DESIGN AND DEVELOPMENT OF A LOW-COST IOT-BASED SMART AIR CLEANER FOR REAL-TIME INDOOR AIR QUALITY CONTROL

Vanessa Anastacia Bong[1], Lay Sheng Ewe[2*], Emadaddin Abdo Mohammed Alazzani[3], Sara Kit Yee Lee[4], Chee Fui Wong[5]

Abstract

Indoor air pollution presents considerable health concerns, including respiratory disorders and diminished overall well-being. Ensuring a healthy and comfortable indoor environment, therefore, necessitates continuous monitoring of key parameters such as air quality, temperature, and humidity. This study presents the design and development of a low-cost, portable IoT-based smart air cleaner for HVAC applications, aimed at enhancing indoor air quality through real-time monitoring and automated control. The proposed prototype incorporates a multistage filtration system comprising a True HEPA filter and an activated carbon filter to effectively remove particulate matter (PM2.5 and PM10), dust, and pollen. The system is powered by an Arduino UNO R4 WiFi microcontroller and integrates MQ135 and MQ2 gas sensors, a DHT11 temperature and humidity sensor, PIR motion sensors, and a two-channel relay module to automatically regulate a DC fan and UV-C LED light. Remote monitoring and system control are enabled via the Blynk mobile platform. The development process involved a comprehensive literature review, mechanical design using CREO, 3D printing, hardware integration, and embedded programming. Experimental results demonstrate accurate real-time measurements of PM2.5, PM10, AQI, temperature, and humidity, with a minimum percentage error of 0.76%. Future enhancements may include the adoption of higher-precision sensors, improved energy efficiency strategies, and integration with centralised HVAC systems for large-scale deployment. Overall, the proposed system provides a compact, automated, and cost-effective solution for improving indoor air quality, health, and occupant comfort in residential environments.

Received: *29 January, 2026*
Revised: *14 February, 2026*
Accepted: *16 March, 2026*

[1,2,3]College of Engineering, Institute of Sustainable Energy (ISE), Universiti Tenaga Nasional (UNITEN), Putrajaya Campus, Jalan IKRAM-UNITEN, 43000 Kajang, Selangor, Malaysia.

[1]Sarawak Energy Berhad, No. 1, The Isthmus, 93050 Kuching, Sarawak, Malaysia.

[4]Faculty of Engineering and Technology Tunku Abdul Rahman University of Management and Technology, Jalan Genting Kelang, Setapak, 53300 Kuala Lumpur, Malaysia.

[5]Lee Kong Chian Faculty of Engineering and Science, Sungai Long Campus, Jalan Sungai Long, Bandar Sungai Long, Cheras, 43000 Kajang, Selangor, Malaysia.

Corresponding author:
laysheng@uniten.edu.my

DOI: *https://doi.org/10.54552/v87i3.341*

Keywords:
Air quality index (AQI), PM2.5, PM10, Air cleaner, HVAC, Air pollution

List of Notations:

I_p	*is the index of pollutant*
I_{HI}	*is the AQI value corresponding to BP_{HI}*
I_{LO}	*is the AQI value corresponding to BP_{LO}*
BP_{HI}	*is the breakpoint that is greater than or equal to C_p*
BP_{LO}	*is the breakpoint that is less than or equal to C_p*
C_p	*is the rounded concentration of the pollutant*

1.0 INTRODUCTION

In recent years, air pollution has emerged as one of the most critical global challenges, demanding urgent attention from regulatory bodies such as the Department of Environment (DOE). Air pollution exerts severe adverse effects on human health, the environment, and economic stability. Prolonged exposure to polluted air has been linked to serious health conditions, including respiratory distress, asthma, cardiovascular diseases, and stroke. Furthermore, rapid technological and industrial development has intensified pollutant emissions, significantly degrading air quality and overall human well-being. According to data reported by the World Health Organisation (WHO), approximately 99% of the global population is exposed to air pollutant levels exceeding recommended limits, resulting in an estimated 4.2 million premature deaths annually, with 91% occurring in low- and middle-income countries (Chen *et al.,* 2022).

From an environmental perspective, air pollution contributes to the formation of acid rain containing elevated concentrations of nitric and sulfuric acids, which adversely affect ecosystems by damaging vegetation and causing acidification of soil and water bodies, thereby threatening aquatic life (Akimoto & Sato, 2022). Economically, the impacts of air pollution are often underestimated, despite its direct consequences on workforce productivity, increased absenteeism, premature mortality, and reduced agricultural output, all of which collectively impose substantial financial burdens on national economies (World Bank & IHME, 2016).

In response to deteriorating air quality, the adoption of air cleaners, commonly referred to as air purifiers (APs), has increased across residential, commercial, educational, and healthcare settings. Commercially available APs vary widely in size, design, and cost, depending on their specifications and performance capabilities. However, many existing air purifiers present maintenance challenges, particularly in relation to the removal and cleaning of High-Efficiency Particulate Air (HEPA) filters used to capture airborne contaminants such as dust, pollen, mould, bacteria, and viruses. Previous studies indicate that Portable Air Cleaners (PACs) offer a cost-effective alternative for improving indoor air filtration, especially in spaces where centralised systems are impractical (Liu *et al.,* 2021).

Conventional air cleaning systems typically employ a multi-stage filtration process, beginning with a coarse pre-filter, followed by a Rota-filter that captures fine dust particles through high-speed rotation, and concluding with a HEPA-type filter capable of removing up to 70% of particles sized 0.3 µm and 95% of particles sized 1.0 µm (Vijayan *et al.,* 2015). Nevertheless, accumulated particulate matter on clogged HEPA filters can restrict airflow and degrade overall system performance. To address this issue, the proposed air cleaner prototype is designed with a user-friendly, detachable filter mechanism that allows for convenient filter removal, cleaning, and maintenance.

Recent advancements in Internet of Things (IoT) technologies have further transformed environmental monitoring systems by enabling autonomous, real-time data acquisition and control through connected devices. IoT frameworks allow physical systems to interact seamlessly with cloud-based applications via Machine-to-Machine (M2M) communication, facilitating intelligent decision-making without continuous human intervention (Mouha, 2021). When applied to air cleaning systems, IoT enables dynamic adaptation to changing environmental conditions, thereby improving operational efficiency and responsiveness.

Motivated by these challenges and technological opportunities, this study presents the design and development of a low-cost, IoT-based smart air cleaner for HVAC applications, intended to enhance indoor air quality in enclosed environments such as bedrooms, offices, and classrooms. The proposed system aims to integrate an affordable filtration mechanism with HVAC compatibility, provide real-time monitoring of critical air quality parameters including PM2.5, CO_2, and volatile organic compounds (VOCs) using a multifunctional air quality sensing unit, and enable remote access and automated control through a mobile interface via the Blynk platform. Similar IoT-enabled indoor air quality monitoring systems have been explored in recent studies, including the work by Saini et al. (Saini *et al.,* 2020), highlighting the growing relevance of smart air purification solutions. Through the integration of sensing, automation, and connectivity, the proposed system seeks to deliver an efficient, accessible, and user-centric approach to improving indoor air quality and occupant comfort.

2.0 BACKGROUND STUDY

2.1 Literature Review

Indoor air quality (IAQ) has emerged as a critical public health and engineering concern due to rapid urbanisation, increased indoor occupancy, and heightened awareness of airborne disease transmission. Pollutants such as particulate matter (PM2.5 and PM10), volatile organic compounds (VOCs), carbon dioxide gas (CO_2), and bioaerosols have been strongly associated with respiratory, cardiovascular, and infectious diseases. In response, portable and smart air purification systems have gained prominence as flexible, cost-effective, and rapidly deployable solutions compared with centralised HVAC retrofitting.

This section presents a systematic review of prior research on air purification technologies, air quality indexing, sensor-driven control mechanisms, energy-efficient operation, and IoT-based intelligent monitoring frameworks. Emphasis is placed on experimental methodologies, system architecture, performance metrics, and reported outcomes, thereby establishing a strong theoretical and empirical foundation for the present research.

2.2 Air Quality Index (AQI) as Control and Evaluation Metric

The Air Quality Index (AQI) has been widely adopted as a standardised metric for translating complex pollutant concentrations into interpretable health-based categories. Datta *et al.* (2023) operationalised AQI as a real-time control variable, wherein sensor measurements update system indices every second, enabling rapid decision-making for purifier activation.

Their classification scheme, ranging from best (0–40) to hazardous (>200) aligns with established environmental health thresholds and demonstrates the practical role of AQI beyond passive monitoring. Importantly, the authors integrated AQI thresholds directly into system logic, such that purifier operation dynamically adapts to pollution severity. This functional coupling between AQI and actuator response represents a shift from descriptive to prescriptive air quality management.

Similarly, Kumar and Doss (2023) expanded AQI utility by embedding it within an IoT ecosystem, where locally computed AQI values are transmitted to cloud infrastructure for forecasting and visualisation. This approach positions AQI as both a real-time indicator and a predictive planning variable, reinforcing its relevance in smart city air management strategies.

2.3 Filtration Technologies and Physical System Design

2.3.1 Hepa-Based Multi-Stage Filtration

High-Efficiency Particulate Air (HEPA) filtration remains the cornerstone of modern air purification systems. Shukla *et al.* (2022) demonstrated that a multi-stage configuration combining pre-filters, activated carbon filters, and HEPA media achieved 99.99% removal efficiency for $PM_{2.5}$, validating the effectiveness of layered filtration architectures.

Lowther *et al.* (2020) provided further quantitative evidence through controlled chamber experiments, revealing that CADR scales positively with purifier size and fan speed, albeit at the expense of higher power consumption. Their findings underscore a critical design trade-off between purification performance and energy efficiency, particularly relevant for long-duration indoor deployment.

Dubey *et al.* (Dubey *et al.,* 2021), conducting real-world indoor evaluations, reported PM reductions ranging from 12% to 53%, with higher CADR models outperforming smaller units under polluted conditions. These results highlight the context-dependency of purifier performance and emphasise the importance of matching purifier capacity to room volume and pollution load.

2.3.2 Portable Purifiers in Large and Shared Spaces

The effectiveness of portable air purifiers in mitigating airborne transmission risks has been rigorously examined in public settings. Zhai *et al.* (2021) evaluated floor-standing and table top purifiers in restaurant environments, demonstrating that appropriately positioned units can significantly alter airflow patterns, drawing contaminated air toward filtration inlets.

Aldekheel *et al.* (2022) extended this investigation to university classrooms, showing that operating HEPA purifiers at high flow rates reduced particle residence time from 4–6 hours to under 40 minutes, effectively accelerating aerosol decay. These findings provide compelling evidence that portable purifiers can serve as viable engineering controls for infection mitigation when HVAC modifications are impractical.

2.4 Sensor-Driven Automation and Smart Control Mechanisms

Recent advances emphasise the integration of environmental sensors and adaptive control logic to enhance purifier responsiveness and efficiency. Datta *et al.* (2023) implemented continuous gas and particulate sensing, enabling second-by-second AQI updates and automatic system actuation.

Ukagwu *et al.* (2024) advanced this paradigm by incorporating microcontroller-based control systems that dynamically adjust fan speed based on real-time air quality measurements. Their design integrates particulate, gas, and humidity sensing with optional UV-C sterilisation, illustrating a comprehensive cyber-physical approach to indoor air management. Notably, Kocak and Bunyatova (2025) introduced occupancy-aware control, where motion sensors reduce energy consumption during periods of inactivity. Their system achieved approximately 30% energy savings without compromising filtration efficiency, highlighting the value of contextual awareness in smart purifier design.

2.5 Sterilisation Technologies and Microbial Inactivation

Beyond particulate removal, microbial sterilisation has become increasingly critical in the post-COVID-19 context. UV-C irradiation, titanium dioxide (TiO_2) photocatalysis, and hydrogen peroxide-assisted disinfection have been widely explored. Kocak and Bunyatova (2025) reported 99.99% microbial filtration efficiency, with an average log reduction of 4.11 within 60 minutes, achieved through UV-C and TiO_2-based sterilisation. These findings align with earlier observations by Shukla *et al.* (2022), who emphasised the synergistic role of filtration and sterilisation in comprehensive air purification systems.

However, while sterilisation technologies enhance pathogen control, their integration introduces additional considerations related to energy consumption, material degradation, and user safety, necessitating careful system-level optimisation.

2.6 IoT-Enabled Air Quality Monitoring and Predictive Analytics

The convergence of air purification with IoT and artificial intelligence has enabled a transition from reactive to predictive air quality management. Kumar and Doss (2023) developed an IoT-based AQI monitoring framework (AIRO) that leverages CNN-BiLSTM models to forecast pollution trends, offering users actionable insights via mobile applications.

This approach demonstrates how distributed sensor networks can democratise access to environmental data while supporting municipal-scale deployment. When integrated with smart purifiers, such systems hold potential for anticipatory control, where purification intensity is adjusted in advance of predicted pollution events.

2.7 Comparative Synthesis of Methodologies and Results

Across the reviewed studies, several methodological patterns emerge:

1. Experimental rigor ranges from controlled chamber studies (Lowther *et al.,* 2020) to real-world residential and public-space evaluations (Lu *et al.,* 2024), (Aldekheel *et al.,* 2022), (Dubey *et al.,* 2021).
2. Performance metrics consistently emphasise PM2.5 reduction, CADR, energy efficiency, and microbial inactivation rates.
3. System intelligence increasingly relies on sensor fusion, occupancy detection, and cloud-based analytics.

Collectively, these findings indicate that smart, adaptive, and energy-aware air purification systems outperform static designs, particularly in heterogeneous and dynamic indoor environments.

2.8 Research Gaps and Motivation for the Present Study

Despite significant progress, several gaps remain evident in the literature:

- Limited integration of AQI-driven logic with occupancy-aware energy optimisation in a unified framework.
- Insufficient longitudinal evaluation of smart purifiers under variable real-world pollution dynamics.
- Lack of standardised benchmarks linking AQI thresholds, purification response, and health-based outcomes.
- These limitations motivate the present research, which seeks to develop and evaluate a holistic smart air purification system that synergistically combines real-time AQI sensing, adaptive control, energy efficiency, and IoT-enabled intelligence.

The following session contemporary research on air purification technologies, AQI-based control, smart sensing, sterilisation mechanisms, and IoT integration. The reviewed evidence confirms the effectiveness of HEPA-based purification while highlighting the transformative role of intelligent control and predictive analytics. These insights directly inform the conceptual design and methodological choices of the present study, which are detailed in the subsequent chapter.

1. Health Risks from Poor Air Quality

The air cleaner addresses health and well-being concerns by employing a multi-stage filtration system capable of removing a wide range of airborne contaminants, including dust, pollen, carbon dioxide (CO_2), and fine particulate matter such as PM2.5 and PM10. It combines a True High Efficiency Particulate Air (HEPA) filter with an activated carbon layer, which effectively captures volatile organic compounds (VOCs) and unpleasant odours. To further enhance indoor air quality, the system integrates ultraviolet C (UV-C) light technology, which targets and eliminates airborne pathogens and bacteria. Additionally, the system is equipped with IoT-enabled smart sensors that monitor air pollutants in real time, including PM2.5, PM10, CO_2, and VOCs. Based on detected pollutant levels, the fan speed is automatically adjusted to maintain optimal air quality without requiring user intervention.

2. Dust, Pollen, and Indoor Allergens

To combat common household allergens, the air cleaner includes a washable pre-filter designed to trap larger particles such as dust, pet dander, and debris. This feature helps to extend the operational lifespan of the main HEPA filter by reducing its load, thereby maintaining airflow efficiency and protecting the internal components. The filtration system meets True HEPA standards, ensuring the capture of 99.97 per cent of particles sized 0.3 microns or larger, which includes most common allergens, thereby improving respiratory comfort and reducing allergy triggers.

3. Maintenance Challenges with Non-Cleanable HEPA Filters

Recognising the inconvenience of traditional, non-replaceable HEPA filters, the air cleaner uses a user-friendly cartridge system that allows for quick and hassle-free replacement. Each HEPA cartridge is equipped with a colour-changing sensor that provides a visual cue when replacement is needed, either due to saturation or damage. To encourage timely maintenance and minimise environmental waste, a filter subscription service is offered, ensuring users consistently maintain peak air cleaner performance without the hassle of sourcing new filters.

2.9 Problem Statement

Poor indoor air quality caused by airborne pollutants such as dust, pollen, VOCs, CO_2, PM2.5 and PM10 continues to pose significant health risks. Existing air purification systems often lack real-time monitoring, automatic pollutant-responsive operation, and multi-stage filtration capable of addressing both particulate and gaseous contaminants. Therefore, there is a need for a smart air quality parameter that automatically adjusts purification performance to maintain safe and healthy indoor environments.

Besides, indoor environments frequently accumulate allergens, which lead to worsening allergic symptoms, reduced air cleanliness and discomfort for users. Traditional air purifiers struggle to effectively trap both large and microscopic particles while maintaining airflow efficiency. As a result, there is a need for a smart, multi-stage air cleaning system capable of continuously detecting a filtration system that incorporates a pre-filter and True HEPA technology to ensure efficient removal of allergens and particulates while sustaining optimal airflow and prolonging filter lifespan.

In addition, many existing air purifiers rely on non-cleanable or difficult-to-replace HEPA filters, which have become one of the challenges for users in maintaining optimal device performance. Without clear indicators for filter damage, users neglect timely filter replacement, resulting in reduced purification efficiency and increased environmental waste. This highlights the need for a user-friendly filter cartridge system and accessible maintenance solutions to ensure consistent, efficient, and sustainable air cleaning performance.

3.0 METHODOLOGY

3.1 Overview Project Flow

Figure 1 presents the overall project workflow. The project began with a briefing by the coordinator to outline the development process. Students conducted preliminary research based on their proposed Final Year Project (FYP) titles to identify relevant studies and research gaps. A literature review was carried out concurrently to examine current technologies, designs, and related projects. The finalised project title was submitted to the supervisor via the Title Approval Form in Week 4; unapproved titles required further research and revision. In parallel with the literature review, a systematic survey of required materials and equipment was conducted from Week 2 to Week 11. A pricing survey using Shopee and Lazada was also performed to ensure the total cost remained within the university's RM 400 budget and to support effective budget control.

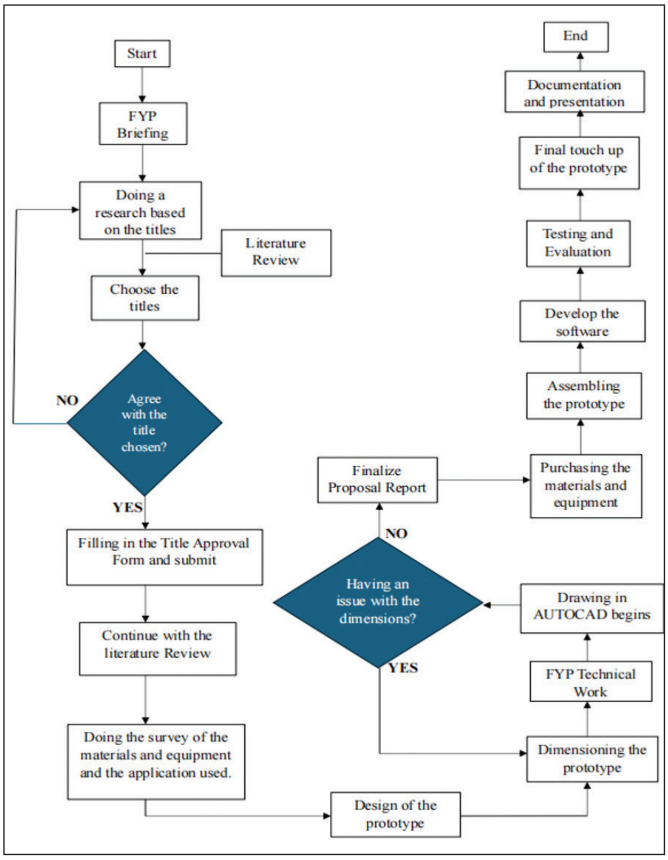


Figure 1: The overview project flow

Designing and dimensioning of the prototype were done, which will guide a drawing in CREO. The designation of the prototype was done by conducting a survey and observing some of the designs available on the market, and the reasons behind their designs, sizes, and specifications. After that, dimensioning of the prototype was done by doing a rough sketching and dimensioning of the prototype for different kinds of views, such as a 3D-view, as shown in Figure 2, and a 2D-view, which is the internal view of the prototype, as shown in Figure 3.

The Final Year Project (FYP) Technical Work was completed in accordance with university requirements and included key components such as the project introduction, prototype sketches, materials and equipment specifications, identification of research gaps, research objectives, detailed methodology, expected outcomes, and referenced literature. The Technical Work was completed with continuous guidance from the supervisor, particularly in areas such as citation methods, critical review of research articles, and clarification of expected outcomes. The completed Technical Work was submitted for assessment in Week 9. Based on the finalised design sketches and prototype dimensions, computer-aided design (CAD) modelling was performed using Creo for each internal component of the prototype. The complete assembly model is shown in the corresponding figure. Iterative redesign, re-sketching, and dimensional reanalysis were carried out throughout the modelling process to accommodate design modifications.

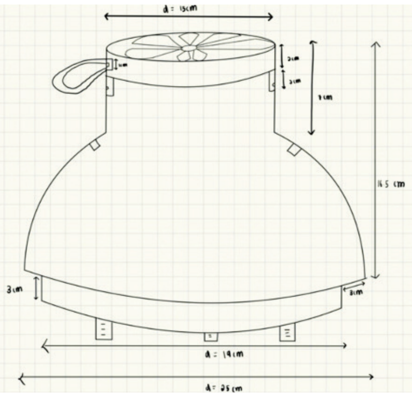


Figure 2: The 3D view of the prototype

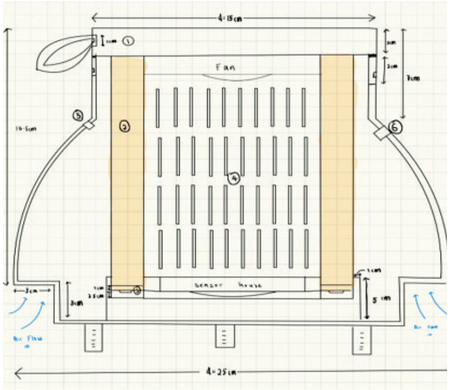


Figure 3: The internal view of the prototype

A project proposal report was prepared to provide an overview of the project, including the research gap, objectives, selected literature reviews, and a detailed list of required components and materials to ensure compliance with the allocated budget. The proposal also included a project flowchart to monitor both documentation progress and prototype development. Procurement of materials and equipment was conducted through the submission of the Material Purchase Form to the designated officer responsible for reimbursement. All purchase receipts were submitted upon receipt of the materials. Once all components were verified to be sufficient and in good condition, prototype assembly was initiated. The prototype enclosure and internal components were fabricated using 3D printing and assembled according to the finalised design specifications.

Software development was implemented using the Blynk platform to enable real-time monitoring of the Air Quality Index (AQI) and remote control of the Air Purifier (AP). System integration testing and performance evaluation were conducted to verify synchronisation between hardware and software, ensure functional reliability, and prevent component damage. Final refinements were performed to improve the prototype presentation. The project concluded with final documentation and presentation, supported by concise slides featuring clear diagrams, system flow, and technical explanations.

3.2 Designation and Dimensioning

The designation and dimensioning of the prototype began with a survey made by observing and identifying issues regarding the size and storage to place the AC. Based on the survey through observation of the AP available on the market, it is found that most of the shapes and designs available are huge and tall. The customers purchased their AP based on their choice and the requirement for the size of their house or office. Based on the research made by Iskandriawan *et al.* (2025), the airflow pattern surrounding an air purifier is greatly influenced by the product design of its constituent components, especially the blow air diffuser and the return air components. With that, the design of the AC is done precisely by comparing it with the AP available on the market.

Therefore, the invention of a small and portable AC is made to allow future users to store it even in a small storage area, and it can be brought everywhere with ease. In addition, a study has proven the effectiveness of a portable AC, where it is much quieter, less drafty, and more energy efficient (Ebrahimifakhar *et al.,* 2024). Hence, the way of designing the prototype was initiated by sketching, which includes the dimensions for each part of the prototype in detail. This includes the dimensioning of each of the small parts found on the prototype, as well as the internal components of the prototype. Figures (4 – 7) are rough sketches of each part of the components in the prototype.

3.3 Structure of the Prototype

The discussion of the structure of the prototype was made to identify what kind of materials were needed for the prototype. Through the discussion, an idea of inventing the prototype by using 3D printing for the body, top lid, filter vent, filter clip stand, and filter clip to fulfill the criteria of a portable AC and be easier to move by the user. For the 3D printing filaments, Polyethylene terephthalate Glycol (PETG) Pro type printing filaments are chosen. This is because during printing, as the temperature increases, the mechanical properties of PETG materials increase (Hsueh *et al.,* 2021).

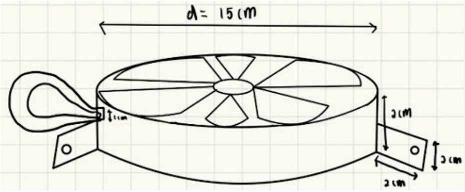


Figure 4: Sketching of the top lid

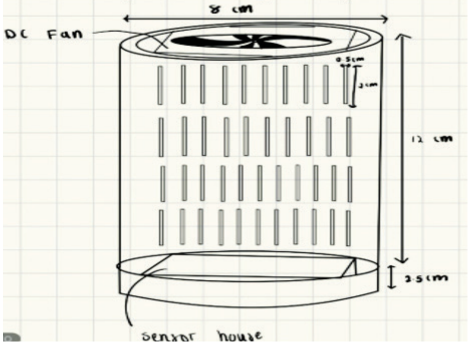


Figure 5: Sketching of the filter vent

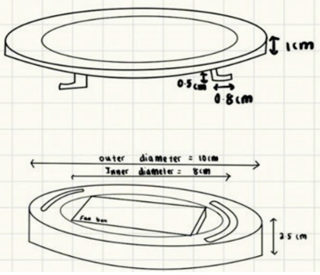


Figure 6: Sketching of the filter clip (top) and filter clip stand (bottom)

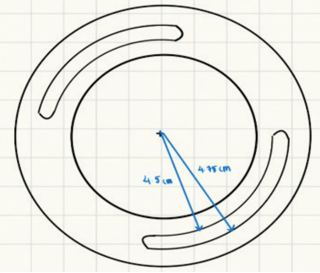


Figure 7: Sketching of the dimensions of the filter clip stand

Also, PETG Pro offers enhanced durability and impact strength, rendering it suitable for a wide array of applications (Marsavina *et al.,* 2024). Table 1 shows the list of materials and components used for the 3D printing process

Table 1: The details of the list of materials and components used and their functions

Materials and Components	Functions
3D Printer	To print out the body, top lid, filter vent, filter clip stand, filter clip, and openers of the prototype.
Model: CreatBot 3600 Pro	
Temperature used: 220°C / 80°C	
3D Printing Filament	To create the structure of the prototype so that it is strong and durable.
Type: PETG Pro	
Sandpaper	To remove the excess layer found on the surface of the printed prototype and to smooth the surface.
Cutting Pliers	To cut the excess filament found on the printed prototype.

However, before the printing of each part of the prototype was made, the realistic design of the prototype model was made by using Creo Parametric 8.0.4.0. The use of Creo Parametric combines two approaches, which are parametric and direct modelling. Furthermore, it is convenient to work with small applications and supports the import of formats from computer-aided design (CAD) systems from other manufacturers (Nariman *et al.,* 2025). The design was made thoroughly to ensure each part of the prototype meets the desired sketches that were prepared initially. As for the dimension, the dimension used in Creo Parametric 8.0.4.0 is millimetres (mm), although the sketches use centimetres (cm) to enlarge the drawings. Figures (8 – 12), shown below are the results of the drawings drawn in Creo Parametric 8.0.4.0.

3.4 System Overview

Figure 13 shows the flowchart of the system overview. Based on the research made, a study uses sensors to detect the condition of the surrounding air, a microcontroller, and fuzzy-logic control to adjust the DC fan speed in response to detected pollution levels (Chen *et al.,* 2022). Hence, the prototype made will use the same method, which is using sensors, a microcontroller, and fuzzy logic to control the DC fan speed (high speed, medium speed, or low speed) and the UVC LED light. Also, research on the usage of the Blynk platform for the user to monitor the condition of AQI is applied in this prototype to support the monitoring, alert the user, and send a predictive logic part of the system (Irdayanti & Robbani, 2022).

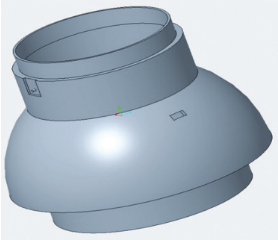


Figure 8: 3D view of body in CREO

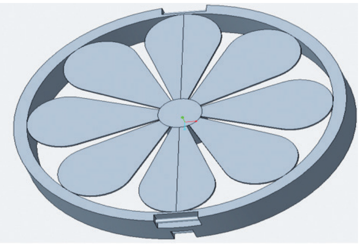


Figure 9: 3D View of top lid in CREO

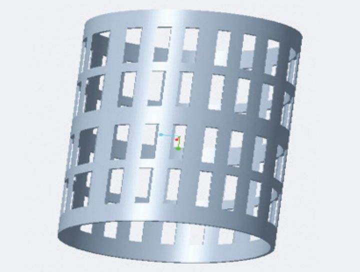


Figure 10: 3D View of filter vent in CREO

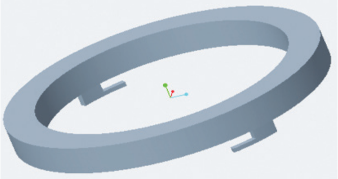


Figure 11: 3D View of filter clip in CREO

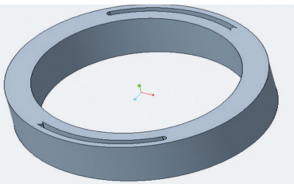


Figure 12: 3D View of filter clip stand in CREO

When the power is switched on manually or as scheduled by the user through the Blynk application, the value of the air quality index and humidity is identified and sent to the Blynk. The movement of surrounding conditions, whether caused by humans or animals, is also detected. When the AQI, temperature, and humidity of the surroundings are high, and the movement of a human is detected, the Air Cleaner (AC) will

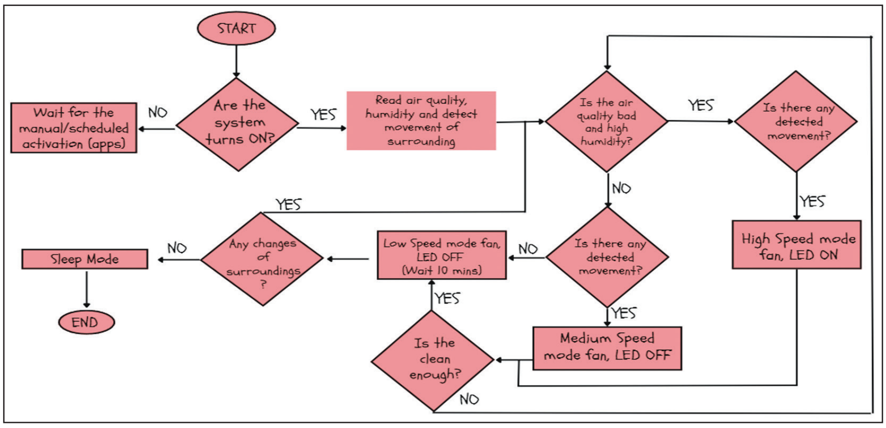


Figure 13: The flowchart of system overview

Table 2: The pin configuration and functional description of components and sensors

Pin	Sensor or Components Used	Functions
-	Arduino UNO R4 WiFi	To control and process the inputs of the sensors such as PIR Sensor 1 and 2, MQ135, and MQ2, by reading the AQI, temperature and humidity of the surroundings and send the data to Blynk so that the user can monitor it on their own and to control the speed of the Fan and the UVC LED Light through a 2 Channel Relay Module based on the commands received through programming.
D2	PIR Sensor 1	To detect the motion of humans and animals and trigger the other sensors to activate. It will be placed on the left side of the AC.
D3	PIR Sensor 2	To detect the motion of humans and animals and trigger the other sensors to activate. It will be placed on the right side of the AC.
D4	DHT11	To capture and identify the temperature and humidity of the surroundings and send the data to Blynk through the Arduino Uno R4 WiFi board.
D5	Fan that is connected to a 2 Channel Relay Module	It sucks air into the AC, which will pass through the filters, and it turns into low-speed mode, high-speed mode, and sleep mode based on the command in the Arduino.
D6	UVC LED Light that is connected to the 2 Channel Relay Module	It kills germs that cannot be seen in the air sucked into the AC and makes it clean before leaving and turns either OFF or ON based on the command in the Arduino.
A0	MQ135	To detect air quality and harmful gases available in the surroundings and help to get the AQI and send it to Blynk through Arduino.
A1	MQ2	To detect flammable gases and smoke available in the surroundings and help to get the AQI and send it to Blynk through Arduino.

put its fan into high-speed mode, and the UVC light is on. In contrast to that situation, if the AQI, temperature and humidity of the surroundings are low, but a human is detected, the AC will put its fan into a medium speed mode and the UVC light is off. For both conditions, if the air surroundings are clean enough, the AC will put its fan into a low-speed mode and the LED will turn off for 10 minutes, but if it is not, it will be processed again. The condition of the surroundings' AQI, temperature, and humidity will be ready again and will be processed until they are clean enough.

Within these 10 minutes, if there are no changes detected by the sensors of the AC, it will be put into sleep mode, unless there is a change in terms of the AQI, temperature, and humidity, and a human is detected around the AC. The AC will be put into sleep mode until the user switches it off through Blynk. Also, the data of the AQI, temperature, and humidity of the surroundings will be sent to Blynk so that it can be accessed and monitored by the user through their smartphones.

3.5 Circuit Connection

Figure 14 shows the circuit connection inside the AC. The Arduino Board used is Arduino UNO R4 WiFi, which will control all the sensors, such as MQ135, MQ2, DHT11, PIR Sensor 1, and PIR Sensor 2. It also controls the fan and UVC LED light through a 2 Channel Relay Module. Table 2 shows the configuration of the connection of the sensors and components used in this AC, as well as their functions.

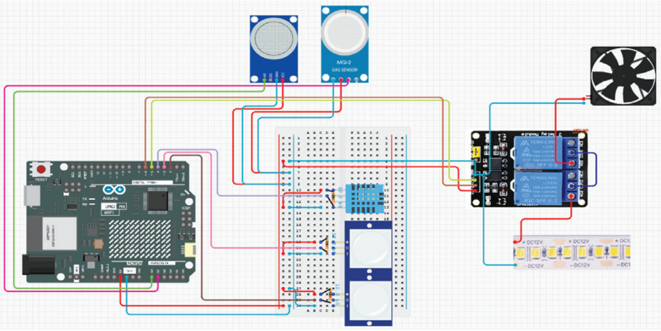


Figure 14: The circuit connection inside the air cleaner

Table 3: Data type used and their functions

Data Type	Functions
bool	For Binary Flags, such as motion detected
int	For counters and compact numeric storage where fractional precision is not required.
float	Fractional values are necessary, such as temperature, if high precision is not required
char	For short textual or Status Codes
const	For threshold constants to avoid accidental mutation
void	For functions that do not return values
loop	For continuous monitoring
string	For small, controlled textual messages, with caution due to heap usage on constrained MCUs

3.6 Arduino IDE Setup

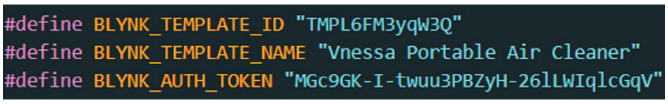
The idea of implementing the Arduino IDE as a hardware component of the prototype is to enhance a person's lifestyle. Based on the research made by Yusop *et al.* (2024), the development of software is important to produce a good quality product to be received by the end user and fulfil stakeholder needs. In addition to that, it was mentioned that the Arduino IDE uses a variant of C/C++ to write, compile, and upload embedded code sketches for microcontrollers, which makes it a flexible and widely adopted platform for IoT and hardware prototyping (Mumtaz *et al.,* 2021).

For the prototype of AC, the C++ programming language is chosen for the prototype. With that, the Arduino IDE Software is used as it can check the commands of the code for errors and translate it into machine-readable instructions so that the microcontroller, which is Arduino UNO R4 WiFi, can understand (Yusop *et al.,* 2024).

To begin with this, the coding commands are prepared and arranged accordingly so that each block is testable, and errors are easier to locate during debugging. In coding, there are several data types used in this programming, such as bool, loop, int, char, const, float, void, and string. Table 3 below shows the functions of each of the data types used in this programming. These choices are guided by embedded systems literature showing trade-offs between integer, fixed point and floating-point arithmetic, and by coding conventions that reduce bugs and resource misuse on constrained hardware (D'Ausilio, 2012).

Also, the board manager and libraries are installed, and the Arduino Board is connected via USB cable. The right COM port is selected in the software so that it can connect easily, and it will be verified once the board detection is successful. The external libraries for Blynk, DHT, and MQ sensors are added so that they can read the data from the sensors on the Arduino UNO R4 WiFi board and transfer it to Blynk.

Before verifying, debugging, and uploading the data, WiFi and Blynk credentials are important to connect the Blynk to the sensors. This also includes the Blynk Auth Token, Blynk Template ID, and Blynk Template Name so that data can be transferred to Blynk. Figure 15 is the sample of the Blynk template ID, template name and auth token used to synchronise Blynk with the Arduino IDE.



```
#define BLYNK_TEMPLATE_ID "TMPL6FM3yqW3Q"
#define BLYNK_TEMPLATE_NAME "Vnessa Portable Air Cleaner"
#define BLYNK_AUTH_TOKEN "MGc9GK-I-twuu3PBZyH-26lLWIqlcGqV"
```

Figure 15: The sample of BLYNK template id, template name

In addition, a calculation to calculate the air quality index is employed in the coding to command the system to automatically calculate the AQI, which will be sent to Blynk. Figure 16 shows the method of inserting and applying the formula to calculate AQI in the coding system. The formula of the calculation used is shown below [27].

$$I_p = \frac{I_{HI} - I_{LO}}{BP_{HI} - BP_{LO}} x\, (Cp - BP_{LO}) + I_{LO} \qquad [1]$$

Where,

I_p= Index of pollutants

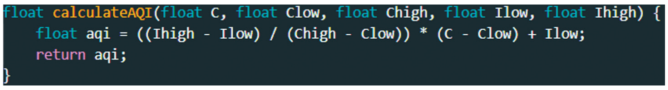
I_{HI}= AQI value corresponding to BP_{HI}

I_{LO} = AQI value corresponding to BP_{LO}

BP_{HI} = Breakpoint that is greater than or equal to C_p

BP_{LO} = Breakpoint that is less than or equal to C_p

C_p = Rounded concentration of pollutants



```
float calculateAQI(float C, float Clow, float Chigh, float Ilow, float Ihigh) {
    float aqi = ((Ihigh - Ilow) / (Chigh - Clow)) * (C - Clow) + Ilow;
    return aqi;
}
```

Figure 16: The method of inserting and applying the AQI formula

3.7 BLYNK Setup

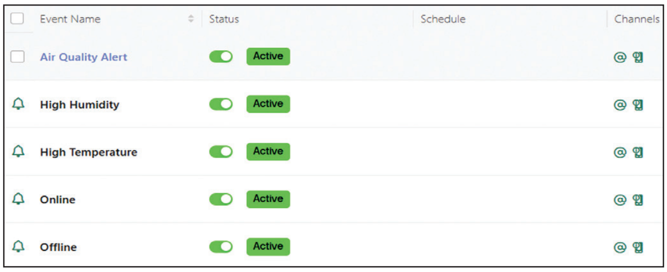
Blynk is an application used to modify and widget in a system. It integrates with Arduino UNO R4 WiFi to receive a command for the control of the AC. Zain *et al.* demonstrate how the Blynk mobile application integrates with microcontroller-based sensing to deliver real-time air quality data to the user's smartphones (Dinčić *et al.,* 2023). Besides, Pramana *et al.* demonstrated how the Blynk platform can be integrated with a microcontroller-based system to remotely monitor and control smart home devices, including sensors for temperature, humidity, and appliance actuation. The study highlights the use of widgets and real time data visualisation to enhance user interaction with IoT devices (Zain *et al.,* 2024). In this situation, proper coding is needed to enable Blynk to execute commands and send signals between the mobile application and the Arduino hardware.

Table 4: The proposed widget design and functional description for air cleaner

Function	Widget	Description
Air Quality Index (AQI)	Gauge	Real-time display of AQI value from MQ135 and MQ2
Temperature	Label	DHT11 temperature in °C
Humidity	Label	DHT11 humidity in %
System Power (ON/OFF)	Switch	Turn the whole system ON/OFF
Air Quality Index Graph Analysis	Custom Chart	Graph trends for analysis

Also, some codes are needed to set up the widgets used in the Blynk, such as the widgets for the AQI, temperature, humidity, a switch to toggle the AC into 'ON' and 'OFF' modes, and the graph analysis of the AQI. The graph analysis of the AQI is used to visualise real-time AQI data trends and provide immediate insights of the indoor air quality for the user. Table 4 shows the data used for the setup of the widgets in Blynk.

Blynk provides real-time notifications that inform users of the AC system status and environmental conditions. It notifies and alerts its users when the AC system is ON', OFF, the temperature is high or low, and the AQI is too high, by sending notifications. Figure 17 shows the list of notifications received by the apps.



☐	Event Name	Status	Schedule	Channels
☐	Air Quality Alert	Active		
	High Humidity	Active		
	High Temperature	Active		
	Online	Active		
	Offline	Active		

Figure 17: The event and notifications configurations of the air cleaner system

3.8 3D Printing Finishing

The final step for finishing the 3D printed prototype is important to ensure a smooth, neat, and proper surface finish. Based on the research made, it is essential to remove residuals and supports of the 3D printed prototype, clean and polish the 3D printed prototype, as it is the best practice in the workflow (Pramana *et al.,* 2025). With that, the final steps, which is removing residual and supports of the 3D printed prototypes, cleaning and polishing, are done to improve the AC's look and to smooth its surface.

Firstly, when the body of the prototype has been printed out by the 3D printing machine, the supports are removed slowly so that the structure of the prototype does not crack or damage by using cutter pliers. After that, the sanding process is done so that the surface of the body is smoothed by using sandpaper to improve its appearance. Kantharos *et al.* (2024) studied the essentials of cleaning, surface finishing, and support structure removal of 3D printed products to refine their qualities. Then, the sanded surface is cleaned by using water to remove the residue of the removed parts. These steps are repeated for other components of the prototype as well. Once cleaning and polishing are done, the components of the prototype are assembled using glue. Let the glue dry, and make sure the assembled components are strong enough.

3.9 Filters Development

The filter development process involved designing a multilayer filtration system to enhance particulate and gas absorption efficiency. The steps of developing a filter involve the selection of suitable filter media, cutting, joining, and assembling them.

As for the filter media, the first internal layer is an activated carbon filter. This is because the activated carbon filter has a high absorption capacity for gaseous pollutants and volatile organic compounds (VOC). Recent studies have demonstrated that activated carbon integrated into filter membranes significantly improves the removal of toxic gases and enhances overall air purification performance (Ryu *et al.,* 2023). Also, it can remove the odour of the surroundings. This activated carbon filter layer is measured and cut according to the required dimensions. As for the second internal layer, thick interlining fabric is used. It provides mechanical support for the thin interlining fabric outside of it so that it does not collapse. It could enhance the filtration of larger particulates and stabilise the arrangement of inner layers. S. Jung *et al.* (2020) conducted research that explains that coarser, thicker textile layers capture larger particles and support finer layers. As for the layer, which is outside of the 2 other layers, thin interlining fabric is used. It serves as a particulate filter, capturing small dust particles while maintaining airflow into the AC. It also has a low-thick surface that allows air to pass through it with minimal pressure drop. Based on the study made, thin fabrics can improve the efficiency of the particulate filtration, while keeping the pressure drop low, and preserving airflow through the system (Jung & Kim, 2020).

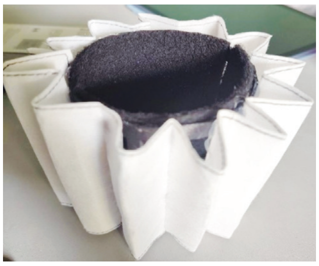


Figure 18: The combined filters which consists of thin and thick interlining fabrics (most outer side) and activated carbon filter (internal side)

Before assembling these layers of filter, each filter was measured along the line drawn, based on the required dimension. Then, the thin and thick interlining fabrics were joined together by using a sewing machine. Studies on multilayer textile filters emphasise that combining different fabric densities significantly enhances particulate matter removal compared to single-layer filters (Ma *et al.,* 2023). After that, they were cut accordingly so that they looked tidy. Once it is done, the joined filters are folded in ‘zigzag’ form. This is because the ‘zigzag’ form can increase the total surface area of the filters so that more particles and air can be absorbed at the same time, although the internal area of the filter vent is small.

To stick the joined thin and thick interlining fabric on the filter vent, they were glued using a hot glue gun. This method of sticking on the filter vent is repeated for the activated carbon filter. Once it is done, the excess glue around the filters is cleaned. Figure 18 shows the combined filters that will be attached to the AC.

4.0 RESULTS AND DISCUSSION

4.1 Hardware Overview

The hardware setup consists of several key components integrated to achieve air quality monitoring and purification functions. Figure 19 above is the outcome of the circuit for the AC prototype. The main control unit is the Arduino Uno R4 WiFi microcontroller, which coordinates all sensor readings and actuator responses. The MQ135 and MQ2 sensors are used to detect carbon dioxide, volatile organic compounds, and smoke levels in the surrounding air. A DHT11 sensor monitors temperature and humidity, ensuring environmental conditions are accurately recorded. The use of sections to divide the text of the paper is optional and left as a decision for the author. Where the author wishes to divide the paper into sections the formatting shown in Table 1 should be used.

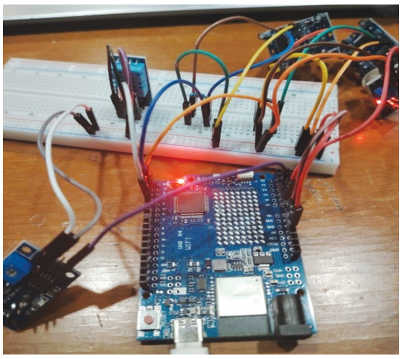


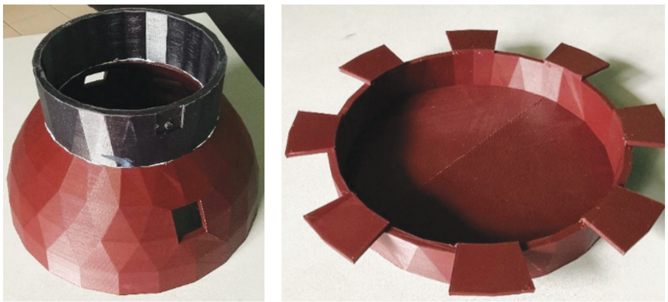
Figure 19: The circuit connection of the prototype

Two PIR sensors are employed to detect human presence, allowing the system to activate only when motion is detected, thereby improving energy efficiency. The 2-2-channel relay module serves as a switching interface, controlling the DC Fan and UV-C light based on signals from the microcontroller. Power is supplied via a regulated 12V DC adapter, ensuring stable operation of all components. Additionally, all components are mounted in a custom-designed 3D-printed enclosure, designed in Creo and sliced in Cura. The final assembly provides both protection and functionality, allowing for efficient airflow and accurate sensor readings. Figures 20 (a – f) are the product of the 3D printed prototypes of the AC.

4.2 BLYNK Overview

Blynk is an application used to monitor the condition of the AC. Figure 21(a) above is the overview of the Blynk for the AC, which includes the essential widgets to monitor the humidity, temperature and AQI and control the AC. As for the Blynk platform used by the prototype, it enables real-time monitoring and remote control of the hardware system. Sensor data from the MQ135, MQ2 and DHT11 modules are transmitted via the Arduino microcontroller to the Blynk mobile application. This allows users to view AQI, temperature, and humidity, as well as the graphs of the condition of the AQI based on time, on their smartphones.

In addition, a notification from Blynk regarding the surrounding conditions is sent automatically when the AQI drops below the threshold, demonstrating the system’s ability to respond dynamically to environmental changes. Here, the user can turn the prototype into ‘ON’ and ‘OFF’ modes. This can help the user to control their AC from a distance to ease their work and save their time since they can control it anywhere and anytime. When the AC is turned ON and OFF, a notification will be sent to the user through the app, as shown in the figure below. Figures 21(b) and 21(c) are examples of the notification received by the user when their AC is turned 'ON' and 'OFF'.

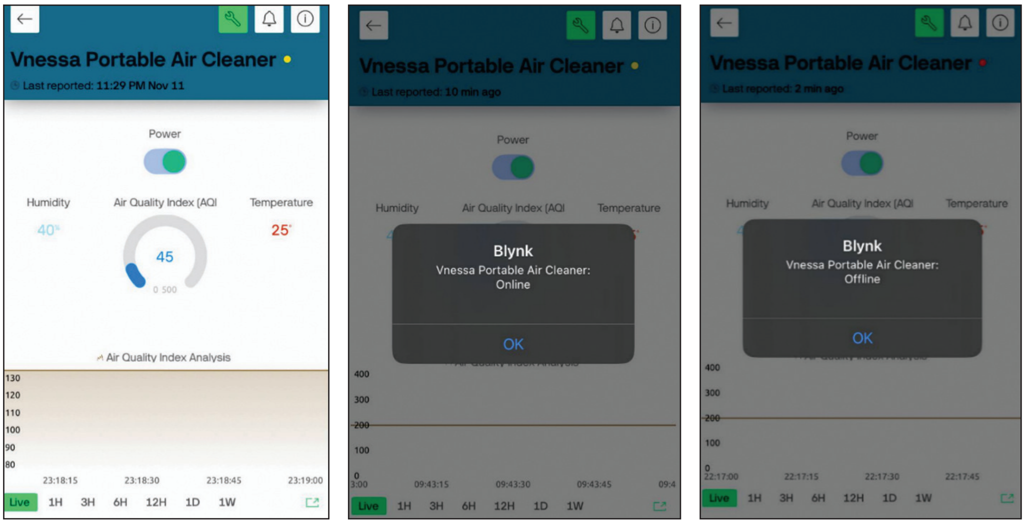


(a) The 3D-printed body *(b) The bottom part of the body*

(c) The top lid *(d) The filter vent*

(e) The filter stand *(f) The filter clip*

Figure 20: Individual mechanical parts developed for the air cleaner prototype



Blynk
Vnessa Portable Air Cleaner:
Online
OK

Blynk
Vnessa Portable Air Cleaner:
Offline
OK

(a) The overview of the Blynk *(b) The notification received when the AC is turned on* *(c) The notification received when the AC is turned off*

Figure 21: IoT mobile application interface for system status monitoring

4.3 Testing of the Air Cleaner

4.3.1 Case 1

The prototype is tested in a living room, 6.02 m x 2.95 m x 3.22 m, with ceiling fan speed 1, and the window is wide open. Testing is done to ensure the sensors used, such as MQ135, MQ2, PIR sensors, and DHT11, are functioning well and can provide accurate readings. Based on Figure 22 above, the readings obtained from Blynk, which is a platform used to detect the surrounding condition of the air as well as the AQI, it was found that the readings obtained are near to the accepted range. For instance, the temperature obtained from the DHT11 sensor is 28 °C and the humidity is 81%.

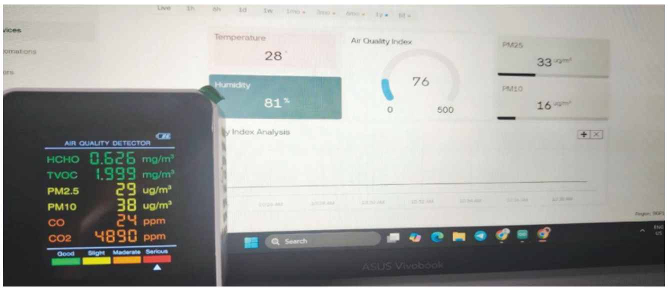


Figure 22: The testing of the accuracy of the sensors

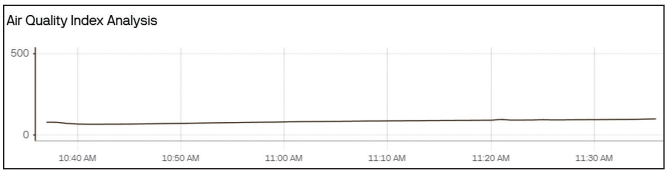


Figure 23: Graph of the AQI increment as the time increases

To test the overall functionality of the prototype, the prototype is tested in a living room (6.02 m x 2.95 m x 3.22 m), and the speed of the ceiling fan is in 'Speed 1' for 1 hour and 15 minutes. The AC is switched ON to let it fully balance for the first 15 minutes. After 15 minutes, a small increase of AQI, PM2.5 and PM10 is detected. This continued for another 30 minutes to observe a gradual increment in the value of the AQI, PM2.5 and PM10. Graph shown in Figure 23 proves the small increment value of the AQI as time increases.

After 45 minutes, a sudden spike of the AQI reaches 99, which means the value starts to get balanced based on the US AQI Standard Guideline as shown in Figure 24. After 1 hour, the AQI reached 101 while its PM2.5 is 37 µg/m³ and PM10 is 20 µg/m³. In order to check the accuracy of the AQI value obtained and measured by the prototype, the AQI formula is used to compare it with theoretical value. Figure 24 shown below is the US AQI

Standard Guideline for PM2.5 which is used to get the range of the accuracy of the AQI.

Based on the formula of the AQI (Zahedi *et al.,* 2024),, the theoretical value of the AQI is obtained based on the step-by-step formula:

$$IP\ (Theoretical\ Value) = [(150-101)/\ (55.4-35.5)]\ (37-35.5) + 101 = 104.69 \qquad [2]$$

$$Percentage\ Error = [(104.69 - 101)\ /\ 101] \times 100\% = 3.65\%$$

Where,
I_{HI} = 150
I_{LO} = 101
BP_{HI} = 55.4 µg/m³
BP_{LO} = 35.5 µg/m³
C_p = 37 µg/m³

After calculating the theoretical value of the AQI, the calculated value, 104.69, is compared with the measured value obtained by the prototype, 101. The percentage error, 3.65%, is found based on the calculation made above. This occurred due to the environmental issue where strong wind came from the open window and entered the MQ sensors' chamber continuously and disrupted the readings. Based on the percentage error obtained, it is found that the value is much smaller than the research made by Afrial *et al.* (2025), where the percentage error is 5% and Santoso *et al.* (2025) where the percentage error is 23.59%.

4.3.2 Case 2

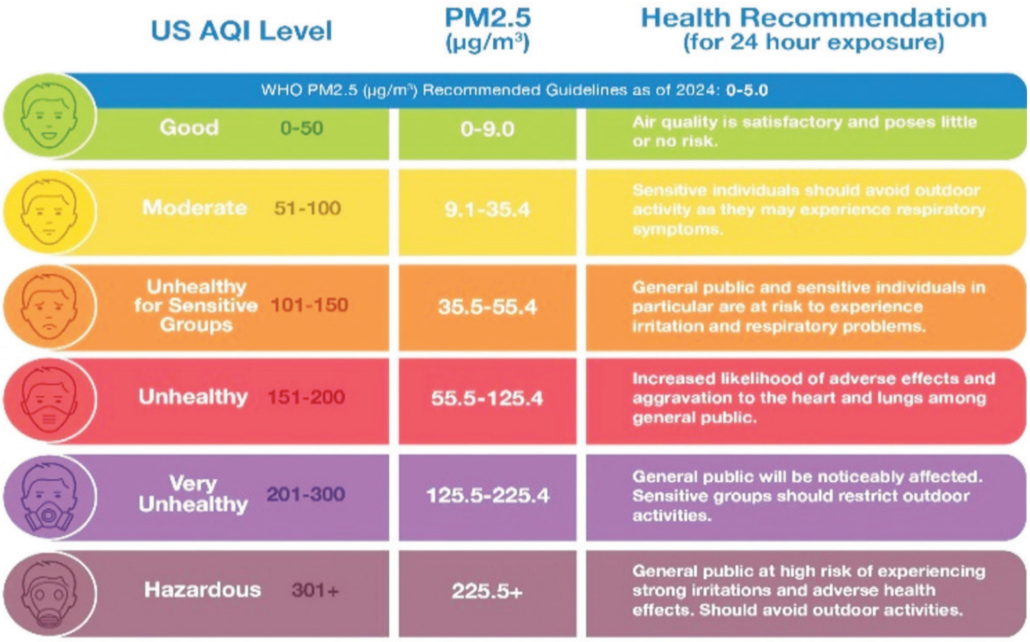
As for case 2, the prototype is tested in a larger room, 12.09 m x 6.2 m x 3.22 m, with no fan from 5:17 PM to 6:35 PM. Also, this case is done continuously, where initially, the door is closed, and then it is opened to obtain the readings throughout the testing process. For almost an hour. For the first 10 to 15 minutes (5:17 PM to 5:32 PM), the system is switched ON to let it balance. After 15 minutes, the data of the AQI, PM2.5 and PM10 measured by the prototype are collected as shown in Table 5 below. In this case, when the doors are both closed and opened, to calculate the theoretical value of the AQI, the range value of the PM2.5 is chosen. Besides, starting from 5:32 PM to 6:30 PM, it is found that the range value of PM2.5 lies within the range of 55.4 to 35.5. Figures from 33 to 45 show the condition of the AQI graph, and the readings of AQI, PM2.5 and PM10 in Blynk throughout the experiment time.

Figure 25: The overview of the large size of the room

Figure 26: The overview of the large size of the room when the three doors are open

Initially, after the system is left to balance for 15 minutes, from 5:32 PM to 6:03 PM, which is 31 minutes, it is found that the values of the AQI start to increase rapidly from 109 to 132 as the time increases. This influences the increase in PM2.5 values from 43 µg/m³ to 51 µg/m³, while PM10 values range from 22 µg/m³ to 28 µg/m³. Based on the results obtained, this shows that in a closed room, with no air flow entering or leaving, the air ventilation is very low, and the air particles and dust are trapped in the room, which leads to the rapid increase of the AQI, PM2.5, and PM10 values. Besides, the Percentage error of the AQI obtained is very large, which ranges from 9.61% to 5.43%. This is due to the imbalance condition of the closed room, which affects the value of the AQI.

However, at 6:03 PM, when the three doors are open as shown in Figure 26, a sudden spike of the AQI is from 132 to 134 while the value of the PM2.5 and PM10 is maintained at 51 µg/m³ and 28 µg/m³, each. As time increases, it is found that the value of the



US AQI Level		PM2.5 (µg/m³)	Health Recommendation (for 24 hour exposure)
WHO PM2.5 (µg/m³) Recommended Guidelines as of 2024: **0-5.0**			
Good	0-50	0-9.0	Air quality is satisfactory and poses little or no risk.
Moderate	51-100	9.1-35.4	Sensitive individuals should avoid outdoor activity as they may experience respiratory symptoms.
Unhealthy for Sensitive Groups	101-150	35.5-55.4	General public and sensitive individuals in particular are at risk to experience irritation and respiratory problems.
Unhealthy	151-200	55.5-125.4	Increased likelihood of adverse effects and aggravation to the heart and lungs among general public.
Very Unhealthy	201-300	125.5-225.4	General public will be noticeably affected. Sensitive groups should restrict outdoor activities.
Hazardous	301+	225.5+	General public at high risk of experiencing strong irritations and adverse health effects. Should avoid outdoor activities.

Figure 24: The US AQI standard guideline for PM2.5

AQI maintains its value over time, and it increases slowly as the time increases. For instance, from 6:03 PM to 6:06 PM, the value of the AQI is 134, while from 6:06 PM to 6:12 PM, the AQI becomes 136, but the value of the PM2.5 and PM10 for these 2 situations is maintained at 51 μg/m³ and 28 μg/m³, each, which is around 6 minutes. In this case, the uncertainty value of the AQI is 2.

From 6:12 PM to 6:16 PM, the AQI becomes 137, and from 6:16 PM to 6:25 PM is 139, while maintaining their PM2.5 and PM10 values at 52 μg/m³ and 29 μg/m³, each. Also, the AQI spikes to 141 at 6:25 PM, and the PM2.5 and PM10 values increase to 53 μg/m³ and 30 μg/m³, each. Here, the percentage error of the AQI obtained starts to decrease from 3.38% to 2.19%.

At 6:30 PM, the AQI spikes again to 143 while maintaining its PM2.5 at 53 μg/m³ and PM10 at 30 μg/m³, while at 6:33 PM, the AQI is 144, PM2.5 is 54 μg/m³ and the PM10 stays at 30 μg/m³. This second and last case shows a much smaller percentage error, which is 0.76% and 1.77% each. This means that it is near to the accuracy of the theoretical value of the AQI. The decreasing percentage error, closer to the accuracy shows that the prototype can get a much smaller percentage error compared to the research made by Afrial *et al.* (2025)., where the percentage error is 5% and Santoso *et al.* (2025), where the percentage error is 23.59%.

With that, when the doors are open, there is air flow entering and leaving the room, and the air ventilation is much better. Therefore, it is obvious that the AQI is unable to increase rapidly during this time, but it still increases slowly. Also, at the same time, the value of the PM2.5 and PM10 increases within the range of 51 μg/m³ to 54 μg/m³, and 28 μg/m³ to 30 μg/m³, each. With that, this shows that the prototype is unable to fully help decrease the AQI of the surroundings as well as the PM2.5 and PM10 content in the air, but it can help to control it so that it does not cause the AQI to be worse.

Table 5 shows a compiled AQI, PM2.5, and PM10 in both situations, with doors closed and open from 5:17 PM to 6:35 PM. Table 6 shows the results of the theoretical value of the AQI when calculated by using the AQI formula, together with the percentage error when comparing the theoretical value with the value obtained by the prototype.

4.4 Assumptions and System Limitations

The development and evaluation of the proposed IoT-based smart air cleaner were conducted under several technical and environmental assumptions. The system is intended for indoor residential environments with moderate pollution levels and limited air exchange. AQI computation is based on the US AQI standard for PM2.5, assuming particulate matter is the dominant pollutant in the tested conditions. The

Table 5: The data obtained for AQI, PM2.5, and PM10 based on time in two different situations

Time	AQI	PM2.5 (ug/m³)	PM10 (ug/m³)	Refer to Appendix	Situation
5:32 PM to 5:34 PM	109	43	22	A1	All doors are closed
5:34 PM to 5:47 PM	122	48	25	A2	
5:47 PM to 5:52 PM	126	49	26	A3	
5:52 PM to 5:57 PM	129	50	27	A4	
5:57 PM to 6:03 PM	132	51	28	A5	
6:03 PM to 6:06 PM	134	51	28	A6	3 doors are open
6:06 PM to 6:12 PM	136	51	28	A7	
6:12 PM to 6:16 PM	137	52	29	A8	
6:16 PM to 6:25 PM	139	52	29	A9	
6:25 PM to 6:30 PM	141	53	30	A10	
6:30 PM to 6:33 PM	143	53	30	A11	
6:33 PM to 6:35 PM	144	54	30	A12	

Table 6: The theoretical value of AQI and percentage error when comparing the theoretical value of AQI with the value obtained by the prototype

Theoretical Value of AQI	Percentage Error (%)
[(150-101)/ (55.4-35.5)] (43-35.5) + 101 = 119.47	[(119.47 – 109) / 109] x 100% = 9.61
[(150-101)/ (55.4-35.5)] (48-35.5) + 101 = 131.78	[(131.78 – 122) / 122] x 100% = 8.02
[(150-101)/ (55.4-35.5)] (49-35.5) + 101 = 134.24	[(134.24 – 126) / 126] x 100% = 6.54
[(150-101)/ (55.4-35.5)] (50-35.5) + 101 = 136.70	[(136.70 – 129) / 129] x 100% = 5.97
[(150-101)/ (55.4-35.5)] (51-35.5) + 101 = 139.17	[(139.17 – 132) / 132] x 100% = 5.43
[(150-101)/ (55.4-35.5)] (51-35.5) + 101 = 139.17	[(139.17 – 134) / 134] x 100% = 3.86
[(150-101)/ (55.4-35.5)] (51-35.5) + 101 = 139.17	[(139.17 – 136) / 136] x 100% = 2.33
[(150-101)/ (55.4-35.5)] (52-35.5) + 101 = 141.63	[(141.63 – 137) / 137] x 100% = 3.38
[(150-101)/ (55.4-35.5)] (52-35.5) + 101 = 141.63	[(141.63 – 139) / 139] x 100% = 1.89
[(150-101)/ (55.4-35.5)] (53-35.5) + 101 = 144.09	[(144.09 – 141) / 141] x 100% = 2.19
[(150-101)/ (55.4-35.5)] (53-35.5) + 101 = 144.09	[(144.09 – 143) / 143] x 100% = 0.76
[(150-101)/ (55.4-35.5)] (54-35.5) + 101 = 146.55	[(146.55 – 144) / 144] x 100% = 1.77

MQ135 and MQ2 sensors are assumed to operate within their specified ranges and to be sufficiently calibrated during short-term testing, while the DHT11 sensor is assumed to provide acceptable accuracy despite its known tolerance limits. The filtration layers are assumed to be clean and unsaturated during experiments. Stable power supply and uninterrupted WiFi connectivity are also assumed for proper system operation and real-time monitoring through the Blynk platform. Several limitations should be acknowledged. The MQ-series sensors are low-cost semiconductor sensors and do not perform direct particle counting like laser-based PM sensors, which may affect AQI precision. The Clean Air Delivery Rate (CADR), airflow distribution, and pressure drop across filters were not experimentally characterised.

The prototype is optimised for small to medium-sized rooms, and performance in larger or heavily polluted environments may be reduced. Testing was conducted over limited durations; long-term sensor drift, filter lifespan, and durability were not evaluated. Although UV-C integration is included, microbial inactivation efficiency was not experimentally validated. In addition, detailed energy consumption analysis and system performance under network disruption were not assessed. Future work should incorporate higher-precision particulate sensors, long-term validation studies, airflow and CADR measurements, UV-C effectiveness testing, and energy optimisation analysis to improve system reliability and scalability.

Table 7: The total price of the materials and equipment used

Materials & Equipment	Price (RM)
PETG Pro Filament	108.46
2 Channel Relay Module	4.74
12V DC Adaptor	5.90
DHT11 Sensor	3.90
Transistor	0.50
Mosfet IRLZ44N	3.95
Male to Male Wire	3.20
Male to Female Wire	3.20
UVC LED Light Strip	12.25
Red & Black Wire	6.60
DC Jack Converter	1.65
Arduino UNO R4 WiFi	69.95
Activated Carbon Filter	6.50
Kain Gam Keras	2.80
Kain Gam Nipis	2.15
Resistor	1.20
PIR Motion Sensor	4.00
DC Fan	7.50
MQ135 Sensor	5.40
MQ2 Sensor	5.40
Breadboard	3.75
Small Tyres	5.20
Glue	12.40
TOTAL	280.60

5.0 CONCLUSION

The progress made so far in developing the AC prototype lays a strong foundation for achieving the project's intended outcomes. This AC is being developed successfully with low-cost materials and equipment. It also consists of a low-cost multistage filtration system, which includes an HEPA and an activated carbon filter. The overall total cost for this AC is RM280.60 as shown in Table 7, which consists of the price of each of the materials used.

Besides, this AC can provide a real-time value of the AQI, PM2.5 and PM10 values that are measured by the multifunctional indoor air quality meter. The results shown by the AC are close to the agreement to the expected values. When calculating the theoretical values, it is found that the results provided by the AC have a small difference and uncertainties from the theoretical values. This also leads to much smaller values of the percentage error. Therefore, as the time increases, the system of the AC will be more balanced and will eventually produce a small percentage error of the AQI. In addition, the usage of Blynk as a platform to control and monitor the AQI, PM2.5 and PM10 successfully provides remote access and control to the AC. For instance, the user can control the switch, either to switch it ON or OFF, of the AC through Blynk. They can also monitor the history of the AQI measured by the system. With that, this AC has proven that the usage of the mobile interface applied in this AC is user-friendly. ■

ACKNOWLEDGEMENT

This research was funded by Universiti Tenaga Nasional, Malaysia.

AUTHORS' CONTRIBUTIONS

Vanessa Anastacia Bong	Conceptualisation, methodology, investigation, data curation, formal analysis, visualisation, writing original draft.
Lay Sheng Ewe	Conceptualisation, supervision, project administration, resources, writing.
Emadaddin Abdo Mohammed Alazzani	Supervision, writing, review & editing.
Sara Kit Yee Lee	Writing, review & editing.
Chee Fui Wong	Writing, review & editing.

REFERENCES

[1] Akimoto, H., & Sato, K. (2022). Development of science and policy related to acid deposition in East Asia over 30 years. *Atmospheric Environment: X.* https://doi.org/10.1186/s42834-022-00120-5

[2] Aldekheel, M., Altuwayjiri, A., Tohidi, R., Jalali Farahani, V., & Sioutas, C. (2022). The role of portable air purifiers and effective ventilation in improving indoor air quality in university classrooms. *International Journal of Environmental Research and Public Health, 19*(21), 14558. https://doi.org/10.3390/ijerph192114558

[3] Afrial, M., Rauf, M., Nouman, M., Khan, M. T., Rizwan, M. A., & Ahmad, N. (2025). Multi-sensor indoor air quality monitoring with real-time logging and air purifier

integration. *Materials Proceedings, 23*(1), 12. https://doi.org/10.3390/materproc2025023012

[4] Chen, H., Oliver, B. G., Pant, A., Olivera, A., Poronnik, P., Pollock, C. A., & Saad, S. (2022). Effects of air pollution on human health: Mechanistic evidence suggested by in vitro and in vivo modelling. *Environmental Research, 212*(Part C), 113378. https://doi.org/10.1016/j.envres.2022.113378

[5] Datta, P., Singh, J., Kumar, N., Sharma, K., & Yadav, R. (2023). Smart air purifier. In *Proceedings of the 2023 International Conference on Disruptive Technologies (ICDT)* (pp. 794–797). IEEE. https://doi.org/10.1109/ICDT57929.2023.10150554

[6] Dinčić, M. R., Perić, Z. H., Denić, D. B., & Denić, B. D. (2023). Optimization of the fixed-point representation of measurement data for intelligent measurement systems. *Measurement, 217,* 113037. https://doi.org/10.1016/j.measurement.2023.113037

[7] Dubey, S., Rohra, H., & Taneja, A. (2021). Assessing effectiveness of air purifiers (HEPA) for controlling indoor particulate pollution. *Heliyon, 7*(9), e07976. https://doi.org/10.1016/j.heliyon.2021.e07976

[8] D'Ausilio, A. (2012). Arduino: A low-cost multipurpose lab equipment. *Behavior Research Methods, 44*(2), 305–313. https://doi.org/10.3758/s13428-011-0163-z

[9] Ebrahimifakhar, A., Poursadegh, M., Hu, Y., Yuill, D. P., & Luo, Y. (2024). A systematic review and meta-analysis of field studies of portable air cleaners: Performance, user behavior, and by-product emissions. *Science of the Total Environment, 912,* 168786. https://doi.org/10.1016/j.scitotenv.2023.168786

[10] Hsueh, M. H., Lai, C. J., Wang, S. H., Zeng, Y. S., Hsieh, C. H., Pan, C. Y., & Huang, W. C. (2021). Effect of printing parameters on the thermal and mechanical properties of 3D-printed PLA and PETG using fused deposition modeling. *Polymers, 13*(11), 1758. https://doi.org/10.3390/polym13111758

[11] Irdayanti, Y., & Robbani, M. I. (2022). Design of a fuzzy logic-based intelligent hybrid air purifier using pollutant-absorbing plants. *Jurnal Elektronika dan Otomasi Industri.* https://doi.org/10.33795/elkolind.v12i2.7896

[12] Iskandriawan, B., Safaat, A., & Tristiyono, B. (2025). Air velocity and pressure measurements of portable air purifiers using numerical simulations based on product component design variation. *Journal of Applied Engineering Science, 23*(1), 141–150. https://doi.org/10.5937/jaes0-54527

[13] Jung, S., & Kim, J. (2020). Advanced design of fiber-based particulate filters. *Polymers*. https://doi.org/10.3390/polym12081714

[14] Kantaros, A., Ganetsos, T., Petrescu, F. I. T., Ungureanu, L. M., & Munteanu, I. S. (2024). Post-production finishing processes utilized in 3D printing technologies. *Processes, 12*(3), 595. https://doi.org/10.3390/pr12030595

[15] Kocak, O., & Bunyatova, U. (2025). Integrating smart air purifiers in building controls: A conceptual approach to infection and energy management. *Energy Reports, 13,* 2545–2554. https://doi.org/10.1016/j.egyr.2025.01.072

[16] Kumar, T., & Doss, A. (2023). AIRO: Development of an intelligent IoT-based air quality monitoring solution for urban areas. *Procedia Computer Science, 218*, 262–273. https://doi.org/10.1016/j.procs.2023.01.008

[17] Liu, D. T., Phillips, K. M., Speth, M. M., Besser, G., Mueller, C. A., & Sedaghat, A. R. (2021). Portable HEPA purifiers to eliminate airborne SARS-CoV-2: A systematic review. *Otolaryngology–Head and Neck Surgery, 166*(4), 615–622. https://doi.org/10.1177/01945998211022636

[18] Lowther, S. D., Deng, W., Fang, Z., Whyatt, J. D., Wild, O., Wang, X., & Jones, K. C. (2020). How efficiently can HEPA purifiers remove priority fine and ultrafine particles from indoor air? *Environment International, 144,* 106001. https://doi.org/10.1016/j.envint.2020.106001

[19] Lu, F. T., Laumbach, R. J., Legard, A., Myers, N. T., Black, K. G., Ohman-Strickland, P., Alimokhtari, S., de Resende, A., Calderón, L., Mainelis, G., & Kipen, H. M. (2024). Real-world effectiveness of portable air cleaners in reducing home particulate matter concentrations. *Aerosol and Air Quality Research, 24,* 230202. https://doi.org/10.4209/aaqr.230202

[20] Ma, W., *et al.* (2023). Efficient, breathable, and compostable multilayer air filter material prepared from plant-derived biopolymers. *Membranes*. https://doi.org/10.3390/membranes13040380

[21] Marsavina, L., Dohan, V., & Galatanu, S. V. (2024). Mechanical evaluation of recycled PETG filament for 3D printing. *Fracture and Structural Integrity, 18*(70), 310–321. https://doi.org/10.3221/IGF-ESIS.70.18

[22] Mouha, R. A. (2021). Internet of Things (IoT). *Journal of Data Analysis and Information Processing, 9,* 77–101. https://doi.org/10.4236/jdaip.2021.92006

[23] Mumtaz, R., Zaidi, S. M. H., Shakir, M. Z., Shafi, U., Malik, M. M., Haque, A., Mumtaz, S., & Zaidi, S. A. R. (2021). Internet of Things (IoT) based indoor air quality sensing and predictive analytic—A COVID-19 perspective. *Electronics, 10*(2), 184. https://doi.org/10.3390/electronics10020184

[24] Nariman, S., Rakhmetov, M., Nurbekova, G., Issakova, G., & Orazbayeva, B. (2025). Teaching 3D engineering modeling and prototyping in Creo parametric in

educational institutions. *International Journal of Innovative Research and Scientific Studies, 8*(4), 460–467. https://doi.org/10.53894/ijirss.v8i4.7872

[25] Pramana, I. G. B. A., Akbar, L. A. S. I., & Ramadhani, C. (2025). Development of an IoT-based smart home prototype using the Blynk application. *Motivection: Journal of Mechanical, Electrical and Industrial Engineering, 7*(1), 25–36. https://doi.org/10.46574/motivection.v7i1.424

[26] Santoso, D., Santosa, S., & Sekaranom, A. (2025). Low-cost sensor based on Internet of Things for $PM_{2.5}$ air quality monitoring. *Indonesian Journal of Geography, 57*(2), 408–422. https://doi.org/10.22146/ijg.104159

[27] Saini, J., Dutta, M., & Marques, G. (2020). Indoor air quality monitoring systems based on Internet of Things: A systematic review. *International Journal of Environmental Research and Public Health, 17,* 4942. https://doi.org/10.3390/ijerph17144942

[28] Shukla, A. K., Koul, K., & Babu, B. (2022). Study of modern air purification and sterilization techniques. *Environmental and Earth Sciences Research Journal, 9*(3), 79–89. https://doi.org/10.18280/eesrj.090301

[29] Ukagwu, K. J., Enzoionzi, A. I., Eze, V. H. U., Uche, C. K. A., & Ukagwu, F. (2024). Innovative design and implementation of portable and rechargeable air purifier and humidifier. *International Journal of Recent Technology and Applied Science, 6*(1), 14–24. https://doi.org/10.36079/lamintang.ijortas-0601.618

[30] Vijayan, V. K., Paramesh, H., Salvi, S. S., & Dalal, A. A. (2015). Enhancing indoor air quality: The air filter advantage. *Lung India, 32*(5), 473–479. https://doi.org/10.4103/0970-2113.164174

[31] World Bank & Institute for Health Metrics and Evaluation. (2016). *The cost of air pollution: Strengthening the economic case for action.* World Bank. https://doi.org/10.1596/978-1-4648-0850-5

[32] Yusop, N., Moketar, N. A., & Sadikan, S. F. N. (2024). Development of Arduino applications for IoT applications in software engineering education: A systematic literature review. *Bulletin of Electrical Engineering and Informatics, 13*(3). https://doi.org/10.11591/eei.v13i3.4506

[33] Zahedi, A., Jaafarzadeh, N., Mirr, I., & Tahmasebi, Y. (2024). Forecasting air quality index (AQI) and air quality health index (AQHI) by time series models in Ahvaz, Iran. *Environmental Health Engineering and Management Journal, 11*(4), 469–476. https://doi.org/10.34172/EHEM.2024.46

[34] Zain, N. M., Othman, M., Mohd Rozi, M. A. R., & Paidi, Z. (2024). The development of an IoT-based air quality monitoring system using the Blynk application. *Journal of Computing Research and Innovation, 9*(1), 157–166. https://doi.org/10.24191/jcrinn.v9i1.426

[35] Zhai, Z., Li, H., Bahl, R., & Trace, K. (2021). Application of portable air purifiers for mitigating COVID-19 in large public spaces. *Buildings, 11*(8), 329. https://doi.org/10.3390/buildings11080329

APPENDICES

Figure A: The AQI, PM2.5 and PM10 Value at 5:32pm to 5:34pm.

Figure B: The AQI, PM2.5 and PM10 Value at 5:34pm to 5:47pm.

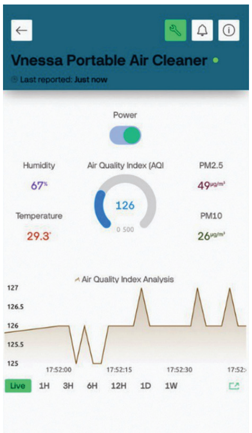

Vnessa Portable Air Cleaner
Last reported: Just now
Power
Humidity 67%
Air Quality Index (AQI 126
PM2.5 49μg/m³
Temperature 29.3°
PM10 26μg/m³

Figure C:
The AQI, PM2.5 and PM10 Value at 5:47pm to 5:52pm.

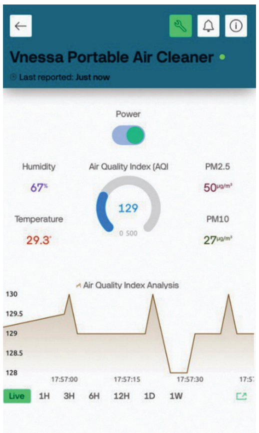

Vnessa Portable Air Cleaner
Last reported: Just now
Power
Humidity 67%
Air Quality Index (AQI 129
PM2.5 50μg/m³
Temperature 29.3°
PM10 27μg/m³

Figure D:
The AQI, PM2.5 and PM10 Value at 5:52pm to 5:57pm.

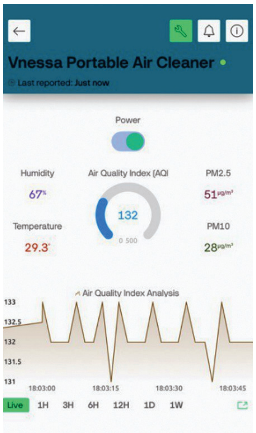

Vnessa Portable Air Cleaner
Last reported: Just now
Power
Humidity 67%
Air Quality Index (AQI 132
PM2.5 51μg/m³
Temperature 29.3°
PM10 28μg/m³

Figure E:
The AQI, PM2.5 and PM10 Value at 5:57pm to 6:03pm.

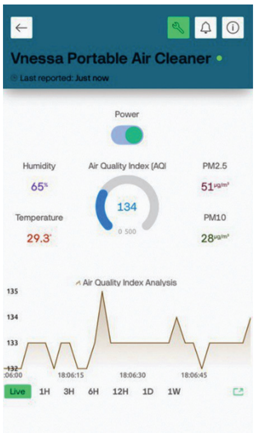

Vnessa Portable Air Cleaner
Last reported: Just now
Power
Humidity 65%
Air Quality Index (AQI 134
PM2.5 51μg/m³
Temperature 29.3°
PM10 28μg/m³

Figure F:
The AQI, PM2.5 and PM10 value at 6:03pm to 6:06pm.

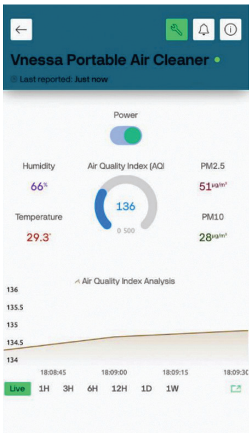

Vnessa Portable Air Cleaner
Last reported: Just now
Power
Humidity 66%
Air Quality Index (AQI 136
PM2.5 51μg/m³
Temperature 29.3°
PM10 28μg/m³

Figure G:
The AQI, PM2.5 and PM10 value at 6:06pm to 6:12pm.

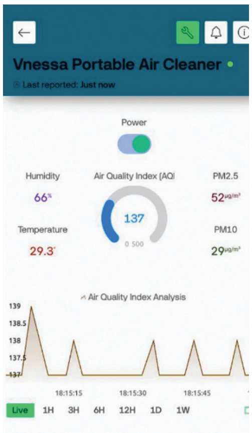

Vnessa Portable Air Cleaner
Last reported: Just now
Power
Humidity 66%
Air Quality Index (AQI 137
PM2.5 52μg/m³
Temperature 29.3°
PM10 29μg/m³

Figure H:
The AQI, PM2.5 and PM10 value at 6:12pm to 6:16pm.

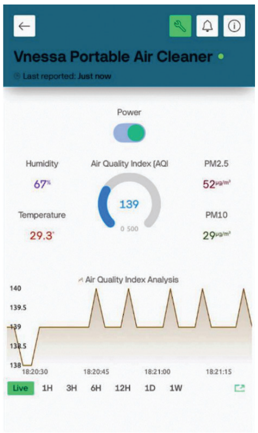

Vnessa Portable Air Cleaner
Last reported: Just now
Power
Humidity 67%
Air Quality Index (AQI 139
PM2.5 52μg/m³
Temperature 29.3°
PM10 29μg/m³

Figure I:
The AQI, PM2.5 and PM10 value at 6:16pm to 6:25pm.

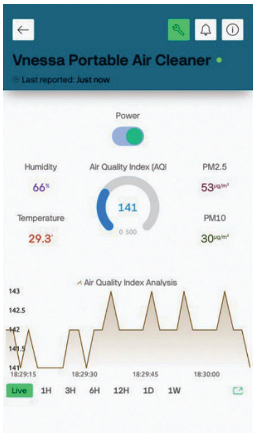

Vnessa Portable Air Cleaner
Last reported: Just now
Power
Humidity 66%
Air Quality Index (AQI 141
PM2.5 53μg/m³
Temperature 29.3°
PM10 30μg/m³

Figure J:
The AQI, PM2.5 and PM10 value at 6:25pm to 6:30pm.

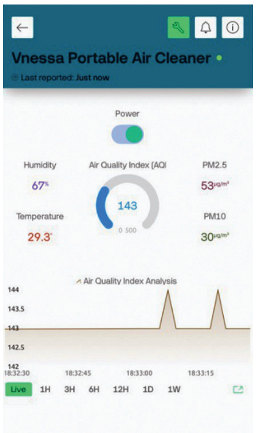

Vnessa Portable Air Cleaner
Last reported: Just now
Power
Humidity 67%
Air Quality Index (AQI 143
PM2.5 53μg/m³
Temperature 29.3°
PM10 30μg/m³

Figure K:
The AQI, PM2.5 and PM10 value at 6:30pm to 6:33pm.

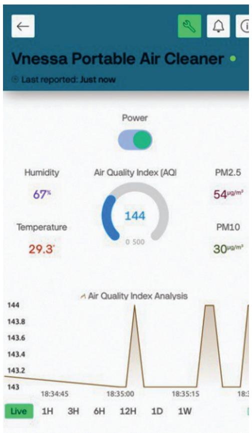

Vnessa Portable Air Cleaner
Last reported: Just now
Power
Humidity 67%
Air Quality Index (AQI 144
PM2.5 54μg/m³
Temperature 29.3°
PM10 30μg/m³

Figure L:
The AQI, PM2.5 and PM10 value at 6:33pm to 6:35pm.

PROFILES

VANESSA ANASTACIA BONG is a final-year Diploma in Mechanical Engineering student at Universiti Tenaga Nasional (UNITEN), Malaysia, currently undergoing industrial training at Sarawak Energy Berhad. Her interests lie in mechanical innovation and the design of practical, efficient engineering solutions that address everyday challenges.
Email Address: vnessabong36@gmail.com

LAY SHENG EWE was born in Penang, Malaysia. She received her Ph.D. in Pure Physics from the National University of Malaysia (UKM). She is currently an Associate Professor at Universiti Tenaga Nasional (UNITEN), Putrajaya Campus, Malaysia. Her research interests include material science, superconductivity, and magnetoresistance (MR). In 2020, she was awarded the Professional Technologist certification by the Malaysia Board of Technologists (MBOT). She also serves as an active committee member of the Malaysia Association of STEM Olympiads (MASO).
Email address: laysheng@uniten.edu.my

EMADADDIN ABDO ALAZZANI is a Master's candidate in Mechanical Engineering at Universiti Tenaga Nasional (UNITEN), Malaysia. He holds a Bachelor's degree in Mechanical Engineering from Universiti Malaysia Pahang (UMP). With over four years of research experience, he has contributed to postgraduate research projects and peer-reviewed publications in renewable energy and sustainable engineering. His technical expertise spans experimental design, statistical analysis (SPSS, R, Python), MATLAB, and data-driven engineering optimisation. His research interests include renewable energy systems, mechanical performance enhancement, and sustainable engineering technologies.
Email address: Emadalezany14@email.com

SARA KIT YEE LEE holds a Bachelor's degree in Mechanical gineering from Universiti Tenaga Nasional (UNITEN), and both her Master's and Ph.D. degrees from Universiti Malaya (UM). She is a registered Professional Engineer and ASEAN Chartered Professional Engineer (ACPE) with the Board of Engineers Malaysia (BEM), a Professional Technologist with the Malaysian Board of Technologists (MBOT), and a Chartered Engineer with the Engineering Council. She is a member of the Institution of Engineers, Malaysia (IEM) and the Institution of Mechanical Engineers (IMechE).
Email address: leeky@tarc.edu.my

CHEE FUI WONG is an Assistant Professor at the Centre of Climate Change and Disaster Risk Reduction, Department of Civil Engineering, Lee Kong Chian Faculty of Engineering and Science, Universiti Tunku Abdul Rahman (UTAR), Malaysia. He holds a Ph.D. in Engineering from UTAR, an M.Sc. in Highway and Transport Engineering, and a B.Eng. in Civil Engineering from Universiti Putra Malaysia (UPM). A registered Professional Engineer (P.Eng) and Professional Technologist (P.Tech), he is also a Fellow of the Institution of Engineers, Malaysia (FIEM), F.TAM, F.AAET, and F.AETDEW. His expertise spans highway infrastructure design, water supply and resources management, dam construction, sewerage systems, and waste management, supported by extensive experience in both local and international construction projects.
Email address: cfwong@utar.edu.my