Semarak Climate Science Letters

Journal homepage:
https://semarakilmu.my/index.php/scsl/index
ISSN: 3083-9580

Smart HVAC Filtration Monitoring for Indoor Air Quality (IAQ): Enhance Efficiency and Environmental Sustainability

Muhamad Asrul Affendi Mat Nor[1,*], Farah Waheda Othman[2], Nurhan Ayub[1], Irdayanti Mat Nashir[3], Sudiyatno[4]

[1] Department of Automotive Technology, Pasir Salak Community College, Jalan Lebuh Paduka, Changkat Lada, 36800 Kampung Gajah, Perak, Malaysia
[2] Department of Information Technology and Communication, Sultan Idris Shah Polytechnic, Sungai Lang, 45100 Sungai Air Tawar, Selangor, Malaysia
[3] Faculty of Technical and Vocational, Sultan Idris Education University, Tanjung Malim, 35900, Perak, Malaysia
[4] Department of Mechahnical Engineering Education, Faculty of Engineering, Universitas Negeri Yogyakarta, Indonesia

ARTICLE INFO

Article history:
Received 20 February 2025
Received in revised form 19 May 2025
Accepted 26 May 2025
Available online 30 June 2025

Keywords:
Indoor Air Quality (IAQ); air quality monitoring; HVAC system; air filters; real-time sensor; energy efficiency; sustainable filtration

ABSTRACT

Air filters play a vital role in HVAC systems by preventing pollutants such as dust and smoke from circulating indoors. Poor air filtration negatively impacts Indoor Air Quality (IAQ) and increases energy consumption. This study aims to develop a real-time air quality monitoring system for ducted air conditioning systems, specifically in an Air Handling Unit (AHU), to enhance filtration efficiency and optimize HVAC performance while improving IAQ. The system integrates humidity, temperature, dust, and airflow sensors with an Arduino microcontroller to collect and display real-time data. Two sensors were placed at pre-filter and post-filter positions to measure airborne particle concentration before and after filtration. Experimental results show that Sensor 1 recorded higher dust levels, while Sensor 2 measured significantly lower values, confirming the air filter's effectiveness. Clogged filters were found to reduce airflow by up to 50%, increasing energy consumption by 15–30%. The findings highlight the importance of real-time monitoring in improving IAQ, optimizing filter maintenance, and reducing energy waste. Implementing smart filtration monitoring systems can enhance HVAC efficiency, lower operational costs, and contribute to environmental sustainability.

1. Introduction

Air pollution remains one of the most critical environmental challenges worldwide, primarily driven by vehicle emissions, open burning, and industrial activities. These sources release hazardous pollutants such as carbon monoxide (CO), nitrogen oxides (NOx), sulfur dioxide (SO_2), volatile organic compounds (VOCs), and particulate matter (PM), all of which significantly degrade air quality and pose severe health risks [1]. Poor air quality has been strongly linked to respiratory diseases,

* *Corresponding author.*
E-mail address: asrul@staf.kkpsa.edu.my

https://doi.org/10.37934/scsl.3.1.114

cardiovascular disorders, and other long-term health complications, particularly in densely populated urban areas where pollution levels are high.

Indoor air quality (IAQ) is an essential aspect of public health, given that individuals spend a substantial amount of time indoors, whether at home, in offices, or in commercial buildings. Air conditioning systems play a crucial role in maintaining IAQ by regulating temperature, humidity, and airflow while filtering airborne contaminants [2]. Effective filtration removes dust, allergens, bacteria, and other pollutants, thereby reducing health risks and ensuring a comfortable indoor environment. However, inadequate maintenance and inefficient air filters can compromise system performance, leading to reduced filtration efficiency and increased exposure to airborne contaminants.

Despite the implementation of air filtration systems, health concerns persist due to variations in filtration efficiency. Over time, air filters accumulate pollutants and debris, diminishing their ability to capture airborne contaminants effectively. Research indicates that air pollution not only affects human health but also impacts the efficiency of air filters, reducing the overall performance of heating, ventilation, and air conditioning (HVAC) systems [3]. When air passes through contaminated ducts, dust accumulation and microbial growth can further degrade air quality. Additionally, clogged or inefficient filters restrict airflow, impair system performance, and prevent occupants from achieving optimal thermal comfort [4].

Another major concern associated with inefficient filtration systems is increased energy consumption. When HVAC filters become obstructed due to accumulated pollutants, the system must exert greater effort to maintain the desired airflow and temperature, leading to higher energy usage. This not only escalates operational costs but also contributes to a larger carbon footprint and greater environmental impact [5-7]. Studies have shown that energy-efficient air filters and intelligent air monitoring systems can significantly reduce energy consumption while enhancing air quality and prolonging system lifespan [8,9].

Neglecting routine maintenance, such as cleaning air conditioning coils, can further impair system efficiency, increasing operational costs and diminishing cooling performance. Regular and professional maintenance is a critical investment that enhances energy efficiency, extends system longevity, and ensures a healthier and more comfortable indoor environment [10].

To address these challenges, researchers and industry experts have been exploring innovative solutions to improve air filtration performance. Recent advancements in filtration technologies, such as electrostatic precipitators, high-efficiency particulate air (HEPA) filters, and smart monitoring systems, have demonstrated promising results in enhancing IAQ and HVAC efficiency. Moreover, international regulations, such as the Kigali Amendment to the Montreal Protocol, emphasize the need for sustainable air conditioning and refrigeration practices to mitigate greenhouse gas emissions and combat climate change [11].

This study aims to evaluate air filter performance in air conditioning systems and optimize efficiency through experimental monitoring and data analysis. By examining factors such as airflow resistance, particle capture efficiency, and energy consumption, this research seeks to contribute to the development of more sustainable and cost-effective HVAC solutions. The findings will provide valuable insights for improving air filtration strategies in residential, commercial, and industrial settings, ultimately fostering healthier indoor environments while minimizing environmental impact. Air conditioning system maintenance should not be limited to reactive problem-solving but should instead be approached as a comprehensive, proactive strategy to prevent system failures, enhance reliability, and optimize overall performance [10].

However, despite the growing awareness of energy efficiency and indoor air quality, there is still a lack of empirical research that systematically integrates real-time experimental monitoring with performance analysis of air filters in actual operating conditions. Most existing studies focus on theoretical simulations or isolated performance metrics, leaving a gap in holistic assessments that consider both filtration effectiveness and energy implications in real-world HVAC environments. This study seeks to address that gap by providing practical data-driven insights that can inform more efficient and sustainable air filtration practices.

1.1 Research Objectives

This study aims to develop an innovative and intelligent monitoring system to enhance air filter performance in air conditioning systems. The specific objectives are:

i. To design and develop a smart sensor-based monitoring system for real-time assessment of air filter efficiency in air conditioning units.
ii. To integrate and optimize advanced sensor technologies for accurate detection of air quality parameters affecting air filter performance.
iii. To evaluate and validate the effectiveness of the proposed monitoring system in enhancing filtration efficiency, optimizing energy consumption, and improving indoor air quality

2. Literature Review

Air conditioning systems play a crucial role in providing thermal comfort and ensuring indoor air quality (IAQ) across various sectors, including residential, industrial, hospitality, and tourism [12,13]. Modern AC units, such as window units, split systems, and centralized HVAC systems, work by regulating temperature, humidity, and ventilation through key components like compressors, condensers, expansion valves, and evaporators. Proper maintenance, including frequent cleaning of condenser and evaporator coils using specialized chemicals, is essential to sustain system efficiency and cooling performance [10].

In addition to thermal comfort, IAQ has become a global concern as indoor air pollution significantly impacts human health, productivity, and overall well-being. Poor IAQ can lead to respiratory issues and reduced work efficiency, particularly in enclosed spaces such as workshops and learning environments [14]. Sustainable building concepts, emphasizing energy conservation, air quality monitoring, and resource management, play a vital role in reducing human exposure to pollutants and ensuring healthier indoor environments [15].

Countries like the United States, Germany, and the Netherlands have implemented advanced air quality monitoring systems due to increasing urban pollution, while Malaysia has developed the Malaysia Air Quality Index (MAQI) to assess and manage air pollution levels [40]. The Department of Occupational Safety and Health (DOSH) in Malaysia recommends maintaining indoor temperatures between 23°C to 26°C and humidity levels between 40% to 70% for optimal comfort.

Given that people spend up to 90% of their time indoors, ensuring good IAQ is critical to preventing health risks associated with air pollution, such as cardiovascular diseases, strokes, and lung cancer [15]. Acid rain, caused by airborne pollutants, further exacerbates environmental degradation, affecting ecosystems, agriculture, and soil composition [16].

To mitigate these issues, Malaysia has aligned its air quality standards with global benchmarks by incorporating fine particulate matter (PM) into its monitoring system since April 2014 [17]. Real-time air pollution monitoring enables authorities to implement mitigation strategies and emergency measures, ensuring safer and healthier indoor and outdoor environments for all.

2.1 The Role of Air Conditioning in Indoor Air Quality

Air conditioning not only provides cooling but also plays a crucial role in maintaining indoor air quality (IAQ). Inconsistent indoor temperatures can affect occupants' productivity and overall work performance. To enhance thermal comfort, research has explored the implementation of active air dampers in centralized air-conditioning systems, which help regulate airflow distribution and maintain optimal temperature levels [18]. Proper ventilation and air filtration systems are essential to remove pollutants, allergens, and airborne contaminants, ensuring a healthier indoor environment [19]. Computational Fluid Dynamics (CFD) simulations indicate that iris dampers can help maintain an acceptable temperature range of 22°C to 24°C, contributing to improved IAQ and comfort [18]. However, inefficient air filters or a lack of maintenance can result in poor IAQ, leading to respiratory illnesses and allergic reactions [20].

IAQ is influenced by various factors, including air temperature, humidity levels, carbon dioxide (CO_2) concentration, airflow rate, and static pressure [20]. To optimize HVAC system performance, smart air quality monitoring systems have been integrated with HVAC units to enhance filtration efficiency and reduce energy consumption. Single and multiple-objective optimization algorithms are being employed to minimize overall building energy usage while maintaining acceptable thermal comfort levels [20]. Additionally, advanced sensor technologies, such as Internet of Things (IoT)-enabled sensors, are being deployed in modern HVAC systems to track real-time air quality parameters and automatically adjust filtration mechanisms [21].

One of the challenges in IAQ management is maintaining appropriate humidity levels, as low humidity can negatively affect human skin and nasal passages. Installing ultrasonic humidifiers in air-conditioning systems has been suggested as a solution to replenish lost humidity and improve comfort [22]. High concentrations of indoor air pollutants, such as particulate matter and carbon dioxide, along with temperature and humidity imbalances, can create unpleasant odors, dusty air, and respiratory issues [23]. To address these concerns, an IAQ alert system has been developed using sensors integrated with a Raspberry Pi controller and wireless communication devices, such as the ESP-32, to monitor and manage air quality in real-time [23]. These innovations align with global sustainability efforts to improve energy efficiency and reduce the environmental impact of HVAC systems.

2.2 Environmental Impact of Air Pollution and HVAC Systems

Air pollution contributes significantly to climate change and environmental degradation, with industrial emissions and vehicular traffic being the primary sources [24]. Poor indoor air quality (IAQ) has been linked to various health issues, including headaches, fatigue, respiratory illnesses, and cardiovascular diseases. Building design plays a crucial role in ensuring a healthy and comfortable indoor environment by reducing exposure to airborne contaminants [25]. However, if not maintained properly, HVAC systems can worsen air pollution by recirculating pollutants and increasing energy consumption. Research suggests that maintaining clean HVAC ducts can contribute to future advancements in health risk assessments, enabling the development of user-friendly tools for IAQ monitoring [25].

Studies indicate that poor HVAC maintenance results in higher carbon emissions, exacerbating global warming [26]. To mitigate this issue, regular maintenance of ducting systems is essential, as airborne particles such as dust, pollen, and mold can accumulate on the inner surfaces, significantly affecting IAQ levels [25]. Furthermore, the adoption of high-efficiency particulate air (HEPA) filters and electrostatic air purification systems has been proposed to mitigate indoor air pollution [27].

These advanced filtration technologies enhance air quality by capturing ultrafine particles and allergens that conventional filters fail to remove [27]. Airborne contaminants, including bacteria, viruses, gases, and chemicals, can become airborne, leading to infectious diseases, allergies, and respiratory irritations among occupants [25].

Malaysia has implemented various air quality monitoring initiatives, including the Air Pollutant Index (API) system, which provides real-time pollution levels nationwide [28]. The inclusion of fine particulate matter (PM2.5) in API calculations has improved pollution assessment accuracy, aiding in more effective environmental policy-making [29]. Additionally, the Malaysian government has promoted green building initiatives and energy-efficient HVAC systems as part of its sustainable development goals. The reliability and stability of HVAC systems are crucial, as even minor malfunctions can lead to significant consequences such as energy wastage and thermal discomfort [30]. Regulations such as the Energy Efficiency and Conservation Act (EECA) further reinforce energy conservation by implementing stringent air quality standards in commercial and residential buildings [31].

This study underscores the importance of air conditioning systems in maintaining IAQ and the necessity of efficient air filtration technologies. The integration of IoT-based air quality monitoring in HVAC systems can enhance filtration performance, reduce energy consumption, and minimize environmental impact. Future research should explore AI-driven air filtration systems to optimize HVAC efficiency and sustainability. Additionally, the development of Arduino-based multichannel temperature and humidity data acquisition systems for industrial applications provides a cost-effective solution for real-time environmental monitoring. This system, equipped with multiple sensors, logs temperature and humidity readings every thirty minutes onto an SD card, demonstrating flexibility and ease of reproduction for various industrial applications [32].

3. Methodology

3.1 System Development

The development of this study consists of software, hardware, and sensor integration. The Arduino Uno microcontroller is utilized, as illustrated in Figure 1.

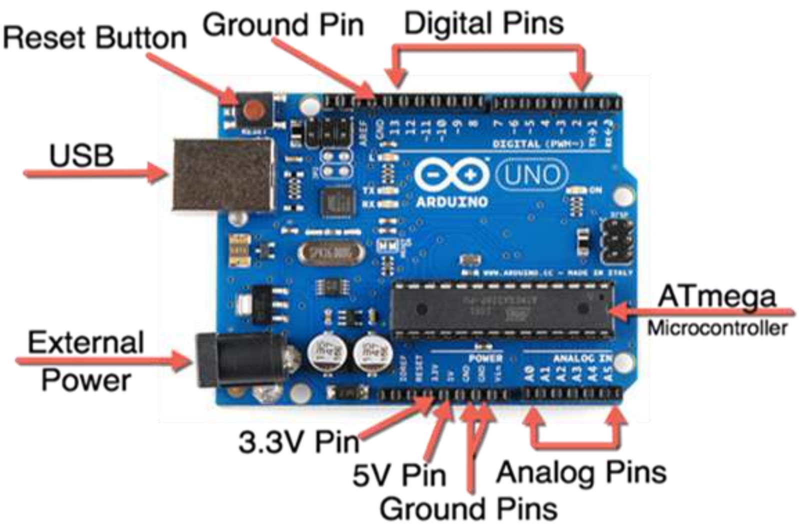

Fig. 1. Arduino Uno microcontroller

To interface all sensors onto a single board and facilitate programming. The Arduino software is employed to design and upload the program onto a laptop, as depicted in Figure 2.

The sensor system comprises temperature, humidity, airflow, and dust sensors, each strategically installed at specific points within the air conditioning system. The DHT11 sensor is utilized for temperature and humidity measurements, positioned at the air supply point as well as before and after the air filter to detect fluctuations in temperature and humidity levels. Airflow monitoring is conducted using a 5V DC motor-based sensor, which assesses ventilation efficiency and identifies potential obstructions resulting from filter clogging.

3.2 Installation and Setup

The installation process starts with assembling the hardware components, followed by integrating the sensors into the system. The primary sensors used include:

i. DHT11 (temperature and humidity sensor)
ii. Airflow sensor (DC motor-based)
iii. Dust particle sensor

As illustrated in Figure 2, proper connections between hardware components are crucial for seamless data transmission. Each sensor is interfaced with the Arduino Uno board using predefined pin assignments to ensure compatibility with the system architecture. Accurate wiring and calibration are essential to guarantee precise real-time air quality monitoring.

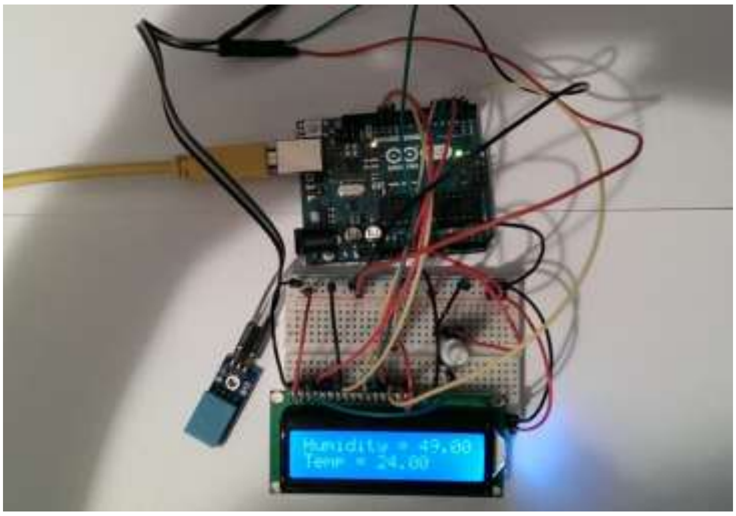

Fig. 2. Hardware and system connectivity

3.3 Program Sketching and Implementation

The program development phase involves writing and uploading C++-based scripts to the Arduino board via a USB interface. Once programmed, the system continuously reads sensor inputs and transmits real-time data to an LCD display or a laptop monitoring interface.

During this phase, sensor functions, operational logic, and pin configurations are defined to ensure seamless data acquisition and processing. The Arduino IDE facilitates this process by providing pre-configured libraries for essential sensor operations, simplifying code implementation. Figure 3 presents a sample Arduino script for sensor integration and data processing.

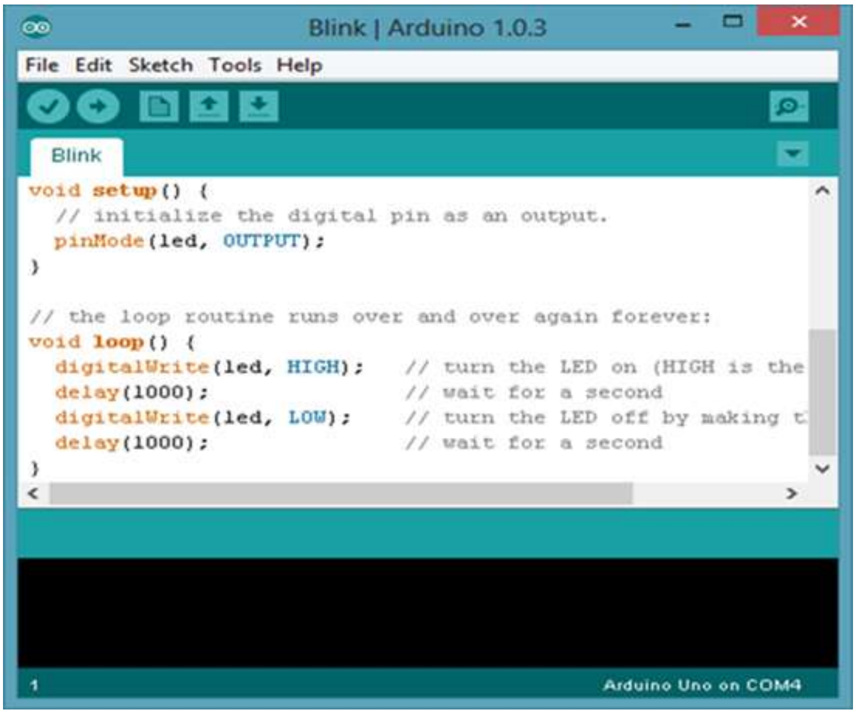

Fig. 3. Example of an Arduino code for sensor integration

3.4 Design and Layout of Air Filter Position in Experimentation

A detailed design layout is developed to illustrate the positioning of the air filter within the experimental setup. This schematic representation serves as a guide for fabrication, analysis, and calibration, ensuring that each component is accurately placed for optimal performance.

The prototype setup incorporates essential airflow components, including:

i. Air supply inlet
ii. Air filter module
iii. Dampers
iv. Air ducts

By adhering to a structured design blueprint, the experimental model maintains precision in sensor placement and enhances data collection accuracy. Figure 4 depicts the schematic representation of the air filter system during the experimentation phase.

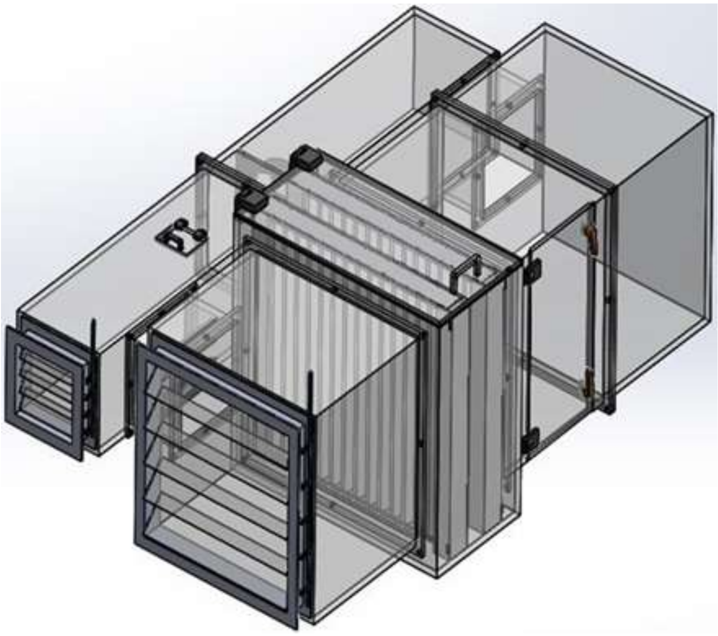

Fig. 4. Schematic design of air filter placement in the experiment

4. Results and Discussion

Figure 5 show that clogged filters were found to reduce airflow by up to 50%, which in turn increased energy consumption by 15–30% [10]. Airflow monitoring was conducted using a 5V DC motor-based sensor to assess ventilation efficiency and identify potential obstructions resulting from filter clogging. When air filters become clogged, airflow is restricted, causing the HVAC system to work harder.

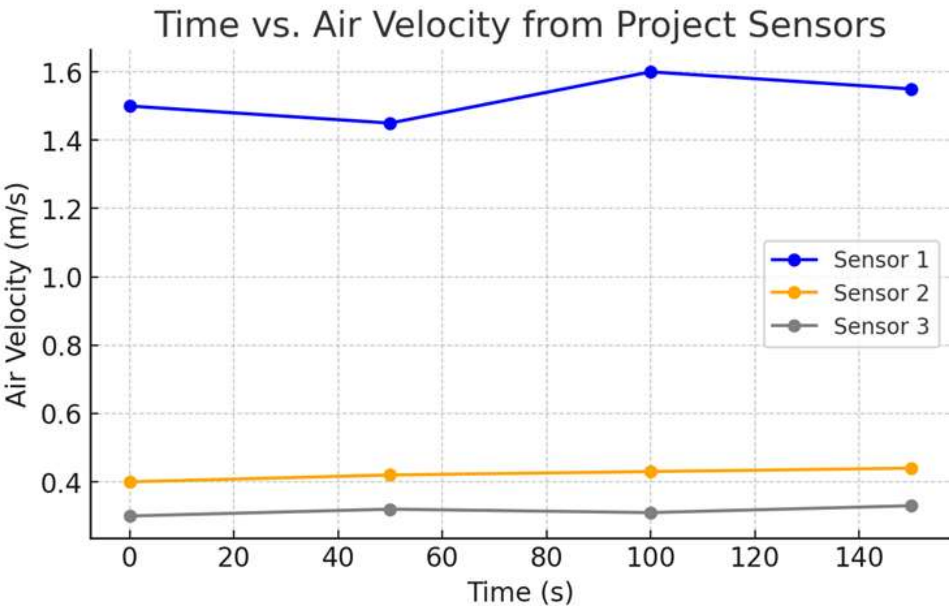

Fig. 5. Air velocity data from the experiment

Figures 6 and 7 show that data collected from the sensors indicate that airborne dust density reaches up to 0.65 µg/m³, beyond which the sensors are unable to detect higher concentrations. Sensor 1, placed before the filter, records a higher dust concentration as it measures unfiltered air, whereas Sensor 2, positioned after the filter, registers significantly lower values. This difference in readings highlights the efficiency of the air filter in capturing airborne contaminants and reducing particulate pollution in air-conditioned environments.

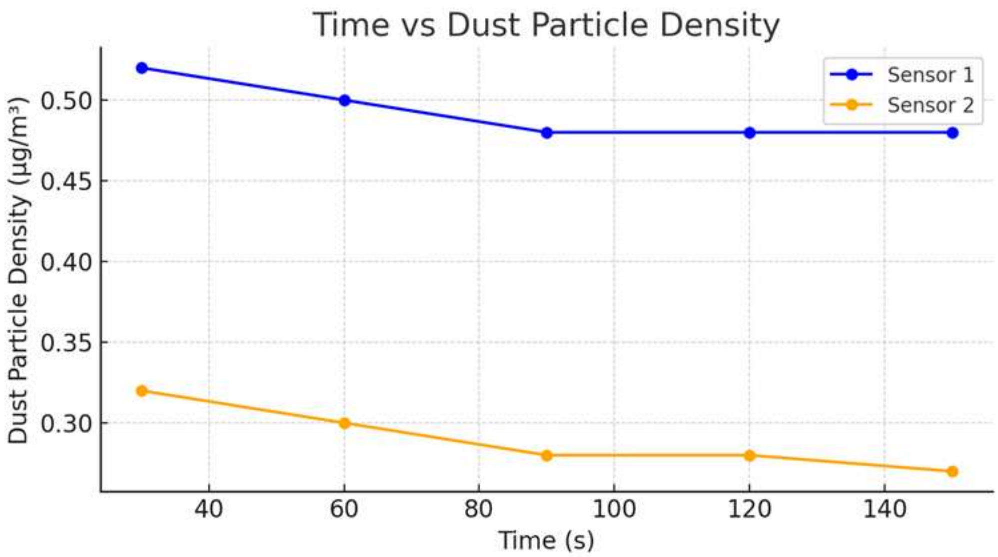

Fig. 6. Dust density using a particle dust sensor

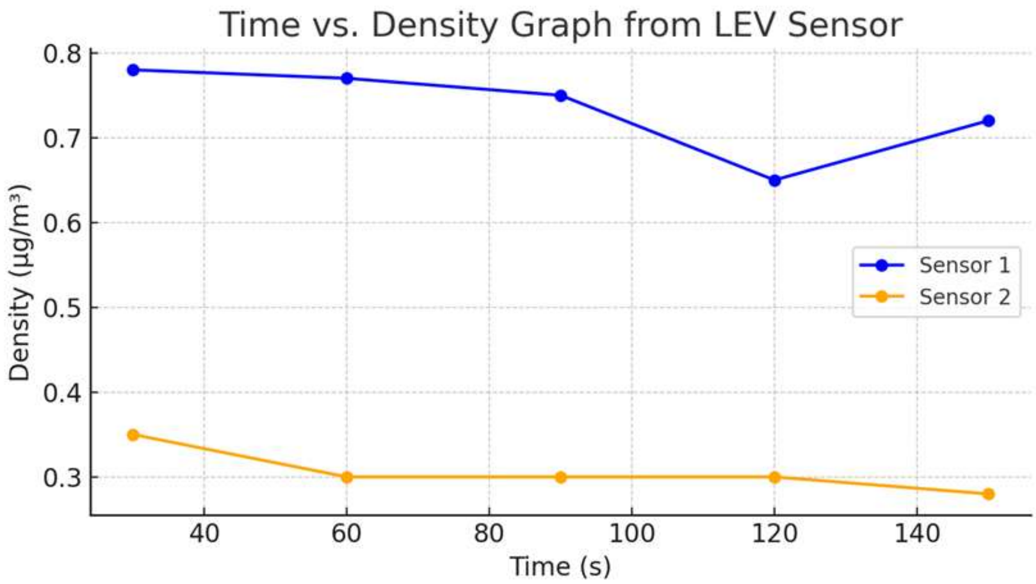

Fig. 7. Dust density data using LEV sensor

Air filters play a crucial role in Heating, Ventilation, and Air Conditioning (HVAC) systems by trapping airborne particles such as dust, allergens, bacteria, and pollutants before they circulate indoors. Airborne contaminants refer to any particles or substances present in the air we breathe. These contaminants include dust, pollen, bacteria, viruses, gases, and chemicals [25]. Elevated indoor humidity levels and mold growth have been attributed to issues related to ventilation, design, and the improper operation and maintenance of HVAC systems [33].

Inadequate maintenance and ineffective filtration in HVAC systems can lead to increased indoor pollution, higher energy consumption, and reduced system efficiency. This research indicates that replacing a MERV 8 filter with a MERV 13/14 filter can increase energy consumption by 11%–18%

due to higher pressure drop, while improving clean-air-delivery-rate [34]. Assesses the energy performance and CO2 emissions of HVAC systems in commercial buildings, highlighting opportunities for improvement through efficient design and operation [35].

Recent advancements in sensor-based air monitoring technologies have enabled real-time assessment of airborne particle concentration and filter efficiency. Sensors capable of detecting particulate matter (PM2.5 and PM10) are now integrated into smart air filtration systems, allowing users to monitor indoor air pollution levels and optimize HVAC performance.

This study strategically placed two sensors within the air conditioning system to monitor air filtration effectiveness. Sensor 1 (pre-filter position) measures incoming, unfiltered air to determine the initial dust concentration, while Sensor 2 (post-filter position) measures air after passing through the filtration system. The results show that Sensor 1 consistently recorded higher dust levels, whereas Sensor 2 registered significantly lower values, confirming that the air filter effectively removes airborne contaminants before air is circulated indoors.

Inefficient air filters not only compromise indoor air quality but also lead to higher energy consumption and environmental degradation. When an air filter becomes clogged with dust and debris, airflow is restricted, causing the HVAC system to work harder to compensate for reduced air circulation. This results in:

i. Higher energy usage, increasing electricity bills by up to 20–30%.
ii. Reduced cooling efficiency, leading to longer operation cycles and excessive wear on HVAC components.
iii. Increased carbon footprint, as higher energy consumption contributes to greenhouse gas (GHG) emissions.

Sustainable HVAC practices now emphasize the use of high-efficiency particulate air (HEPA) filters, electrostatic filters, and AI-driven monitoring systems to enhance filtration performance while minimizing energy waste. The performance measure is the criterion that measures the agent's success, the environment dictates the restrictive factors an agent may encounter in its operating space, and the actuators and the sensors work together continuously, as sensors process information and relay information to the actuator to carry out the physical changes in the environment. For example, in building environments, thermostats and HVAC systems are traditionally interlinked to accomplish the same goal. While thermostats only function to detect changes in temperature HVAC systems primarily provide heating and cooling, but despite their different immediate primary functions, both are geared at maintaining comfortable indoor temperature [36].

Given the increasing concerns over airborne pollution, energy efficiency, and environmental sustainability, this study highlights the importance of integrating sensor-based air filtration monitoring in HVAC systems. The data collected through these sensors provide valuable insights into air quality trends, filter degradation rates, and system performance, enabling predictive maintenance where smart HVAC systems alert users when a filter replacement is required. This reduces unexpected failures and maintenance costs while enhancing air quality control by continuously monitoring particulate matter levels.

The integration of behavioral science insights substantially enriches our understanding of how occupants respond to air quality changes. The bidirectional relationship between air quality and behavior demonstrates that any comprehensive approach to indoor air quality management must consider occupant behaviors as both contributors to and mitigators of pollution exposure. The psychological effects of air pollution extend beyond direct health impacts to influence fundamental aspects of human behavior, including arousal needs and consumer choices. These findings open up new considerations for public health messaging and commercial strategies during pollution events, especially in indoor environments managed by HVAC systems.

Future research should explore how the air pollution-induced need for arousal affects other stimulus-seeking behaviors beyond consumer choices [37]. Additionally, more work is needed on the differential impacts of air quality on diverse populations, given the observed gender differences in SBS (Sick Building Syndrome) susceptibility [38]. Finally, the development of novel materials for sensors, IAQ-monitoring systems, and smart homes represents a promising strategy for the control and enhancement of indoor air quality in the future [39]. By incorporating behavioral science perspectives into air quality research and management, we can develop more effective interventions that account for the complex ways humans interact with their environment, ultimately improving health outcomes and building performance in an increasingly pollution-challenged world.

5. Conclusion

This study successfully establishes the importance of an automated air filter performance monitoring system within air conditioning (AC) systems, ensuring improved indoor air quality and enhanced system efficiency. The implementation of sensor-based real-time monitoring has proven to be an effective approach in detecting air quality changes, optimizing airflow regulation, and reducing overall energy consumption. By integrating advanced monitoring technologies, HVAC systems can operate more efficiently, leading to significant electricity savings and prolonged equipment lifespan.

One of the primary findings of this research is the direct relationship between air filter efficiency and overall HVAC system performance. When air filters become clogged with dust and pollutants, airflow resistance increases, forcing the system to work harder to maintain the desired indoor climate. This not only results in higher operational costs but also increased carbon emissions due to excessive energy consumption. By deploying an automated filter performance monitoring system, maintenance scheduling can be optimized, preventing unnecessary servicing while ensuring timely filter replacements based on real-time data analysis.

Moreover, this study emphasizes the crucial role of air filtration in protecting human health. Exposure to airborne pollutants such as fine particulate matter (PM2.5) and volatile organic compounds (VOCs) has been linked to various respiratory diseases, cardiovascular conditions, and decreased cognitive function. An efficient air filtration system reduces the presence of these harmful particles, improving overall air quality and promoting better health outcomes for building occupants. The integration of high-performance filters combined with real-time monitoring technology ensures that indoor air remains clean and free from harmful contaminants.

From an environmental sustainability perspective, the implementation of smart air filtration monitoring systems contributes to global energy conservation efforts by minimizing electricity waste and reducing greenhouse gas emissions. Improving HVAC efficiency through advanced air filtration technology can significantly lower energy consumption in commercial buildings. Furthermore, adopting smart air quality monitoring aligns with international environmental policies advocating for sustainable energy practices and reduced carbon footprints in building operations.

In conclusion, integrating sensor-based air filter monitoring in HVAC systems is a critical advancement in ensuring optimal air quality, energy efficiency, and environmental sustainability. As technology evolves, future innovations in smart filtration systems will continue to enhance HVAC performance, reduce maintenance costs, and contribute to global sustainability initiatives.

Acknowledgement
This research was not funded by any grant. The author would like to express his gratitude to the parties involved directly and indirectly in the compilation of this article.

References

[1] Manisalidis, Ioannis, Elisavet Stavropoulou, Agathangelos Stavropoulos, and Eugenia Bezirtzoglou. "Environmental and health impacts of air pollution: a review." *Frontiers in public health* 8 (2020): 14. https://doi.org/10.3389/fpubh.2020.00014
[2] Jia, Lizhi, Jufeng Ge, Zhiqiang Wang, Wufeng Jin, Congcong Wang, Zhanwei Dong, Cheng Wang, and Ren Wang. "Synergistic Impact on Indoor Air Quality: The Combined Use of Air Conditioners, Air Purifiers, and Fresh Air Systems." *Buildings* 14, no. 6 (2024): 1562. https://doi.org/10.3390/buildings14061562
[3] Elsaid, Ashraf Mimi, and M. Salem Ahmed. "Indoor air quality strategies for air-conditioning and ventilation systems with the spread of the global coronavirus (COVID-19) epidemic: Improvements and recommendations." *Environmental Research* 199 (2021): 111314. https://doi.org/10.1016/j.envres.2021.111314
[4] Baharudin, Fauzi, Nur Fatt-Hiyyah Mohd Adlan, Jalina Kassim, Nurhidayah Hamzah, and Suriati Ghazali. "Effect of heating, ventilation, and air conditioning (hvac) system on indoor air quality in a medical facility." *Journal of Sustainable Civil Engineering & Technology (JSCET)* 2, no. 2 (2023): 80-90. https://doi.org/10.24191/jscet.v2i2.80-90
[5] Olatunde, Tosin Michael, Azubuike Chukwudi Okwandu, Dorcas Oluwajuwonlo Akande, and Zamathula Queen Sikhakhane. "Review of energy-efficient HVAC technologies for sustainable buildings." *International Journal of Science and Technology Research Archive* 6, no. 02 (2024): 012-020. https://doi.org/10.53771/ijstra.2024.6.2.0039
[6] Ebirim, Wisdom, Favour Oluwadamilare Usman, Danny Jose Portillo Montero, Nwakamma Ninduwezuor-Ehiobu, Emmanuel Chigozie Ani, and Kehinde Andrew Olu-lawal. "Assessing the impact of climate change on HVAC system design and project management." *International Journal of Applied Research in Social Sciences* 6, no. 3 (2024): 173-184. https://doi.org/10.51594/ijarss.v6i3.848
[7] Mistry, Vrushank. "Environmental Impact of HVAC Systems and Mitigation through Automation." *International Journal of Science and Research (IJSR)* 9, no. 11 (2020): 1701-1706. https://doi.org/10.21275/SR24203204710
[8] Mistry, Vrushank. "Energy Efficiency in HVAC Systems through Building Automation." *Journal of Biosensors and Bioelectronics Research* 1, no. 1 (2023): 1-4. https://doi.org/10.47363/JBBER/2023(1)113
[9] Pan, Yonghao. "Review of energy saving technologies research in HVAC systems." In *E3S Web of Conferences*, vol. 438, p. 01006. EDP Sciences, 2023. https://doi.org/10.1051/e3sconf/202343801006
[10] Nor, Muhamad Asrul Affendi Mat, Farah Waheda Othman, Irdayanti Mat Nashir, and Sudiyatno Sudiyatno. "Air Conditioning System Maintenance Automation with Smart Sensors for Energy Efficiency." *Future Energy and Environment Letters* 1, no. 1 (2024): 36-47. https://doi.org/10.37934/feel.1.1.3647
[11] United Nations Environment Programme. "Kigali Cooling Efficiency Programme." *OzonAction*, 2018.
[12] Oh, Sukjoon, and Suwon Song. "Detailed analysis of thermal comfort and indoor air quality using real-time multiple environmental monitoring data for a childcare center." *Energies* 14, no. 3 (2021): 643. https://doi.org/10.3390/en14030643
[13] Lin-Rui, Jia, Jie Han, Xi Chen, Li Qing-Yun, Lee Chi-Chung, and Yat-Hei Fung. "Interaction between Thermal Comfort, Indoor Air Quality and Ventilation Energy Consumption of Educational Buildings: A Comprehensive Review." *Buildings* 11, no. 12 (2021): 591. https://doi.org/10.3390/buildings11120591
[14] Wei, Tiew Soo, Muhammad Hafeez Abdul Nasir, Ahmad Sanusi Hassan, Hazril Sherney Basher, Mohd Nasrun Mohd Nawi, and Tajudeen Dele Mustapha. "The Influence of Window-To-Wall Ratio (WWR) on Airflow Profile for Improved Indoor Air Quality (IAQ) in a Naturally-Ventilated Workshop in a Hot-Humid Climate." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 116, no. 1 (2024): 139-157. https://doi.org/10.37934/arfmts.116.1.139157
[15] Cincinelli, Alessandra, and Tania Martellini. "Indoor air quality and health." *International journal of environmental research and public health* 14, no. 11 (2017): 1286. https://doi.org/10.3390/ijerph14111286
[16] Tran, Vinh Van, Duckshin Park, and Young-Chul Lee. "Indoor air pollution, related human diseases, and recent trends in the control and improvement of indoor air quality." *International journal of environmental research and public health* 17, no. 8 (2020): 2927. https://doi.org/10.3390/ijerph17082927
[17] Greenpeace Malaysia. "The Health and Economic Impacts of Ambient Air Quality in Malaysia." *Greenpeace Malaysia*, November 6, 2024.
[18] Busu, Nur'Amirah, Norasikin Mat Isa, Azian Hariri, and Mohamed Hussein. "Air Damper Effect on Temperature and Airflow Distribution in Enhancing Thermal Comfort Performance." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 100, no. 1 (2022): 152-164. https://doi.org/10.37934/arfmts.100.1.152164

[19] Azizan, Nurul Alia, Ahmad Syibli Othman, Asheila AK Meramat, Siti Noor Syuhada Muhammad Amin, and Azman Azid. "A framework to spatially cluster air quality monitoring stations in Peninsular Malaysia using the hybrid clustering method." *Malaysian Journal of Fundamental and Applied Sciences* 19, no. 5 (2023): 804-816. https://doi.org/10.11113/mjfas.v19n5.2620
[20] Revichandran, Rajeanderan, Jaffar Syed Mohamed Ali, Moumen Idres, and A. K. M. Mohiuddin. "A review of HVAC system optimization and its effects on saving total energy utilization of a building." *J Adv Res Fluid Mech Therm Sci* 93 (2022): 64-82. https://doi.org/10.37934/arfmts.93.1.6482
[21] Blinova, Tatiana, Sanjay Singh Chauhan, Tara Singla, Shweta Bansal, Apeksha Mittal, and V. Sahithi Yellanki. "Performance Evaluation of IoT Sensors in Urban Air Quality Monitoring: Insights from the IoT Sensor Performance Test." In *BIO Web of Conferences*, vol. 86, p. 01088. EDP Sciences, 2024. https://doi.org/10.37934/arfmts.93.1.6482
[22] Balthazar, Pravinth, Mohd Azmi Ismail, A. S. B. A. Soberi, Muhammad Iftishah Ramdan, and Hussin Mamat. "Experimental study of the effect of piccolo tube pipe on the air-conditioning experimental rig." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 53, no. 1 (2019): 95-105.
[23] Jethi, Permesh Lal, Fan Hau Pin, and Eriki Ananda Kumar. "Engineering Laboratory IAQ Monitoring: A Real-Time Solution using Raspberry PI and Grafana Dashboard." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 124, no. 2 (2024): 53-70. https://doi.org/10.37934/arfmts.124.2.5370
[24] Stanisci, Ilaria, Giuseppe Sarno, Olivia Curzio, Sara Maio, Anna Antonietta Angino, Patrizia Silvi, Liliana Cori, Giovanni Viegi, and Sandra Baldacci. "Air Pollution and Climate Change: A Pilot Study to Investigate Citizens' Perception." *Environments* 11, no. 9 (2024): 190. https://doi.org/10.3390/environments11090190
[25] Rosli, Mohd Arif, Muhamad Shahril Mohd Abdullah, Azian Hariri, Amir Abdullah Muhamad Damanhuri, Berkah Fajar Tamtama, and Nor Mohd Razif Noraini. "Comprehensive Review on the Relationship Between Duct Cleanliness and Airborne Contaminants." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 115, no. 2 (2024): 61-69. https://doi.org/10.37934/arfmts.115.2.6169
[26] Saengsikhiao, Piyanut, Juntakan Taweekun, and Chayapat Prapaipornlert. "The Improvement of Energy Efficiency in Refrigeration Systems Using Ultrasonic Sensors." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 119, no. 1 (2024): 189-195. https://doi.org/10.37934/arfmts.119.1.189195
[27] Chen, Chiu-Fan, Chun-Hsiang Hsu, Yu-Jung Chang, Chao-Hsien Lee, and David Lin Lee. "Efficacy of HEPA air cleaner on improving indoor particulate matter 2.5 concentration." *International Journal of Environmental Research and Public Health* 19, no. 18 (2022): 11517. https://doi.org/10.3390/ijerph191811517
[28] Awang, Muhamad Bin, Abu Bakar Jaafar, Ahmad Makmom Abdullah, Marzuki Bin Ismail, Mohd Nasir Hassan, Ramdzani Abdullah, Shamsuddin Johan, and Hamdan Noor. "Air quality in Malaysia: impacts, management issues and future challenges." *Respirology* 5, no. 2 (2000): 183-196. https://doi.org/10.1046/j.1440-1843.2000.00248.x
[29] Abdullah, Samsuri, Amalina Abu Mansor, Nur Nazmi Liyana Mohd Napi, Wan Nurdiyana Wan Mansor, Ali Najah Ahmed, Marzuki Ismail, and Zamzam Tuah Ahmad Ramly. "Air quality status during 2020 Malaysia Movement Control Order (MCO) due to 2019 novel coronavirus (2019-nCoV) pandemic." *Science of the Total Environment* 729 (2020): 139022. https://doi.org/10.1016/j.scitotenv.2020.139022
[30] Elsaid, Ashraf Mimi, Hany A. Mohamed, Gamal B. Abdelaziz, and M. Salem Ahmed. "A critical review of heating, ventilation, and air conditioning (HVAC) systems within the context of a global SARS-CoV-2 epidemic." *Process Safety and Environmental Protection* 155 (2021): 230-261. https://doi.org/10.1016/j.psep.2021.09.021
[31] Ghazali, Farahdilah, and Wan Mohd Zahari. "Energy efficiency management towards sustainable development: The need for an energy efficiency legal framework." *IIUMLJ* 31 (2023): 179. https://doi.org/10.31436/iiumlj.v31i2.829
[32] Komolafe, Clement Adekunle, Acheampong Antwi Afari, Sullaiman Alhasan, and Ebenezer Adu Kyeremeh. "Development of an Arduino-Based Multi-Channel Temperature and Relative Humidity Data Acquisition System for Domestic and Industrial Applications." Journal of Advanced Research in Fluid Mechanics and Thermal Sciences 114, no. 1 (2024):43-55. https://doi.org/10.37934/arfmts.114.1.4355
[33] Syazwan, MM Syafiq, Mohammad Zainal M. Yusof, C. K. Chang, and MD Amir Abdullah. "Monitoring of Selected Indoor Air Quality Parameters and Cooling Energy Usage in Hotel Restaurant Malaysia." *Applied Mechanics and Materials* 564 (2014): 250-255. https://doi.org/10.4028/www.scientific.net/AMM.564.250
[34] Faulkner, Cary A., John E. Castellini Jr, Wangda Zuo, David M. Lorenzetti, and Michael D. Sohn. "Investigation of HVAC operation strategies for office buildings during COVID-19 pandemic." *Building and Environment* 207 (2022): 108519. https://doi.org/10.1016/j.buildenv.2021.108519
[35] Al-Waked, Rafat, Mohammad Shakir Nasif, Nathan Groenhout, and Lester Partridge. "Energy performance and CO2 emissions of HVAC systems in commercial buildings." *Buildings* 7, no. 4 (2017): 84. https://doi.org/10.3390/buildings7040084
[36] Ghahramani, Ali, Parson Galicia, David Lehrer, Zubin Varghese, Zhe Wang, and Yogesh Pandit. "Artificial intelligence for efficient thermal comfort systems: Requirements, current applications and future directions." *Frontiers in built environment* 6 (2020): 49. https://doi.org/10.3389/fbuil.2020.00049

[37] Zhang, Han, Guanling Huang, Ping Lin, Xiuqi Chen, and Wenhe Lin. "Visual effect of air pollution on the need for arousal and variety-seeking behavior." *Frontiers in Psychology* 15 (2024): 1342267. https://doi.org/10.3389/fpsyg.2024.1342267

[38] Fahad Alomirah, Haya, and Haruna Musa Moda. "Assessment of indoor air quality and users perception of a renovated office building in manchester." *International journal of environmental research and public health* 17, no. 6 (2020): 1972. https://doi.org/10.3390/ijerph17061972

[39] Tran, Vinh Van, Duckshin Park, and Young-Chul Lee. "Indoor air pollution, related human diseases, and recent trends in the control and improvement of indoor air quality." *International journal of environmental research and public health* 17, no. 8 (2020): 2927. https://doi.org/10.3390/ijerph17082927

[40] Abas, Azlan, and Azahan Awang. "Penentuan tahap pencemaran udara di Malaysia menggunakan pendekatan penunjuk bio (Liken): Kajian kes Bandar Baru Bangi." *Geografia: Malaysian Journal of Society and Space* 11, no. 9 (2015): 67-74.