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SMAP: Design And Development Of A Sustainable Modular Air Purifier For Energy-Efficient Indoor Air Quality Management

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Abstract:
This paper presents the design and development of the Sustainable Modular Air Purifier (SMAP), an innovative solution aimed at improving indoor air quality while minimizing energy consumption. The system features a modular architecture that allows for customizable and targeted air purification based on specific pollutants, including particulate matter, mold spores, and animal dander. Each module is equipped with specialized filters—high-efficiency particulate air, UV-C sterilization, and activated carbon—and operates selectively based on real-time air quality data from advanced sensors. This intelligent activation mechanism is aimed to reduce energy consumption, thus enhancing the system's sustainability. Its modularity also allows for easy maintenance and adaptability to different indoor environments, making it scalable to a variety of use cases. Through a combination of energy-efficient components and a user-friendly interface, the SMAP ensures high purification efficiency and also contributes to the broader goal of environmental sustainability. The system's performance, flexibility, and low energy footprint offer a promising solution for maintaining healthy indoor air quality in an environmentally responsible manner.

Key Word*: Air Purification Technology; Sustainable Design, Energy Efficiency, Modular Design*

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I. Introduction

Interest in Indoor Air Quality (IAQ) has steadily increased in recent years, driven by a greater understanding of its significant effects on human health and well-being[1]. Prolonged exposure to poor indoor air quality is associated with various health issues, including respiratory diseases[2], allergies[3], and cardiovascular problems[4]. Consequently, the demand for effective air purification solutions has grown, especially following the COVID-19 pandemic[5], which highlighted the importance of maintaining clean and healthy indoor environments.

Despite this rising demand, most commercially available air purifiers have notable limitations, such as high power consumption[6] and large physical sizes[7]. These issues lead to higher operational costs for users and pose challenges to energy sustainability and environmental impact[8, 9]. The high energy usage of conventional air purifiers contributes to increased carbon emissions[10], which goes against global efforts to combat climate change. Additionally, the bulky size of these devices restricts their placement flexibility[7], making them less suitable for various indoor settings where space might be limited.

Given these challenges, there is a clear need for more sustainable air purification technologies. Sustainability, defined as the efficient use of resources and reduction of environmental impact[11], is becoming an essential criterion in the design and implementation of modern appliances. For air purifiers, this is crucial not only for lowering energy consumption[12] and carbon emissions[13] but also for improving the economic viability[14] and longevity[15], thereby supporting broader sustainability goals.

To address these issues, this study presents the design of a Sustainable Modular Air Purifier (SMAP) that integrates sustainability principles by reducing power consumption and improving operational efficiency. SMAP is designed to reduce carbon emissions through minimizing energy use and extended operational lifespan, thereby achieving economic sustainability. This innovative approach involves creating a compact, modular system that operates within a smaller range than traditional models. This modular design enables easy attachment and detachment of units in specific locations as needed, ensuring that the purifier functions efficiently and only when and where required. Furthermore, the proposed design is categorized based on the target pollutants, enabling purification solutions customized to different types of indoor air contaminants. This specialization improves purification effectiveness while also optimizing energy consumption by activating only the necessary modules in response to detected pollutants.

This paper reviews current air purification technologies and their limitations, along with advances in sustainable and modular designs. It then outlines the filters and components used, including the criteria for selecting sensors and filters, and describes their integration into a modular framework. The discussion assesses the system's performance in pollutant removal and energy efficiency, as well as research contributions and directions for future work.

This study contributes to the advancement of environmentally friendly technologies by developing a sustainable, energy-efficient, and modular air purifier. The proposed solution addresses the immediate concerns of high power consumption and large device size while aligning with global sustainability objectives, thereby offering a practical pathway toward healthier and more sustainable indoor environments.

Figure no 1: expected design of SMAP device

II. Related Works

Air Purification Technologies

Air purifiers employ various technologies to remove contaminants from indoor air, each with distinct mechanisms, advantages, and limitations. Filter-based technologies[16, 17] are the most prevalent, and utilize materials such as high-efficiency particulate air (HEPA) and activated carbon filters to trap particulate matter (PM2.5, PM10) and volatile organic compounds (VOCs), respectively. HEPA filters are able to capture at least 99.97% of airborne particles down to 0.3 microns, making them highly effective for reducing respiratory irritants and allergens[18]. However, their efficiency can lead to increased air resistance[19], necessitating more powerful (and energy-consuming) fans to maintain airflow[20].

In addition, ionization technologies[21] generate charged ions that attach to airborne particles, causing them to clump together and either settle out of the air or adhere to surfaces. Although ionizers can effectively reduce particulate concentrations without the need for physical filters, they often produce ozone as a byproduct[22], which poses additional health risks and environmental concerns. The tradeoff between particulate removal and ozone generation remains a significant drawback of ionization-based air purifiers.

Moreover, ultraviolet (UV) sterilization[23] employs UV-C light to deactivate microorganisms, such as bacteria, viruses, and mold spores, by disrupting their DNA. This method is particularly effective for improving microbiological air quality[24], making it a valuable addition to multifunctional air purification systems. However, UV sterilization does not remove particulate matter or chemical pollutants[25], limiting its efficacy to microbial control alone.

Each of these technologies offers advantages against specific types of indoor air pollutant. However, their inherent limitations—such as high energy consumption in filter-based systems, ozone production in ionizers, and inability to address all pollutant types with UV sterilization—highlight the need for more sustainable and efficient air purification solutions.

Miniaturization and Modularization for Energy Efficiency and Sustainability

The miniaturization and modularization of air purifiers present promising avenues for reducing power consumption and enhancing sustainability. Miniaturization involves designing compact units that require less energy to operate, making them suitable for a broader range of environments, including small living spaces and portable applications[26, 27]. Smaller devices typically have lower power demands[28] owing to their reduced airflow requirements and smaller motor sizes, which contribute to overall energy savings.

Modularization complements miniaturization by allowing air purifiers to be customized and scaled according to specific needs. Modular systems comprise interchangeable units or modules, each targeting specific pollutant types or enhancing certain functionalities[29]. This flexibility enables users to activate only the necessary modules based on real-time air quality assessments, thereby optimizing energy usage[30, 31]. For example, a user may engage a HEPA filter module during high particulate matter conditions and switch to an activated carbon module when VOC levels rise, ensuring that the device operates efficiently without unnecessary energy expenditure.

Several studies[32, 33, 34, 35] have demonstrated the advantages of advanced airflow design and sensor integration in cleanrooms and industrial environments, particularly in enhancing air quality and energy efficiency. For instance, Xu[34] developed an efficient airflow system for cleanrooms that significantly improved contamination control by optimizing air circulation patterns, thus reducing the overall energy required to maintain cleanroom standards. Such advancements in design and control technologies have contributed to cleaner environments with lower operational costs; and underscore the potential of miniaturization and modularization to enhance the sustainability of air purification technologies by making them more energy-efficient, adaptable, and user-friendly.

Sustainability in Air Purification Technologies

Integrating sustainability into air purification technologies involves adopting practices and materials that minimize environmental impact throughout the product lifecycle[36]. Sustainable air purifiers emphasize energy efficiency[37], use of eco-friendly materials[38], and designs that facilitate longevity and recyclability. Several approaches have been explored for enhancing the sustainability of air purifiers.

Recent research highlights the potential of renewable-energy-powered air purifiers for addressing indoor and outdoor air pollution. Solar-powered outdoor air purification systems offer a sustainable approach to filtering contaminants and reducing reliance on non-renewable energy sources[39]. One study proposed a novel ambient air purifier utilizing renewable energy, which removed 74% of particulate matter[40]. Another design that incorporated solar panels and wind turbines demonstrated significant reductions in automotive emissions, with 98% reduction in CO and 95% in HC emissions[41]. These systems not only improve air quality but also combat climate change by curbing greenhouse gas emissions[39].

Eco-friendly materials also play a crucial role in the design of sustainable air purifiers. Utilizing recycled or biodegradable materials for filters and housing components not only reduces the environmental impact of production but also simplifies end-of-life disposal[38]. Chemical recycling of biodegradable polymers shows promise for reducing the environmental impact of disposable items such as face masks[42].

These initiatives demonstrate that sustainability can be effectively integrated into air purification technologies, addressing both environmental and economic concerns while maintaining high performance standards. By prioritizing energy efficiency, eco-friendly materials, and durable designs, the air purification industry can contribute significantly to global sustainability efforts.

III. Material

The design and functionality of the SMAP are based on a careful selection of materials and components that ensure high performance, energy efficiency, and sustainability. This section provides an in-depth overview of the key technologies and materials used in the system, detailing their specific roles and technical specifications. Table 1 summarizes functions and names of these components.

Sensors and Control Components

Accurate detection of indoor air pollutants is essential for effective air purification. The system integrates a range of advanced sensors and control components to monitor air quality in real time and efficiently manage the purification process.

Particulate Matter Sensors: The PurpleAir PA-II-SD sensor was employed to detect fine particulate matter (PM2.5, PM10). This sensor utilizes laser scattering technology to precisely measure airborne particles, providing reliable data for system control. It has a detection range of 0 to 1000 µg/m³ with ±5% accuracy, allowing for effective monitoring of particle concentrations in various indoor environments.

Volatile Organic Compounds (VOCs) Sensors: The Bosch BME680 sensor measures VOC concentrations alongside humidity, temperature, and pressure. This multifunctional sensor enables comprehensive monitoring of indoor air quality, with a VOC detection range of 0–1000 ppb and a response time of less than 10 seconds. Its integrated capabilities allow for holistic assessment of air quality parameters.

Carbon Dioxide (CO_2) Sensors: The Senseair S8 LP sensor accurately detects CO_2 levels using non-dispersive infrared (NDIR) technology. It offers a measurement range of 0 to 5000 ppm and features low power consumption, making it ideal for continuous air quality assessment. The sensor ensures that CO_2 levels are maintained within safe limits, contributing to overall indoor air health.

Temperature and Humidity Sensors: The DHT22 sensor is used to monitor ambient temperature and humidity. With a temperature range of -40 to 80°C and humidity range of 0–100% RH, it provides accurate climate data for optimizing air purifier performance and energy usage. Maintaining appropriate temperature and humidity levels enhances the efficiency of the purification process.

Microcontroller Unit (MCU): The Arduino MKR WiFi 1010 serves as the central control unit, processing sensor data and managing communication between modules. It features a 32-bit ARM Cortex-M0+

processor, 256 KB of flash memory, and built-in Wi-Fi connectivity. This MCU enables real-time data processing, remote monitoring, and seamless integration with smartphone applications for user control.

Filter Types and Specifications

The air purifier combines various specialized filters to target specific indoor air pollutants. Each filter type maximizes purification efficiency while minimizing energy consumption. The modular design facilitates easy interchangeability of filter modules, allowing users to customize the device to the predominant pollutants in their environment. This approach ensures that only the necessary filters are activated, thereby optimizing purification performance and energy usage.

High-Efficiency Particulate Air (HEPA) Filters: A 3M HEPA H14 filter was chosen for its ability to capture at least 99.995% of airborne particles down to 0.3 microns. This filter is highly effective in removing allergens, dust, and other fine particulates, thereby ensuring superior air quality. The filter dimensions are 30 cm × 30 cm × 5 cm, providing a large surface area for enhanced filtration. The H14 classification ensures compliance with stringent air quality standards, making it suitable for environments requiring high purification levels.

Activated Carbon Filters: The Honeywell HAF-100 activated carbon filter serves as an excellent alternative for adsorbing VOCs, odors, and gaseous pollutants. This filter's substantial surface area of 400 m^2/g enhances the capture of a wide range of organic compounds. Designed for high-efficiency applications, the HAF-100 ensures long-term performance and reliability.

UV-C Light Modules: The Philips UV-C germicidal lamp deactivates microorganisms such as bacteria, viruses, and mold spores. Operating at 254 nm wavelength, the UV-C module disrupts the DNA of pathogens, enhancing microbiological air quality. The lamp has an output power of 9 watts and is enclosed in a protective casing to ensure safe operation. The UV-C module is designed for easy integration into modular frameworks, providing an additional layer of purification without significantly increasing energy consumption.

Motor, Fan Design, and Airflow Management

Efficient airflow management is crucial for air purifier performance and energy efficiency. The system employs optimized motors and fans to achieve the desired airflow with minimal power consumption.

Brushless DC (BLDC) Motors: A Noctua NF-A12x25 fan motor was selected for its high efficiency and low-noise operation. This 12 V motor provides efficient air purification (200 m^3/h flow rate) and quiet operation (22 dB). The BLDC motor provides superior performance-to-power ratios, contributing to the overall energy efficiency of the air purifier.

Axial Fans: Delta Electronics AFB120 series axial fans provide consistent and efficient airflow through the filter media. These fans can operate at variable speeds of 500–2000 RPM, allowing for dynamic adjustment based on real-time air quality data. The fans are designed to minimize energy consumption while maintaining effective air circulation (maximum airflow 250 m^3/h). Their compact design ensures compatibility with modular frameworks, enabling seamless integration and easy maintenance.

Air Resistance Reduction Technologies: The system incorporates advanced airflow management techniques that minimize air resistance to reduce energy consumption. Filters are configured in layers with a gradient density to facilitate smooth airflow, reducing turbulence and pressure drops. Perforated filter frames enhance airflow distribution across the filter surface, preventing channeling and ensuring uniform air intake. Additionally, low-resistance filter materials maintain high purification rates with reduced energy input. These strategies collectively ensure that the air purifier operates efficiently, delivering high-quality air at minimal energy expenditure.

Table no 1: Functions and names of electronic components used in SMAP

	Role	Name of Component
Sensors	Particulate matter	PurpleAir PA-II-SD
	Volatile organic compound	Bosch BME680
	Carbon dioxide	Senseair S8 LP
	Temperature and humidity	DHT22
Filters	High-efficiency particulate air	3M HEPA H14
	Activated carbon	Honeywell HAF-100
	UV-C light module	Philips UVC germicidal lamp
Mechanical parts	BLDC Motor	Noctua NF-A12x25
	Axial fans	Delta electronics AFB120 series

Functional Testing

Comprehensive functional testing is planned to validate the performance and reliability of the SMAP, encompassing both laboratory-based and real-world evaluations to ensure that the air purifier meets the desired standards of performance, efficiency, and sustainability.

Performance Testing: Accurate detection and effective purification of indoor air pollutants are fundamental for the air purifier's operation. Each sensor, including particulate matter and VOC sensors, is meticulously calibrated against standardized reference instruments to ensure precise measurements. The PurpleAir PA-II-SD sensors are set to demonstrate consistent accuracy within ±5% for detecting PM2.5 and PM10 concentrations. Similarly, the Bosch BME680 VOC sensors are expected to exhibit response times of less than 10 seconds, effectively capturing varying concentrations of different chemical compounds.

Filter efficiency will be rigorously evaluated to confirm the system's purification capabilities. The 3M HEPA H14 filters are designed to remove more than 99.99% of particles down to 0.3 microns, effectively eliminating allergens, dust, and other fine particulates. Activated carbon filters, specifically the Honeywell HAF-100, are expected to demonstrate high adsorption capacity for VOCs and odors, efficiently capturing organic compounds and mitigating airborne chemical contaminants. Testing will establish the filters' ability to maintain superior air quality while operating efficiently.

Energy Consumption Analysis: Assessing energy efficiency is a critical aspect of functional testing. Power usage will be measured across various operational modes, including idle, active purification, and energy-saving states. The energy-saving modes and selective module activation are expected to significantly contribute to overall efficiency and the system's sustainability objectives. These tests will demonstrate the SMAP's ability to remove pollutants at minimal energy expenditure.

Reliability and User Experience: Testing will evaluate the long-term reliability of the motors, fans, and electronic components. Continuous operation cycles simulate real-world usage, identifying any potential wear and tear issues. The Noctua NF-A12x25 BLDC motors and Delta Electronics AFB120 series axial fans are projected to demonstrate robust performance with minimal degradation over extended periods. The system is designed to maintain optimal airflow rates and consistent purification performance throughout the testing phase, ensuring longevity and sustained efficiency. Such durability is essential for economic sustainability of the air purifier, as it reduces the need for frequent replacement and maintenance.

Additionally, the usability of the air purifier's user interface will be assessed to ensure a seamless and intuitive experience for users. The touch panel controls will be tested for ease of use, responsiveness, and reliability. User feedback collected through surveys and usability tests will reflect how well the interface meets ergonomic and usability standards. Features, such as real-time air quality monitoring, module control, and energy usage reports aim to facilitate user interactions with the system.

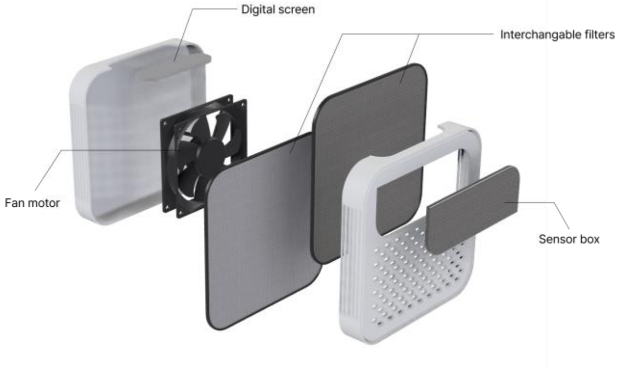
IV. System

The SMAP system will be meticulously engineered to deliver efficient air purification in confined indoor spaces while maintaining low power consumption. The system's design emphasizes modularity, allowing for targeted pollutant removal and energy optimization based on specific environmental needs.

Design objectives

The primary objective of the SMAP system is to develop a compact air purifier capable of cleaning narrow areas with minimal energy usage. This is achieved through a modular design that facilitates the selection and attachment of specific purifier types based on predominant indoor pollutants. By focusing on localized purification, the system ensures that energy is utilized only when and where necessary, thereby enhancing overall sustainability.

Figure no 2: Exploded view of SMAP device



Modular Architecture and Mechanical Structure

The SMAP system features interchangeable modules targeting different pollutants, allowing customization for specific air quality challenges. Each module is designed for easy attachment and integration into various indoor environments. Each module features a standardized mounting that can be securely attached to walls, ceilings, or other designated areas within an indoor space. The filters are housed within removable cartridges that slide into the module's frame, ensuring straightforward replacement without specialized tools. For instance, Type A modules designed for particulate matter and pollen feature HEPA H14 filters that can be easily inserted or removed from the front panel of the module. Similarly, Type B modules targeting mold spores incorporate UV-C sterilization units alongside HEPA filters, within a compact enclosure that attaches effortlessly to existing fixtures. Table 2 shows examples of possible module types.

The physical dimensions of each module are optimized for minimal spatial footprint, allowing multiple units to be deployed in close proximity without obstructing movement or occupying excessive space. The modules' lightweight construction facilitates easy handling and repositioning, enabling users to adapt the purifier layout to address changing air quality conditions. Additionally, each module is equipped with adjustable brackets that allow different mounting angles, ensuring optimal airflow distribution and pollutant capture based on the specific indoor layout.

Table no 2: Examples of possible different types of modules

	Activation Threshold	**Sensors**	**Filters**
Type A Particulate matter and pollen	PM2.5 levels exceed 35 μg/m^3	PurpleAir PA-II-SD for detecting particulate matter	HEPA H14 filters for capturing fine particulates and pollen
Type B Mold spores	Mold spore counts surpass 500 spores/m^3	Bosch BME680 for detecting VOCs	HEPA filters combined with UV-C sterilization units to deactivate mold spores
Type C Animal dander	Animal dander concentrations exceed 1500 particles/m^3	Senseair S8 LP for monitoring CO_2 levels	Activated carbon filters for removing animal dander and associated allergens

Activation Mechanism

The SMAP integrates its components through a cohesive framework that ensures seamless communication and efficient operation. A central control unit manages the operation of individual modules based on data received from the sensors. This unit coordinates module activation, ensures optimal airflow distribution, and maintains overall system efficiency.

Modules communicate with the central control unit via wireless protocols such as Wi-Fi or Bluetooth. This wireless connectivity facilitates easy integration of additional modules and enables remote monitoring and control. The Arduino MKR WiFi 1010 MCUs within each module process data from the integrated sensors and manage module activation based on pollutant levels. This decentralized processing approach enhances scalability and flexibility, allowing adaptation to varying air quality conditions and user requirements without significant modifications.

The system employs an energy management strategy that prioritizes the activation of necessary modules while minimizing power consumption. Low-power modes are utilized during periods of low pollution, and energy-efficient components such as brushless DC (BLDC) motors (Noctua NF-A12x25) and axial fans (Delta Electronics AFB120 series) are further reduce energy usage. This strategy ensures that the SMAP system operates sustainably and aligns with global energy conservation objectives.

Figure no 3: Spatial distribution of each module

Operational Workflow

The operational workflow of the SMAP system is designed to ensure efficient and effective air purification with minimal energy consumption. The process begins with integrated sensors that continuously monitor air quality parameters, detecting the presence and concentration of specific pollutants. The MCU evaluates pollutant levels against predefined thresholds and activates the relevant purification module if levels exceed these thresholds. For example, if PM2.5 levels exceed 35 µg/m^3, Type A modules with HEPA filters are activated to remove particulate matter. Once pollutant levels drop below the threshold, the modules are deactivated, conserving energy until the next pollution event.

All purification activities and air quality data are monitored through a user-friendly interface accessible via a digital screen on the top of the device. Users can view real-time air quality data, receive notifications about pollutant levels, and manually control module activation if desired. This workflow ensures that the air purifier operates only when necessary, thus maximizing energy efficiency while maintaining high air quality standards.

V. Discussion

The SMAP represents a significant advancement in indoor air quality management by addressing the critical limitations of conventional air purification systems. One of the primary contributions of this research is the introduction of a modular architecture that allows for targeted pollutant removal and energy optimization. Unlike traditional all-in-one air purifiers, the SMAP enables users to customize their purification process by selecting and attaching specific modules to target predominant indoor pollutants.

The originality of the SMAP lies in its combination of modular design with intelligent activation mechanisms. While prior research has explored modular and energy-efficient air purifiers separately, the integration of these two aspects within a single system is novel. The SMAP's ability to activate only the necessary modules in response to real-time air quality data differentiates it from similar technologies. This selective activation ensures that energy is conserved during periods of low pollution, thereby aligning with global sustainability goals and reducing the device's overall carbon footprint. Additionally, the inclusion of specialized modules addresses a wide range of indoor air contaminants.

The design implications of the SMAP extend beyond its immediate functionality. By demonstrating the effectiveness of a modular and sustainable approach, this research encourages the development of future air purification systems that prioritize energy efficiency and customization. The standardized mounting interfaces and easy interchangeability of modules highlight the importance of user-centric design in creating adaptable and scalable air purification solutions. Furthermore, the use of advanced sensors and microcontroller units (MCUs) for real-time monitoring and control underscores the potential of integrating smart technologies into environmental management devices. These design principles can inspire innovations in other areas of sustainable technology, promoting a more resource-efficient and adaptable approach to appliance design.

Despite its promising features, the system faces several limitations. The initial cost of acquiring multiple specialized modules may be higher than that of single-function air purifiers, potentially limiting its audience. Another significant limitation is the dependency on sensor accuracy for effective module activation. Although advanced sensors are employed to ensure precise pollutant detection, inaccuracies or sensor malfunctions can compromise overall performance. Regular calibration and maintenance of sensors are essential to mitigate this risk and maintain reliable air quality monitoring.

Future research should focus on several key areas to further enhance the SMAP system. Optimizing cost-effectiveness is essential for making the system affordable to more users. Exploring alternative materials and manufacturing processes could help reduce production costs without compromising performance. Additionally, integrating renewable energy sources, such as solar panels, could further enhance the system's sustainability by reducing reliance on grid electricity. Long-term performance evaluations in diverse real-world settings are necessary to assess the system's adaptability and effectiveness under varying conditions. Expanding the range of specialized modules to target additional pollutants, such as formaldehyde or nitrogen dioxide, would broaden the system's applicability and effectiveness. Enhancing the user interface with advanced features such as predictive analytics and automated maintenance alerts could improve the user experience and system management. Incorporating machine learning algorithms to predict pollutant trends and dynamically optimize module activation would further enhance the SMAP's efficiency and responsiveness, ensuring that it remains effective in maintaining high indoor air quality.

In summary, the SMAP system offers a novel and effective solution for indoor air purification by combining modular design with energy-efficient technologies. The ability to customize purification processes based on specific pollutant profiles not only improves air quality, but also supports sustainability goals through significant energy savings. While there are challenges to address, the contributions and originality of this research provide a strong foundation for future advancements in sustainable air purification technologies.

VI. Conclusion

This study introduces the Sustainable Modular Air Purifier (SMAP), which enhances indoor air quality while promoting energy efficiency and sustainability. The SMAP's modular architecture allows for targeted pollutant removal through interchangeable filter modules tailored to specific contaminants such as particulate matter, mold spores, and animal dander. The integration of advanced sensors and intelligent activation mechanisms enables real-time air quality monitoring and selective module operation, distinguishing the SMAP from existing technologies and aligning it with global sustainability objectives. To assess the system's adaptability and effectiveness, long-term evaluations in diverse real-world settings are required to be conducted. Future research will focus on optimizing cost-effectiveness, incorporating renewable energy sources, and expanding the range of specialized modules to address additional pollutants. Overall, the SMAP represents a significant advancement in sustainable air purification technology, offering a flexible and energy-efficient solution for maintaining healthy indoor environments and contributing to broader environmental sustainability goals.

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