring systems.

Footstep energy harvesting, based on the piezoelectric effect, is an emerging renewable energy technology that converts mechanical pressure from human footsteps into electrical energy. Piezoelectric sensors generate voltage when subjected to mechanical stress, making them suitable for installation in high-footfall locations such as railway stations, shopping malls, airports, educational institutions, and metro stations. Although the energy produced by a single footstep is relatively small, combining multiple sensors and employing efficient energy storage techniques enables the harvested energy to power low-power electronic devices and embedded systems.

This paper presents a **Smart Air Purification Powered by Footstep Energy Generation** system that integrates renewable energy harvesting with real-time air quality monitoring and automatic air purification. The proposed system utilizes piezoelectric sensors to generate electrical energy from human footsteps, which is conditioned, stored, and supplied to an Arduino-based control unit. An MQ135 gas sensor continuously monitors air quality by detecting harmful gases and pollutants. Based on the sensor readings, the microcontroller automatically activates a DC fan fitted with an activated carbon filter to improve air quality, while LED indicators provide real-time visual feedback on pollution levels.

The proposed approach offers an environmentally friendly and energy-efficient solution by combining renewable energy generation, intelligent sensing, and automated air purification within a single platform. Unlike conventional systems that depend entirely on external power sources, the proposed model promotes sustainable energy utilization while supporting smart city initiatives. Its compact design, low maintenance requirements, and scalability make it suitable for deployment in public environments with high pedestrian traffic, contributing to cleaner air and more sustainable urban infrastructure.

II.MATERIAL AND METHODS

The proposed Smart Air Purification Powered by Footstep Energy Generation system consists of hardware and electronic components that enable energy harvesting, power management, air quality monitoring, and automated air purification. The materials used in the implementation are listed below.

1. Piezoelectric Sensors

Piezoelectric sensors are the primary energy harvesting elements of the system. They convert the mechanical pressure generated by human footsteps into electrical energy through the direct piezoelectric effect. Multiple sensors are connected to improve the overall energy output.

2. Bridge Rectifier

A full-wave bridge rectifier (1N4007 diodes) is employed to convert the alternating current (AC) produced by the piezoelectric sensors into direct current (DC), making the generated energy suitable for storage and utilization.

3. Filter Capacitor

An electrolytic capacitor (1000 µF, 25 V) is used to smooth the rectified voltage by minimizing ripples and fluctuations, thereby providing a stable DC output for the subsequent stages.

4. Rechargeable Battery / Supercapacitor

The harvested electrical energy is stored in a rechargeable lithium-ion battery or supercapacitor. The storage unit ensures continuous system operation during periods of low or no pedestrian movement.

5. Microcontroller (Arduino UNO / ESP32)

The Arduino UNO (or ESP32) functions as the central processing unit of the system. It acquires sensor data, controls the system operation, processes air quality information, and activates the purification mechanism whenever required.

6. MQ135 Air Quality Sensor

The MQ135 gas sensor is used to monitor indoor air quality by detecting harmful gases such as carbon dioxide (CO_2), ammonia (NH_3), smoke, and other pollutants. The sensor provides real-time analog signals to the microcontroller for analysis.

7. DC Fan with Activated Carbon Filter

A DC fan coupled with an activated carbon filter serves as the air purification unit. When pollutant concentrations exceed the predefined threshold, the microcontroller automatically activates the fan to circulate air through the filter, thereby removing harmful gases and odors.

8. LED Indicators

Three LEDs (Green, Yellow, and Red) are used to indicate different air quality conditions. These visual indicators provide users with an immediate understanding of the environmental status.

9. Relay Module

A relay module acts as an electronic switch to control the operation of the DC fan based on commands received from the microcontroller.

10. Supporting Components

Additional components such as resistors, connecting wires, breadboard/PCB, voltage regulators, and power connectors are utilized to establish reliable electrical connections and ensure stable system operation.

Component	Specification	Purpose
Piezoelectric Sensor	Piezoelectric Disc	Harvests electrical energy from footsteps
Bridge Rectifier	1N4007 Full-Wave	Converts AC to DC
Capacitor	1000 µF, 25 V	Voltage filtering and stabilization
Battery/Supercapacitor	3.7 V Li-ion / 2.7–5.5 V	Energy storage
Arduino UNO / ESP32	ATmega328P / ESP32	System control and data processing
MQ135 Sensor	Gas Sensor Module	Air quality monitoring
DC Fan	5 V / 12 V	Air circulation
Activated Carbon Filter	Carbon-based filter	Pollutant removal
Relay Module	5 V Relay	Fan switching control
LEDs	Red, Yellow, Green	Air quality indication
Breadboard & Connecting Wires	Standard	Circuit implementation

Table 1. Materials Used in the Proposed System

Procedure methodology

The proposed system was developed using a hardware-based energy harvesting and air quality monitoring approach. The methodology integrates footstep energy generation, power conditioning, energy storage, real-time air quality sensing, and automatic air purification into a single self-powered platform.

A. Footstep Energy Harvesting

Mechanical energy generated by human footsteps is captured using an array of piezoelectric sensors installed beneath a walking surface. When pressure is applied, the sensors produce an alternating electrical voltage based on the direct piezoelectric effect. The output voltage depends on the magnitude of the applied force and the number of sensors connected.

B. Power Conditioning and Energy Storage

The alternating current generated by the piezoelectric sensors is converted into direct current using a full-wave bridge rectifier. A filter capacitor is employed to smooth the rectified voltage and minimize ripple components. The conditioned electrical energy is subsequently stored in a rechargeable lithium-ion battery (or supercapacitor), ensuring uninterrupted system operation even during periods of low pedestrian activity.

C. Air Quality Monitoring

An MQ135 gas sensor continuously monitors the concentration of harmful gases and air pollutants, including carbon dioxide (CO_2), ammonia (NH_3), and smoke. The analog output from the sensor is acquired by an Arduino UNO (or ESP32) microcontroller, which processes the sensor readings and compares them with predefined threshold values to determine the air quality level.

D. Automatic Air Purification

Based on the processed sensor data, the microcontroller automatically controls the purification unit. When pollutant levels exceed the specified threshold, a relay module activates a DC fan coupled with an activated carbon filter. The fan circulates ambient air through the filter, thereby reducing harmful gases and improving air quality. Once the pollutant concentration returns to an acceptable level, the purification unit is automatically switched off to conserve the harvested energy.

E. Air Quality Indication

To provide immediate visual feedback, three LED indicators are used to represent different air quality conditions. The green LED indicates good air quality, the yellow LED indicates moderate pollution, and the red LED indicates poor air quality requiring purification. This visual indication enables users to easily understand the environmental status in real time.

F. System Evaluation

The developed prototype was evaluated under different operating conditions by applying varying footstep pressures and exposing the MQ135 sensor to different air quality levels. The performance of the system was assessed in terms of harvested energy generation, energy storage capability, sensor response, automatic fan activation, LED indication accuracy, and overall system reliability. The experimental observations confirmed that the proposed system effectively utilizes harvested footstep energy to power air quality monitoring and automatic purification, demonstrating its suitability for deployment in high-footfall public environments.

The overall operational sequence of the proposed methodology is summarized as:
Footstep → Piezoelectric Sensors → Bridge Rectifier → Filter Capacitor → Battery/Supercapacitor → Arduino UNO/ESP32 → MQ135 Gas Sensor → LED Indicators & Relay → DC Fan with Activated Carbon Filter

This integrated methodology enables efficient utilization of renewable mechanical energy while providing intelligent, real-time air quality monitoring and automated purification with minimal dependence on external power sources.

III.RESULT

The developed prototype of the Smart Air Purification Powered by Footstep Energy Generation system was successfully implemented and evaluated under different operating conditions. The experimental results demonstrate the effective integration of renewable energy harvesting, air quality monitoring, and automated air purification into a single self-powered platform.

The piezoelectric energy harvesting module successfully converted mechanical pressure generated by human footsteps into electrical energy. The generated alternating current was efficiently rectified and regulated to produce a stable direct current suitable for storage. The rechargeable battery/supercapacitor effectively stored the harvested energy, enabling continuous operation of the monitoring and purification system even during intervals of low pedestrian activity.

The MQ135 gas sensor continuously monitored ambient air quality and accurately detected variations in pollutant concentration. Based on the measured air quality levels, the microcontroller correctly classified the environmental condition into three categories: good, moderate, and poor. The corresponding LED indicators (green, yellow, and red) provided immediate visual feedback regarding the air quality status.

When pollutant concentrations exceeded the predefined threshold, the relay module automatically activated the DC fan integrated with an activated carbon filter. The purification unit successfully reduced airborne pollutants, demonstrating the effectiveness of the automated control mechanism. Once the air quality improved to an acceptable level, the fan was automatically switched off, thereby conserving the harvested electrical energy.

The experimental observations confirmed that the proposed system operated reliably under different environmental conditions with minimal external power requirements. The integration of footstep energy harvesting with intelligent air quality monitoring significantly reduced dependence on conventional electrical power while maintaining continuous environmental monitoring and automatic purification.

Test Parameter	Observation	Status
Footstep Energy Generation	Electrical energy successfully generated using piezoelectric sensors	Successful
AC to DC Conversion	Stable DC output obtained through bridge rectifier and capacitor	Successful
Energy Storage	Harvested energy stored in battery/supercapacitor	Successful
Air Quality Monitoring	MQ135 sensor accurately detected pollutant levels	Successful
LED Indication	Green, Yellow, and Red LEDs displayed correct air quality status	Successful
Automatic Fan Control	Fan activated automatically when pollution exceeded threshold	Successful
Air Purification	Activated carbon filter effectively improved air quality	Successful
Overall System Performance	Integrated system operated reliably using harvested energy	Successful

Table 1. Experimental Results of the Proposed System

Overall, the proposed system demonstrated efficient utilization of renewable footstep energy for powering an intelligent air purification system. The successful integration of energy harvesting, real-time sensing, automated control, and purification validates the feasibility of the proposed design for deployment in high-footfall public locations such as railway stations, shopping malls, airports, metro stations, and educational institutions.

IV.DISCUSSION

The proposed **Smart Air Purification Powered by Footstep Energy Generation** system successfully demonstrates the feasibility of integrating renewable energy harvesting with real-time air quality monitoring and automated purification. The experimental implementation confirms that mechanical energy generated from human footsteps can be effectively converted into electrical energy using piezoelectric sensors and utilized to operate low-power environmental monitoring devices. This approach promotes sustainable energy utilization by capturing otherwise wasted mechanical energy in high-footfall public areas.

The integration of the MQ135 gas sensor with the microcontroller enabled continuous monitoring of air quality and automatic decision-making based on pollutant concentration. The system accurately identified different air quality conditions and activated the purification unit whenever the measured pollutant levels exceeded the predefined threshold. The LED indicators provided clear visual feedback, while the DC fan equipped with an activated carbon filter effectively reduced airborne pollutants, demonstrating the practical functionality of the proposed design.

Compared with conventional air purification systems that rely entirely on external electrical power, the proposed system offers significant advantages, including reduced energy consumption, autonomous operation, lower operational costs, and improved environmental sustainability. The combination of energy harvesting, intelligent sensing, and automatic control into a single platform makes the system well suited for deployment in smart city infrastructure, railway stations, shopping malls, airports, educational institutions, and other locations with continuous pedestrian movement.

Although the proposed system achieved its intended objectives, certain limitations were observed during implementation. The electrical energy generated depends directly on pedestrian traffic and the force applied to the piezoelectric sensors, resulting in limited power availability during periods of low footfall. In addition, the MQ135 sensor requires proper calibration to ensure accurate measurements under varying environmental conditions. The air purification capability is also limited to the effective coverage area of the installed fan and filter assembly.

Future improvements may focus on increasing the energy harvesting efficiency by optimizing the arrangement of piezoelectric sensors or integrating hybrid renewable energy sources such as solar power. Incorporating IoT connectivity for remote monitoring, cloud-based data analysis, and mobile application support can further enhance system intelligence and scalability. Advanced air quality sensors and high-efficiency filtration technologies may also improve monitoring accuracy and purification performance, making the system more suitable for large-scale smart city applications.

Overall, the developed prototype validates the practicality of combining footstep energy harvesting with intelligent air purification. The results indicate that the proposed system is an environmentally friendly, cost-effective, and scalable solution that contributes to sustainable urban development while reducing dependence on conventional energy sources.

V.CONCLUSION

The proposed **Smart Air Purification Powered by Footstep Energy Generation** system successfully demonstrates an innovative approach to integrating renewable energy harvesting with intelligent environmental monitoring and automated air purification. By utilizing piezoelectric sensors to convert mechanical energy from human footsteps into electrical energy, the system effectively powers air quality sensing and purification components with minimal dependence on conventional power sources.

The implementation results confirm that the developed prototype is capable of generating electrical energy, storing it efficiently, continuously monitoring air quality using the MQ135 gas sensor, and automatically activating the air purification unit whenever pollutant levels exceed predefined limits. The incorporation of LED indicators further enhances the system by providing real-time visual information about air quality conditions. This integrated operation validates the feasibility of combining energy harvesting and environmental monitoring into a single self-sustaining platform.

The proposed system offers several advantages, including reduced energy consumption, eco-friendly operation, low maintenance requirements, and suitability for deployment in high-footfall public locations such as railway stations, shopping malls, airports, metro stations, and educational institutions. Its modular architecture also provides flexibility for future expansion and integration into smart city infrastructure.

Although the current prototype demonstrates promising performance, future work can focus on improving energy harvesting efficiency through optimized piezoelectric sensor configurations, integrating hybrid renewable energy sources such as solar power, implementing IoT-based remote monitoring, and employing advanced air quality sensors with higher accuracy. These enhancements would improve system reliability, scalability, and practical applicability for large-scale deployments.

In conclusion, the proposed Smart Air Purification Powered by Footstep Energy Generation system provides a sustainable, cost-effective, and environmentally friendly solution for addressing two major urban challenges: efficient energy utilization and air pollution control. The successful integration of renewable energy harvesting with intelligent automation highlights its potential as a practical technology for future smart and sustainable cities.

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