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ORIGINAL PAPER

Development of an IoT-Enabled Air Pollution Monitoring and Air Purifier System

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Abstract: Air Pollution is one of the severe hazards which affect the health quality of all living beings and the environment itself, especially in urban areas. It creates significant health issues in many countries and harms human health if its concentration exceeds tolerable levels. Monitoring these pollutants and their concentrations is a crucial preventative measure to alert the public to the air quality in the area. The primary objective of this paper is to design a smart air pollution prototype to purify the air with the help of a PM sensor, gas sensors, analog to digital converter (ADC), Raspberry Pi 3 B+ microcontroller, and multiple filters (Step-by-step filtering of particles from sizes 200 to 0.3 µm will be done by different filters). The gas sensors, MQ2 and MQ135, measure the presence/concentration of the LPG, smoke, CO, CO_2, and NH_4 before and after the filtering process. The PMSA003 sensor detects Particulate Matter (PM) in the range of 0.3 microns to 10 microns. ADC and Raspberry Pi 3 B+ convert the outputs of gas sensors and PM sensors into concentrations of particles. These results are transmitted to the Thingspeak Cloud platform through the WiFi Module. The sensor outputs can be viewed in any system/mobile in the Thingspeak Cloud platform. The concentration of different gases and the measured size concentration of various particles are plotted before and after the filtration, and the results are compared. It is found that the designed filter effectively filters all the particles above 0.3 µm. The performance and efficiency test of both air quality monitoring and air purifier system is done.

Keywords: Air pollution; Sensor; Filter; Particle size; Gas concentration; Raspberry Pi

1. Introduction

Air pollution causes damage to crops, animals, forests, and water bodies and contributes to the depletion of the ozone layer. As per WHO (World Health Organization), 93% of children breathe polluted air that contains Particulate Matter (PM) of less than 10, which causes chronic diseases [1]. The SARS-CoV-2 (Severe Acute Respiratory Syndrome Coronavirus 2) virus was the primary cause of the spread of corona disease worldwide in 2019 through airborne transmission. It generally spreads via the respiratory tract of infected persons with respiratory droplets > 5 µm and aerosol droplets < 5 µm [2]. Aerosols are pollutants present in the atmospheric air in the form of liquid and solid, a major source of air pollution [3]. Particulate Matter, or PM for short, is also known as particle pollution. Particles with a diameter of 10 µm or less are classified as respirable PM_{10}. The same is true for $PM_{2.5}$, which contains particles with a diameter of 2.5 µm or less. Particles with a diameter of less than 1 µm are referred to as PM_1 or ultra-fine particles [4]. Worldwide, the existence of PM causes nearly seven million early death per year [5].

The analysis of the Aerosol Optical Depth (AOD-one of the properties of the aerosols) at Gandhi College, Jaipur, Karunya University, New Delhi, and Pune using a Ground-based remote sensing network (AERONET-Aerosol Robotic NETwork) in the years 2017 and 2018 is done in [6]. It is found that the AOD varies from 0.13 (at Karunya University) to 2.26 (at Gandhi College) at the five places considered. AOD value greater than 0.4 corresponds to a polluted area [7].

The pollution level in major cities is increasing day by day. As of 2019, New Delhi is the world's most polluted city [8]. In November 2021, India's capital imposed a lockdown for more than a week due to the degradation of air quality in the city [9]. World Health Organization revised the air quality guidelines worldwide after a gap of 15 years. This indicates the increased level of harmful

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pollutants in the atmospheric air around the globe, and these new guidelines almost put India under the polluted category [10].

India struggles to maintain urban air emission norms that follow WHO criteria [11]. The annual mean and 24-h mean values of $PM_{2.5}$, as per WHO new guidelines, are 5 and 15 $\mu g/m^3$, respectively. Similarly, for PM_{10}, the annual mean and 24-h mean values are 15 and 45 $\mu g/m^3$, respectively [12]. Due to the pollution, the day-to-day life of the people is affected. Continuous lockdowns and many other mitigating steps are to be taken to control such air pollution.

Wind-driven dust, huge sea salt particles, and mechanically produced anthropogenic particles, including those from agriculture and surface mining, are all considered coarse particles (larger than 2.5 m and smaller than 10 m in diameter). They are heavy in mass and settled out on the surface. These particles only stay in the atmosphere for a short while. But the fine aerosol particles (Particles of 2.5 µm in diameter and smaller) are very dangerous to human health. They can penetrate the respiratory system and result in diseases such as asthma and bronchitis or can even lead to cancer. These fine particles are the major reason for deaths caused by cardiovascular disease. A global study on the burden of the disease proved that indoor air pollution and outdoor atmospheric pollutant particles, respectively, secured the third and seventh position in the risk factors contributing to the burden of disease [13]. They take a long time to enter the atmosphere, and they are the reason for the majority of atmospheric visibility impacts.

Several factors that emerge in the link between $PM_{2.5}$ particles to the increase in COVID-19 are as follows: High exposure to chronic air pollution produces more complications in the human respiratory system and tends to produce cardiovascular disease, which leads to death. Fine particles induce cell inflammation, cause cell damage, and stimulate the human cell surface for the reception of viruses. Hence, the presence of fine particles in the atmospheric air increases the virus transmission [14]. Air Quality Index (AQI) is a number and is calculated by measuring emissions of 8 major pollutants present in the air. They are $PM_{2.5}$, PM_{10}, Ozone, CO, NO_2, SO_2, Pb and NH_3. The concentration of these pollutants rises daily as a result of factors including traffic pollution, industrialization, population growth, and others [15]. Measurements of these parameters are done every hour, and each country has the AQI based on its air quality standards. If AQI is higher, the harmful pollutant level in the air is higher, and it causes severe health problems for many people. The health impacts of each type of AQI pollution level on people are detailed in [16]. The pollution concentration and corresponding AQI values for $PM_{2.5}$ and PM_{10} are given in [17].

Some of the dust particles created by industry are poisonous. The high concentration of CO and CO_2 in the atmospheric air creates massive health problems for humans, increases global warming, and its effects are explained in [18]. To control such a massive scale of pollution, proper control measures need to be taken. Therefore, it is essential to filter the aerosol particles (especially the fine poisonous particles) which are released into the earth's atmosphere. Also, it is much more important to develop an IoT (Internet of Things)-based sensing network for finding the concentration of various gaseous pollutants present in the atmosphere and sending the sensor readings via the cloud to further analyze it. The other Sections of the paper are organized as follows.

Section 2 describes the works related to the air purifier design. The block diagram and its corresponding explanations are provided in Sect. 3. The hardware components and software tools used are explained in Sect. 4 and Sect. 5, respectively. The hardware prototype is explained in Sect. 6. Section 7 is intended for the Results and Discussions. Finally, the conclusion and future work are given in Sect. 8.

2. Related Literature

Over the past ten years, the design and implementation of the Air Pollution Control Prototype have gained much attention due to advancements in science and technology and increased air pollution levels. Some of the literature related to air quality monitoring and air pollutant filtration are explained as follows.

An air quality measurement system was developed by [19] using Raspberry Pi. The proposed system utilized two Arduino Nano boards, a Raspberry Pi 3, a GPS module, and three gas sensors. The measured information such as temperature, humidity, state of the air, Latitude and Longitude of the current position, and API (Application Program Interface) address are displayed using a web server and LCD (Liquid Crystal Display) screen. This system measures the concentration of $PM_{2.5}$, PM_{10}, and four hazardous gases such as sulphur dioxide, carbon monoxide, nitrogen dioxide, and ground ozone. The system functionality is tested in high- and low-traffic areas. An estimated error of 3.23% was observed after validating the proposed system result with CAQMs (Continuous Air Quality Monitoring Stations) in Malaysia.

Dinesh Panicker et al., employed a method to monitor the environment's air quality to raise concerns about the quality of the air while conducting regular activities both indoors and outside. The system consists of two primary components: a filtering unit and an air quality monitor. The filtering unit consists of a dust filter, pre-filter, and fine filter. Depending on the dust sensor measurement, the software automatically ON and OFF the air purifying unit based on the threshold. For the purpose of detecting a variety of gases, such as NH_3, NO_x, alcohol, benzene, smoke, and CO_2, this smart air purifier employs MQ135. The air pollution and particulate matter present in the environment are found using the air quality monitoring unit. The prototype of this sensing device is tested to validate the system's functionality. The results shown by this device are promising for daily air quality monitoring. The only drawback of this device is that the sensors used in the prototype are of small scale. They do not sense the pollutants in the air efficiently if the filtration area is larger [20].

An indoor air quality monitoring framework was created with the use of an IoT platform for the real-time monitoring of environmental pollution [21]. This system uses components including gas sensors, temperature sensor, humidity sensor, dust sensor, LCD display, Arduino UNO microcontroller, and ESP8266 (an IoT packaged enabled board). It uses the WiFi module for real-time transmission of measurement data to the Thingspeak cloud and mobile app. It has many advantages, such as mobility, a low-cost design framework, easy implementation, and uses open source technology. This designed system monitors the concentration levels of CO, CO_2, NO_2, PM_{10}, temperature, and humidity. It warns the user if the pollutant emission levels exceed the threshold through the mobile phone application.

An IoT-based system for real-time monitoring of air quality has been developed [22]. This proposed system uses various components like ESP32 MCU (Microcontroller Unit), SDS011 dust optical sensor, MQ 135 sensor, temperature, and humidity sensor for monitoring gases such as CO_2, CO, ammonia, $PM_{2.5}$, and PM_{10} present in the industrial atmosphere to ensure the safety and health concern of workers. The measured AQI index is displayed in the Virtuino app and Thingspeak platform, where the measurement reading is taken every 5 min are updated continuously. And these data can be transferred via mail to the particular user for monitoring and control. The main intention of the system is to avoid fire explosions in the industry due to the existence of gas leakage.

Manisha Sharma et al., developed an I2P (Impure to Pure) air quality monitoring and filtering system to help old age homes, hospitals, and offices prevent environmental pollution. This system uses components such as an MQ2 sensor (sense LPG, CO, smoke), temperature, and humidity sensor for monitoring gaseous pollutants in the atmosphere and environmental parameters. This system sets the threshold for such pollutants, and if its level exceeds, it notifies the user through the alarm and displays on the LCD to switch ON the filtering part. This section consists of several filters, namely Net mat followed by HEPA (High-Efficiency Particulate Air) filter, Activated carbon filter, Silica gel, and UV (Ultra Violet) lamp. Once switched on the filtering part, the air at a particular place is getting purified [23].

It is clear from the literature review that most of the prototypes did not have either multiple sensors (to sense gases such as LPG, smoke, CO, CO_2, and NH_4) or a separate filtering unit (multiple filters). Those prototypes that had a filtering unit did not use HEPA filters. In this prototype, three filters, namely the pre-filter, activated carbon filter, and HEPA filter (class 14), are used to improve the already existing prototypes. Most of the existing prototypes update the values in the cloud at an interval of 1 min or more, but the proposed prototype in this paper updates the sensor output every 15 s. The designed prototype contains two pairs of monitoring units, both at the rear and the front end, to compute the efficiency of the prototype. Pre-filters are installed before the filtering unit to filter the larger dust particles before they reach the HEPA filter. Pre-filters help to extend the lifetime of the filtering unit. Many of the existing air pollution monitoring prototypes did not use PM sensors along with gas sensors for pollution monitoring. The PMSA003 sensor is a highly versatile sensor that can measure particles of sizes from 0.3 to 10 microns. The block diagram of the proposed IoT-enabled air pollution monitoring and air purifier system is explained next.

3. Block Diagram of Proposed System

The block diagram for the proposed IoT-enabled air pollution monitoring and air purifier system is shown in Fig. 1, which consists of a pre-filter unit, filtering unit, IoT-based sensing unit, and control unit. The system has three types of filters, gas sensors, PM sensors, Raspberry Pi 3 B+ for data acquisition, a power unit, and fans. As can be seen from Fig. 1, the polluted air coming from the atmosphere is first passed through a pre-filter, which is placed before the filtering unit. This filter is capable of filtering naked eye particles from fumes and removing them. It filters out the larger particulate matter and dust particles of sizes greater than 10 μm. It reduces the filtering load of the entire system. It is easy to clean this filter frequently.

In the filtering unit, an exhaust fan is placed, as shown in Fig. 1, for fast suction. Then, three filters are arranged sequentially. The first filter is the primary filter which can absorb the biggest contaminant particles like dust. This filter is made up of cotton and thin cloth material. The second one is the activated carbon filter developed by activated carbon particles. It removes VOCs (Volatile Organic Compounds), odor, and other gaseous pollutants by adsorption method. The HEPA filter is placed next to the activated carbon filter and removes particles of sizes

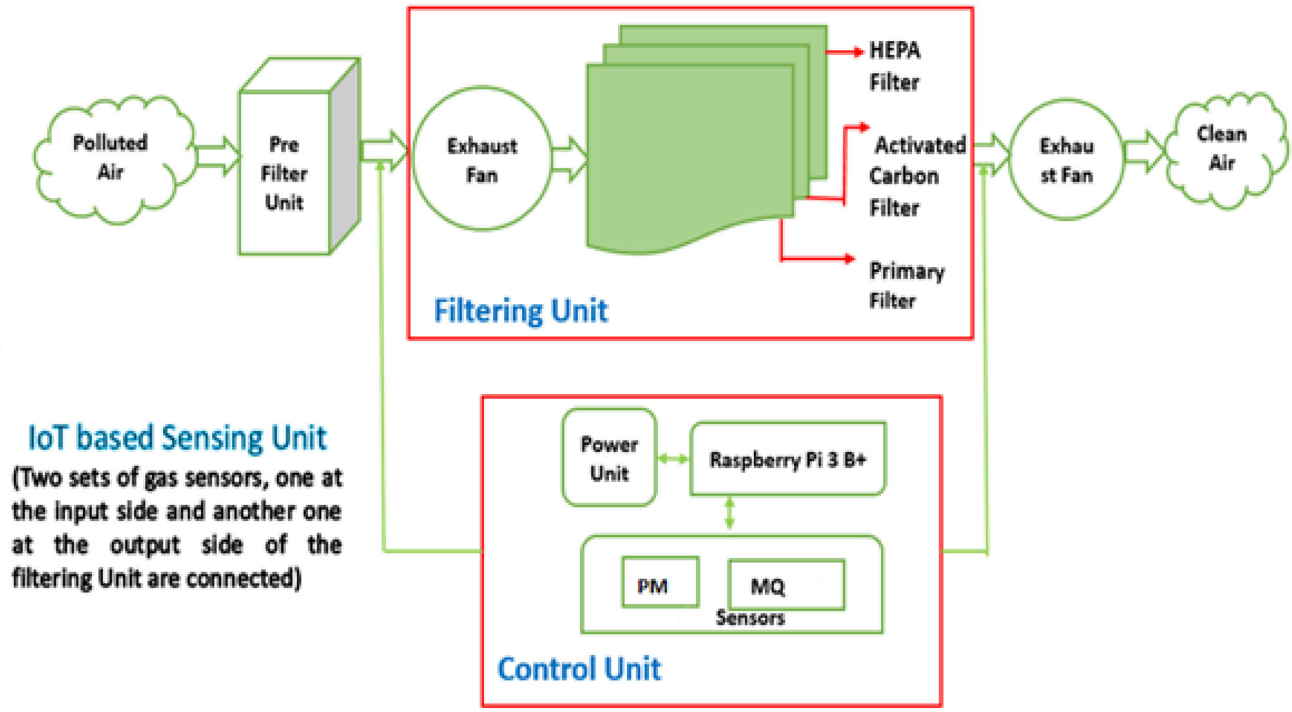


Fig. 1 Block Diagram of the IoT-based Air Pollution Monitoring and Air Purifier System

around 0.3 microns. This filter releases the cleanest air into the atmosphere.

This prototype has two sets of sensors to check the quality of air before and after filtration. One set of sensors is placed before the filtering unit after the pre-filter, and another set of sensors is connected after the filtering unit. Each IoT-based sensing unit has gas sensors (MQ2 and MQ135 sensors) and PM sensors. These sensors are connected to a Raspberry Pi 3 B+ through an Analog to Digital converter and 5 to 3.3 V Logic level shifter. The gas sensors can sense the gases such as LPG, Carbon dioxide, Carbon monoxide, Smoke, and Ammonia present in the polluted air. The concentrations of the particles present at the inlet and outlet of the filtering unit are identified by gas sensors. Similarly, dust particle concentration in terms of mass and number is identified by the PM sensor. The units of the detected particles can be either in $\mu g/m^3$ or the number of particles per cubic meter. The PMSA003 sensor is used to detect Particulate Matter in the range of 0.3 to 10 microns.

The Raspberry Pi 3 B+ board is used for data acquisition, which interfaces all the sensors. The data collected by the sensors is processed by the Raspberry Pi unit, and the values of each gas and PPM level in the location are transmitted through the WiFi Module and are viewed in the Thingspeak Cloud platform. The Thingspeak IoT analytics software is used for sending the concentration of polluted particles measured by the sensors to other users for further analysis. At the end of the filtering unit, another fan is placed to push clean air into the atmosphere. The concentration of various gases and particles is plotted before and after filtering, and the results are analyzed in Sect. 7. The hardware and software tools used for the development of the prototype are given in Sect. 4 and Sect. 5, respectively.

4. Hardware Components Used

4.1. Filters

There are three different filters used to filter particles of various sizes. They are pre/primary filter, activated carbon filter, and HEPA filter, which are shown in Fig. 2.

4.1.1. Pre/Primary Filter

Before filtering, the air is exposed to the pre-filter. This execution ensures the removal of larger dust particles, pollen, organic debris, hair, insects, and particles that we can see by the naked eye. The primary purpose of the pre-filter is to extend the lifetime of the other two filters. The main advantage is its low cost and easy replacement [24]. This filter is made up of cotton and thin cloth material. It removes the particle size from 10 to 25 micron levels [20].

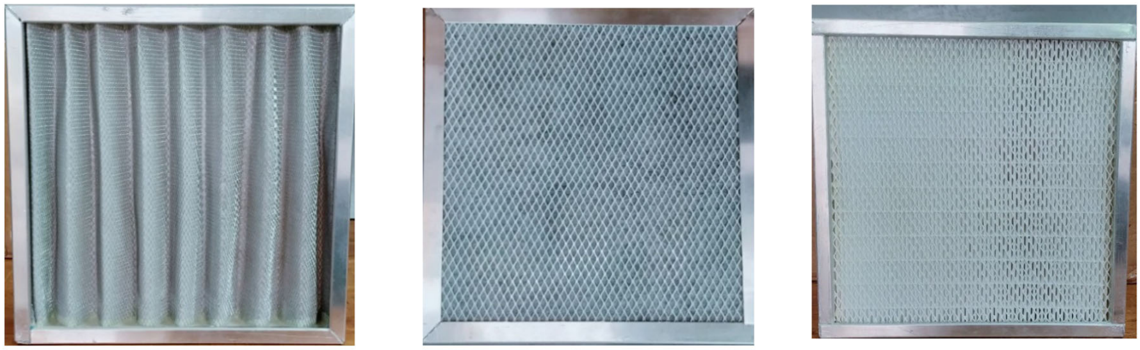


Fig. 2 Three types of filters used in the air purifier

4.1.2. Activated carbon Filter

By using adsorption, a carbon filter traps contaminants inside the pore structure of a carbon substrate. Numerous carbon granules, each of which is very porous, makeup the substrate. As a result, pollutants are confined inside the substrate's substantial surface area. The carbonaceous material used to create activated carbon is often utilized to make filters since it has a significantly larger surface area than untreated carbon. This filter is used at room temperature along with a HEPA filter in most cases to absorb contaminant particles. Its main intention is to remove Volatile Organic Compounds (VOCs), odor, and gaseous pollutants [25].

4.1.3. HEPA (High-Efficiency Particulate Air filter)

Because of their demonstrated capacity to capture particles, allergens, and toxins down to a very small level, HEPA filters (Class-14) are frequently utilized. Any residence with dogs or smokers should use HEPA filters, which are constructed of pleated fiberglass material. HEPA filters are warranted to remove 99.97% of all particles with a diameter of atleast 0.3 microns. It ensures a flow rate capacity of 150 cubic feet per minute and has a pressure drop of 15 mm. The working of HEPA filter uses the principle of Brownian motion for trapping the particles where it has three mechanisms, namely, interception, impact, and diffusion [26]. The size of the filter used in the prototype is 305 $\times$ 305 $\times$ 75 mm.

The frequency of replacing pre-filter, activated carbon filter, and HEPA filter can vary depending on several factors, such as the type of filter, quality of the filter, usage of the filter, and the level of air pollution in the area. Depending on the level of dirt and debris, pre-filter can be replaced every 3–6 months. Activated carbon filters are designed to remove odors, gases, and volatile organic compounds (VOCs) from the air. They need to be replaced every 6–12 months, depending on usage. HEPA filters are designed to remove 99.97% of particles that are 0.3 microns or larger. According to the Environmental Protection Agency (EPA), HEPA filters should be replaced as soon as possible when they become visibly dirty or clogged. A clogged filter can reduce the efficiency of an air purifier, leading to increased levels of pollutants in the air. The existing air purifier model's HEPA filter life span is provided in [27]. According to that, HEPA filters should be replaced every 6–24 months, depending on usage. It is important to note that regular maintenance of the air purifier can also help extend the life of the HEPA filter. This includes regularly cleaning the pre-filter and any other filters and keeping the air purifier in a clean and well-ventilated area.

4.2. Raspberry Pi

The Raspberry Pi is a credit card-sized miniature computer developed by the Raspberry Pi foundation in the UK, and its creation was mainly intended for learners who have more discovering knowledge and creative ideas. Its performance is the same as a common computer except for the hardware storage; rather, it relies on an SD card for storing data, operating system, and programs to start up. It uses the ARM processor for its entire functionality as it has a highly efficient performance speed and faster response [28].

The Raspberry Pi 3 B+ features a processor speed of 1.4 GHz in a compact board that supports Linux, and Python (making it easy to build applications), has many interfaces (HDMI (High Definition Multimedia Interface), multiple USB (Universal Serial Bus), Ethernet, onboard WiFi, Bluetooth, and many GPIOs (General Purpose Input/Output). It is equipped with 2.4 GHz WiFi 802.11b/g/n/ac (150 Mbit/s) and Bluetooth 4.2 (24 Mbit/s) and has a Gigabit Ethernet port, 4 USB ports, 40 GPIO pins, full HDMI port, combined 3.5 mm audio jack and composite video [29].

4.3. Particulate Matter Sensor

The PMSA003 is a laser-based sensor that detects and counts particles in a particular environment by using the light scattering technique. A particle is illuminated by a laser light source as it is drawn through the detecting chamber. The light source becomes obscured as particles move through the laser beam and are captured on the photo or light detector. The electrical signal that is created after the light has been processed and translated into the particulate size and amount information allows for real-time concentration calculations.

It has an inbuilt fan in it to increase the airflow. PM sensor is capable of measuring particulate matter in the range of 1 micron or higher. We can program it to measure at various micron levels. The working principle is the optical scattering of the laser. If the particle size is larger, it scatters a large amount of light at a greater angle. The data obtained from the PM Sensor is stored in the memory of the Raspberry Pi as an object which contains various information regarding the count and density of the particulate matter. The detailed specification of this PM sensor can be found in [30]. The VCC and GND Pins are connected to the USB-TTL (Transistor-Transistor Logic) converter directly. The Transmitter and Receiver pin of the sensor and the USB-TTL converter are interconnected.

4.4. Gas Sensors

Gas sensors are commonly used to detect toxic or explosive gases and measure gas concentration. Gas sensors work on the principle of variable resistance. If the presence of oxygen in the atmosphere is high, the electrons in the sensing material, SnO_2, are attracted to the oxygen molecule. This reduces the flow of electrons. In the presence of a toxic or combustible gas environment, the level of oxygen content is low. So, it reduces the chemical bonding between oxygen and electrons and releases more free electrons back to their initial position. Thus, electrons will be higher, which contributes to higher current flow. The gas sensor senses this current flow, and the gas concentration of the gas sensor is proportional to the current flow.

The MQ2 sensor is also called a smoke sensor, as it is sensitive to smoke and flammable gases. It has the advantage of high sensitivity and fast response time [31]. It detects gases like LPG, CO, propane, Alcohol, CH_4, H_2, and smoke. It has a built-in potentiometer for varying the resistance of the sensor to adjust the sensitivity and get the accurate detection of gases [32]. The MQ135 sensor uses SnO_2 as the sensitive material. Its property increases the conductivity of the sensor if the pollution level in the volume of air increases and detects unhealthy gases [33]. It is otherwise called an air quality sensor, and its cost is very low. It is suitable for detecting Ammonia, NO_x, alcohol, Benzene, smoke, and CO_2 [34].

The accuracy of the MQ2 and MQ135 sensors depends on various factors such as environmental conditions, calibration, and the target gas. In general, these sensors have a good accuracy when detecting certain gases. For example, the MQ2 sensor has an accuracy of around 0–50 ppm for detecting carbon monoxide (CO) and 0–50 ppm for detecting smoke [35]. Similarly, the MQ135 sensor has an accuracy of around 10–10,000 ppm for detecting harmful gases such as ammonia, nitrogen oxides (NO_x), and carbon dioxide (CO_2) [36]. The sensors may react to other gases in the environment, leading to false positives. For example, the MQ2 sensor may also detect alcohol and hydrogen gas, while the MQ135 sensor may also detect humidity. In addition, these sensor's response time can be slow, which means that it may not be suitable for applications that require rapid detection of gases. The sensor also requires periodic calibration to maintain its accuracy and may degrade over time due to exposure to the target gas.

The properties of various gases are described in [37]. MQ sensors have four pins for connection. The VCC and GND pins are used to power the MQ Sensor. The Analog Pin of the Sensor is used to transmit the data from the sensor to the Raspberry Pi with the help of ADC (Analog to Digital Converter) and TTL Converter. The digital pin of Raspberry Pi is not used. In this paper, various gases such as CO_2, NH_4, LPG, CO, and smoke are detected using the MQ sensors.

4.5. Other Components

MQ sensor uses serial communication for the transfer of data to the Raspberry Pi, whereas the PM sensor uses UART Protocol for the transmission of data.

4.5.1. ADC (MCP3008)

This device is used to convert the analog output from the MQ sensor into a digital value which is the required voltage format for the GPIO pins. It has eight channels, a set, and a reset pin.

4.5.2. TTL (BSS138)

N-Channel Logic Level (5 to 3.3 V Bidirectional Converter) Enhancement Mode Field Effect Transistor. This is a logical component capable of converting a higher voltage to a lower voltage value and vice versa.

4.5.3. USB to TTL Converter (CP2102)

To convert a TTL signal to a USB interface, utilize the USB-TTL Converter. Any application that supports serial communication is able to use the USB-TTL module as a native COM Port.

5. Software Tools Used

5.1. Python

For the development of this prototype, Python Language is used to program the microcontroller. Python is a high-level, all-purpose programming language that is interpreted. Its design philosophy places a strong emphasis on code readability through the usage of substantial indentation. Its language constructs and object-oriented methodology are intended to aid programmers in creating clean, comprehensible code for both little and big projects. Python uses garbage collection and has dynamic typing. It supports a variety of programming paradigms, including procedural, object-oriented, and functional programming, as well as structured programming (particularly procedural).

Python programming language is used since it has a large set of libraries. From the given datasheets of the MQ sensors, the appropriate curve for each gas is implemented in the program. This ensures that the sensors measure the accurate amount of the respective gas present in the atmosphere. First, the sensing resistance of the sensor is calibrated in the program by averaging the value of several sensing resistance values after measuring them in each trial in normal conditions. Thereafter, the sensors start measuring the amount of each gas present in the atmosphere and give us the data. The datasheet of MQ sensors contains the resistance ratio (R_O to R_S ratio) for a given amount of particular gases present. Since only for a considerable amount of increase in the PPM value, the R_O to R_S ratio increases slightly, a logarithmic scale is used to view the values. An antilog function at the end of the program is used to get the actual PPM value. The PM sensor data are also transmitted to the cloud platform. Using the urllib library in Python, we upload the data collected using the sensors to the ThingSpeak Cloud Platform.

5.2. ThingSpeak Cloud Platform

IoT is the interoperable technology that connects uniquely identified smart objects with the environment for interaction [38]. Thingspeak is one of the IoT-based open-source cloud platforms. To integrate the Raspberry Pi with Thingspeak, a user account must be created so that necessary channels are accessed for gas concentration monitoring and analysis purpose. The data transfer between Raspberry Pi to Thingspeak is performed by importing the required API keys and necessary libraries to the python program [39]. This software has the provision to display the live value digitally in the widget, which helps to graphically represent the concentration of gases before and after the filtering process every 15 s. With the use of an internet connection, the client can log on to the user account and view the recorded data anywhere and anytime. The recorded data can also be downloaded in the form of a CSV file, and we used MATLAB software for plotting those values.

6. Developed Prototype Structure and Implementation

Figure 3a shows the complete hardware prototype setup. The monitoring and filtering units are encased within the wooden box. The controller is placed over the top. Figure 3b shows the control unit (i.e., the Raspberry Pi along with the sensors). This unit is placed outside the complete setup for easy tampering with the circuit connections. The Raspberry Pi is connected to a 5 V power supply. Gas sensors are connected to Raspberry Pi via an Analog to Digital converter and logic level shifter. The GPIO pins of Raspberry Pi work at 3.3 V. The level shifter converts 5 to 3.3 V, and this voltage is given to the GPIO pins. To get a proper digitalized value from the MQ sensor and for multiplexing various inputs from the different sensors, ADC is used. The PM sensor is also integrated with the help of a USB-TTL Logic Convertor, and MQ sensors use the GPIO pins of the Raspberry Pi. Thingspeak IoT analytics software is used for data transmission and analysis purpose. Section 7 describes the results of gas sensors and PM sensors under various testing conditions.

7. Experimental Results and Discussions

The developed air filtering prototype was tested under various conditions, such as normal airflow, combustion (smoke from burning paper), and agarbathi smoke. The PM sensor produces the results in terms of particle mass concentration in μg/m^3 (number of each particle with different sizes per unit volume) for PM_1, $PM_{2.5}$, and PM_{10} particle sizes, and number concentration (particle count for each particle size in 0.1 L of air) for $PM_{0.3}$, $PM_{0.5}$, and PM_1 particle sizes. For understanding, the sensor provided particle count output in the number of particles in 0.1 L of air is converted to the number of particles per cubic meter using the standard conversion formula. As per the datasheet of the PM sensor, $PM_{0.3}$ is the number of particles from 0.3

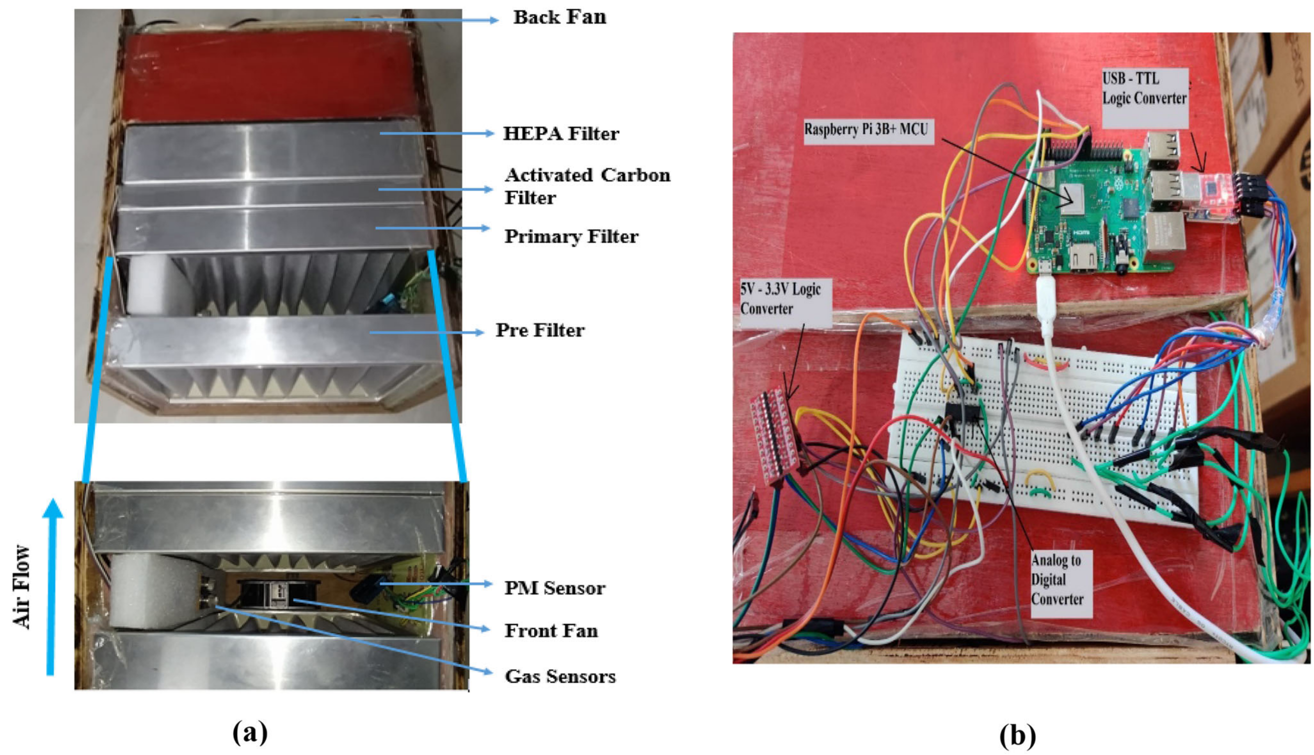


Fig. 3 Complete setup and Raspberry Pi Connections with Sensors

to 0.5 µm, $PM_{0.5}$ indicates the number of particles from 0.5 to 1 µm, and PM_1 is for the particles beyond 1 µm in number concentration outputs. Similarly, the gas sensors (MQ2 and MQ135) provide the particle count of different gases in PPM under the three testing conditions. The sensed concentration of different particles and gases before and after filtration are transmitted to the connected cloud network called Thingspeak. As discussed earlier, the sensed readings are updated every fifteen seconds to the cloud. To verify the performance of the designed prototype, the graphical representation of both sets of sensor readings before and after filtration under various inputs are provided next.

7.1. PM Sensor: Particle Mass Concentration Under Various Test Conditions

7.2. PM Sensor: Particle Number Concentration Under Various Test Conditions

Figure 4 shows the graphical representation of the PM sensor measured particle mass concentration in µg/m^3 under various testing conditions. The plots from Fig. 4a–c show the PM_1, $PM_{2.5}$, and PM_{10} mass concentrations before and after filtration under normal air, combustion, and agarbathi smoke conditions. The values of mass concentration are higher in values, especially under the combustion and agarbathi smoke testing conditions before filtering, whereas after the filtering, the mass concentration values become nearly straight lines with lower values. PM_{10} always shows high concentration, followed by $PM_{2.5}$ and PM_1 at all testing conditions. The highest PM_{10} concentration that occurred under combustion smoke is 294 µg/m^3, whereas a high concentration of 573 µg/m^3 is sensed at agarbathi smoke input before filtration. After passing through the filter setup, the concentration levels are considerably reduced to 65 µg/m^3 for combustion and 75 µg/m^3 for agarbathi smoke. Similarly, in Fig. 4b, under combustion between 300 to 400 s, the mass concentration of PM_1, $PM_{2.5}$, and PM_{10} increase to 199, 245, and 294 µg/m^3, respectively, before filtration. As can be seen from the 'after filtering' graphs in Fig. 4b, the filtration reduces the mass concentration (µg/m^3) of PM_1, $PM_{2.5}$, and PM_{10} to around 50 µg/m^3. Figure 4d–f shows the plots of individual particle mass concentration, PM_1, $PM_{2.5}$, and PM_{10}, under the three testing conditions, and the particle concentration values are always higher before filtration, and it reduces after the filtration. It proves that the designed air purifier filters the particles efficiently.

PM sensor measured particle counts are plotted in Fig. 5. Figure 5a–c are intended for the particle counts of $PM_{0.3}$, $PM_{0.5}$, and PM_1 under normal air, combustion, and

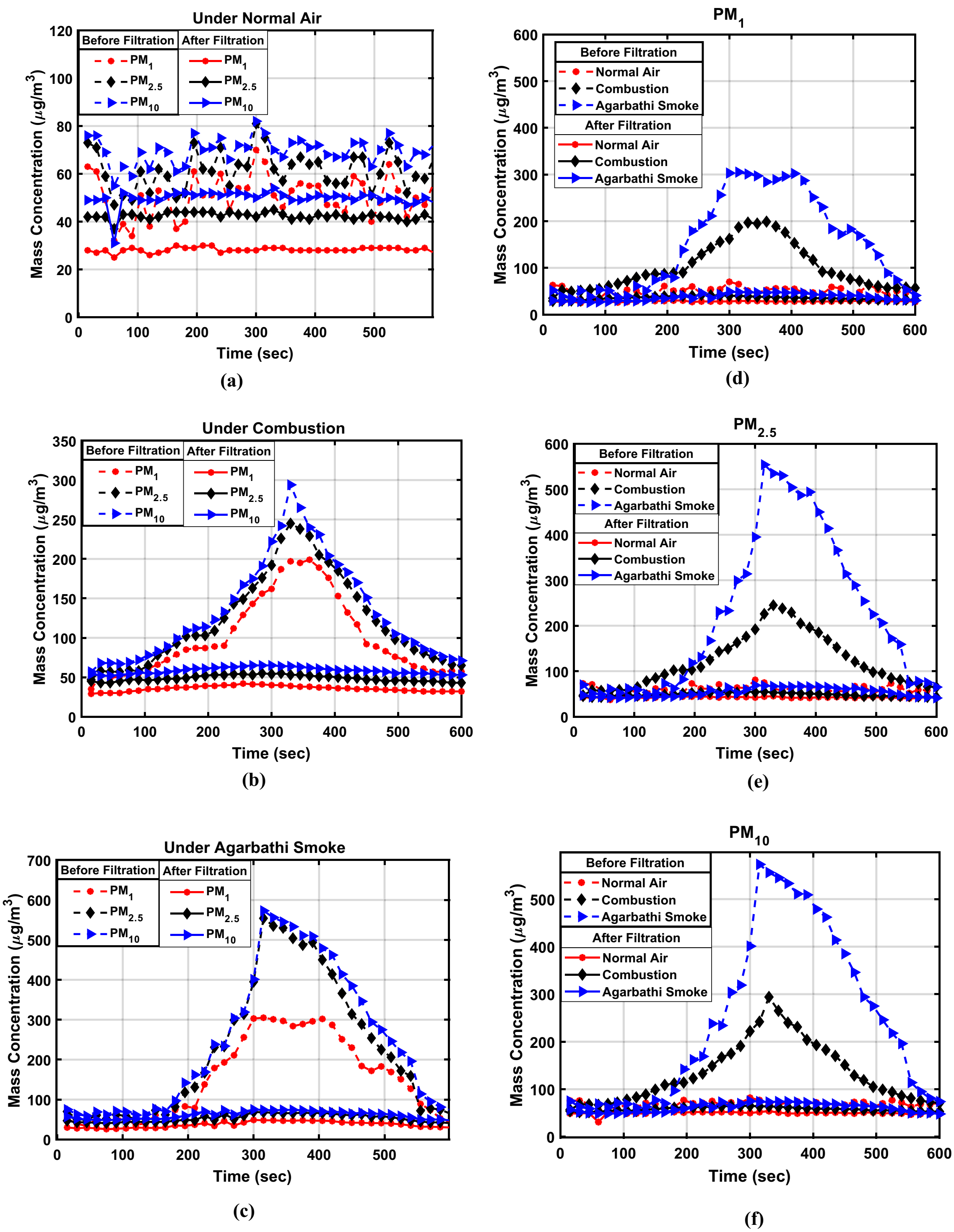


Fig. 4 Results of the PM sensor measured particle mass concentration

agarbathi testing conditions, respectively. Similarly, Fig. 5d–f shows the particle counts of $PM_{0.3}$, $PM_{0.5}$, and PM_1, respectively, under the three different testing conditions. The number of particles encountered in $PM_{0.3}$ is higher, followed by $PM_{0.5}$ and PM_1 under all conditions. Before filtration, the ranges for the particle counts of PM_1, $PM_{0.5}$, and $PM_{0.3}$ are $183*10^4$ to $433*10^4$, $1603*10^4$ to $9298*10^4$, and $5400*10^4$ to $35{,}133*10^4$, respectively, in normal air conditions. During combustion, the number of $PM_{0.3}$ and $PM_{0.5}$ particles rapidly increased from 0 to 380 s, and then the particle count decreased. It shows the sensing capability of the PM sensor. When the agarbathi

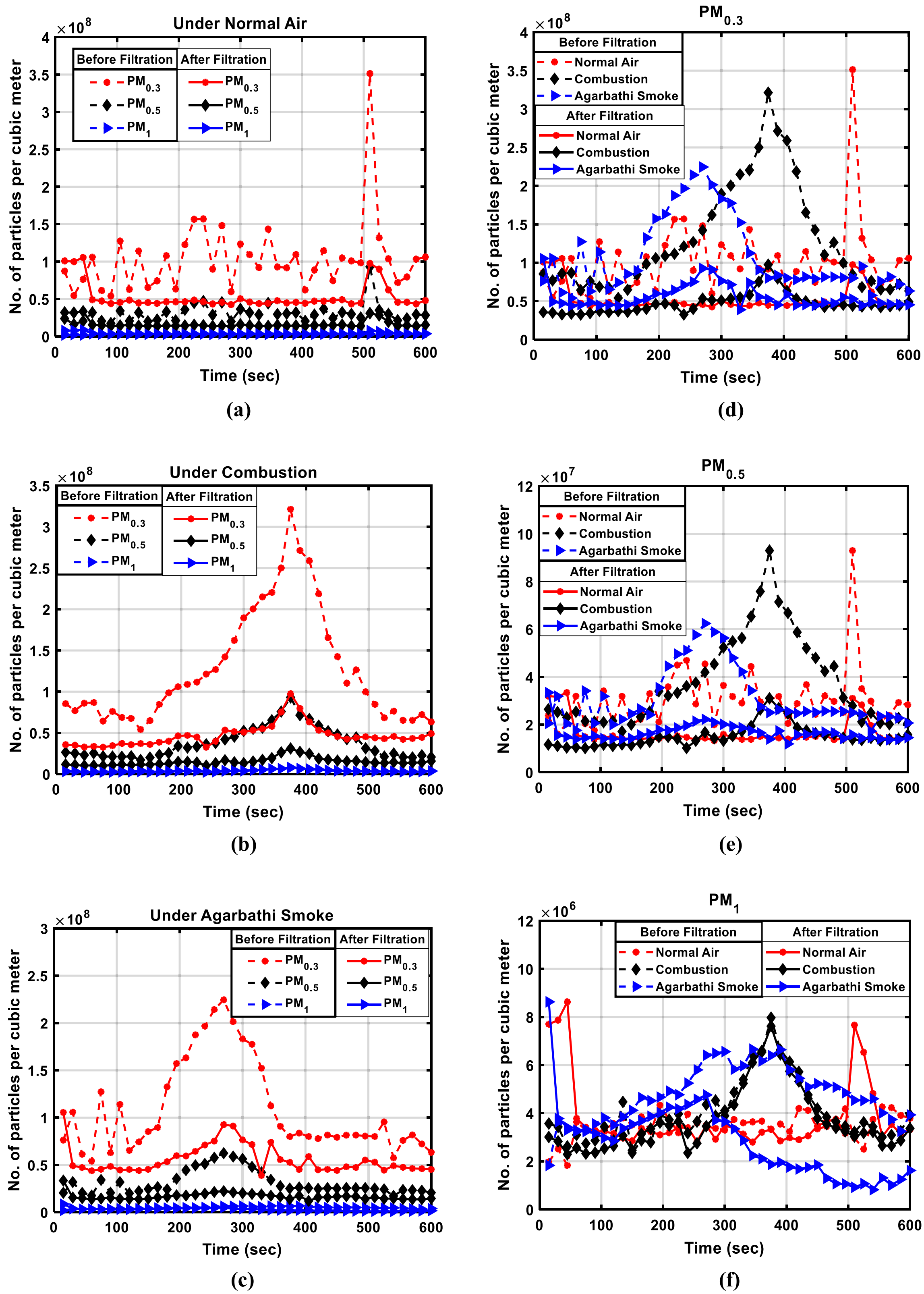


Fig. 5 Results of the PM sensor measured particle number concentration

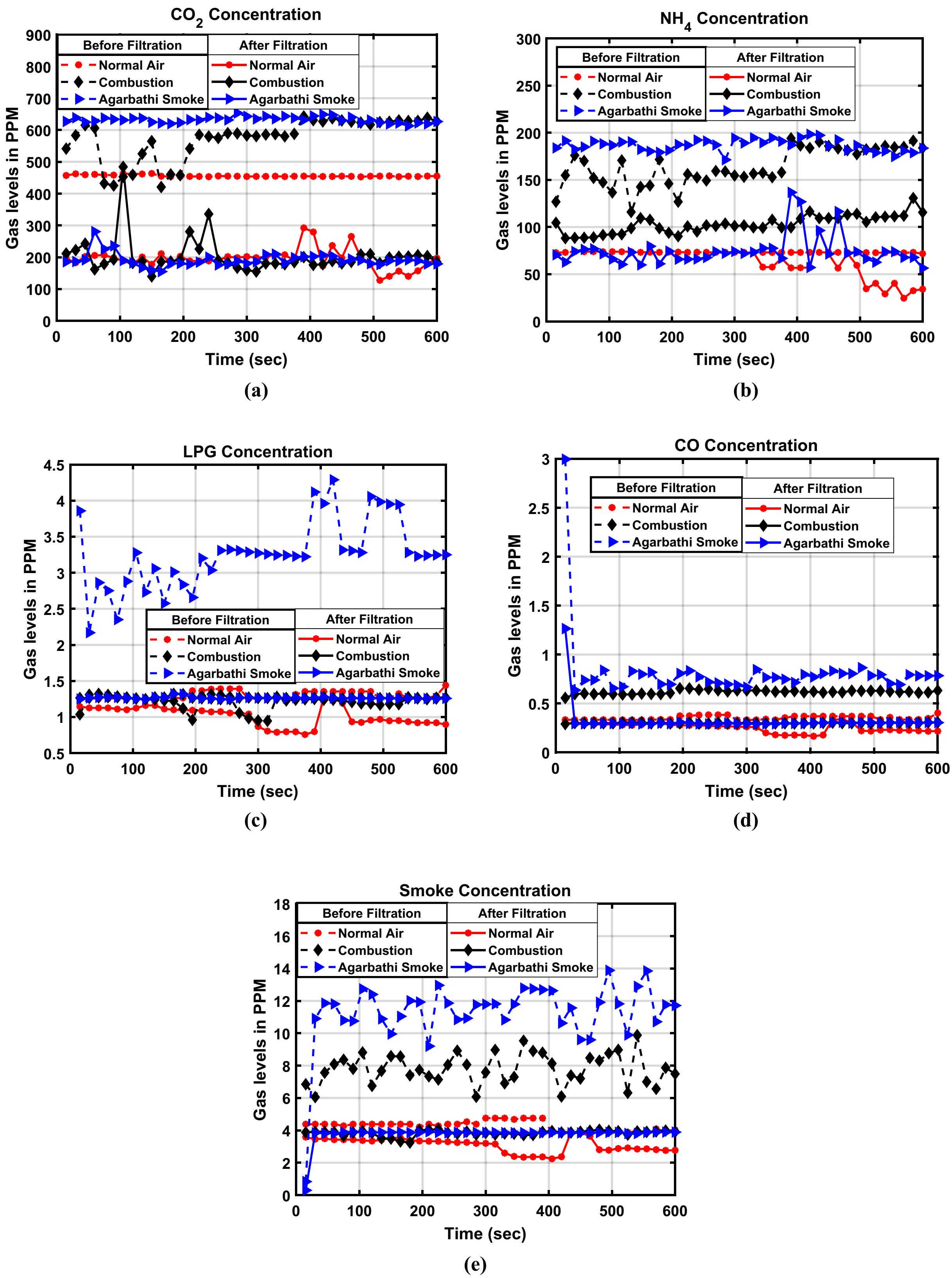


Fig. 6 Results of MQ135 and MQ2 sensors measured various gas concentration

Table 1 Gas concentration ranges during agarbathi smoke

S. no.	Name of the gas	Gas concentration range (PPM)	
		Before filtration	After filtration
1	CO_2	613 to 654	155 to 281
2	NH_4	171 to 198	56 to 137
3	LPG	2 to 4	1.2 to 1.3
4	CO	0.6 to 3	0.3 to 1.3
5	Smoke	0.8 to 14	0.3 to 4

started to burn, the low values of particle counts were there. The increase in smoke increases the particle counts, reaches the maximum value, and then the decrease in smoke levels decreases the same. It is clear from Fig. 5 that combustion and agarbathi smoke release finer particles ($PM_{0.3}$, $PM_{0.5}$, and PM_1), and they cause respiratory diseases. The particle counts shown in Fig. 5 prove the effectiveness of the prototype, as particle counts are higher before filtering and reduced significantly after filtering. The sensitivity of the PM sensor is very good, and it is able to sense well the particles of sizes from very low (closer to 0.3) to 10 µm.

7.3. Gas Concentration Under Various Testing Conditions

The sensing of various gas concentrations by MQ135 and MQ2 sensors is graphically represented in Fig. 6. As discussed earlier, the MQ135 sensor has a high sensitivity to gases like CO_2 and NH_4, whereas LPG, CO, and smoke are effectively sensed by the MQ2 sensor. Similar to particle concentration values in Fig. 4, the agarbathi smoke produces a high concentration of gases, followed by combustion and normal air. The gas concentration ranges before and after filtration during agarbathi smoke are tabulated in Table 1.

At all the testing conditions, the concentration of CO_2 is higher (Range → 127–654 PPM) followed by NH_4 (Range → 25–198 PPM), Smoke (Range → 0.3–14 PPM), LPG (Range → 0.8–4 PPM), and CO (Range → 0.2–3 PPM).

The concentration of all the gases sensed by the prototype under the applied combustion input is presented in Fig. 7. During the burning of paper, high levels of carbon dioxide particles originated, and their range varies from 421 to 643 PPM. The concentration of CO_2 and NH_4 gases in the air is reduced after the air is passed through the three staged filter setup. There are not many variations observed for LPG gases and CO gas before and after filtration.

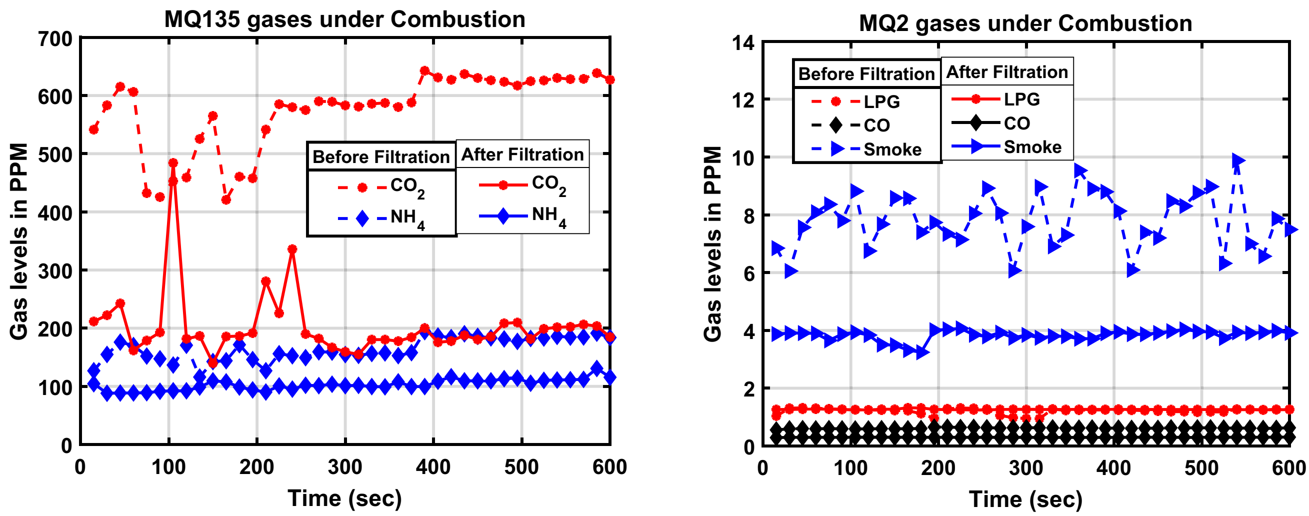
The prototype has been tested with different inputs, such as normal air, combustion, and agarbathi smoke. The PM sensor (PMSA003) and gas sensor (MQ2 and MQ135) output were measured at 300 s under the three different testing conditions before filtration (outputs of sensors placed at the input side of the prototype) and after filtration (outputs of sensors placed at the output side of the prototype) are provided in Tables 2 and 3. As seen from Table 2, the application of agarbathi smoke makes the high mass and number concentration of particles compared to the other two testing conditions. During normal airflow, less amount of particles are present and filtered out.

It is clear from Table 2 that at all the testing conditions, values of PM_{10} are higher in particle mass concentration, and values of $PM_{0.3}$ are higher in particle number concentration. As can be seen from Table 3 and Fig. 7, the testing conditions considered increasing the particle counts of ammonia and carbon dioxide. The proposed prototype is able to filter the particles of all sizes from very small (very close to 0.3 µm) to bigger (around 10 µm) effectively.

A cleanroom is a room where the particulate matter concentration is considerably low compared to a normal environment, and also, the atmospheric parameters such as temperature, pressure, and humidity are kept under control. ISO 14644-1 cleanroom standards and cleanroom classifications are provided in [40]. The prototype is then put to the test by observing it in different environments. As per cleanroom standards, the maximum number of allowed $PM_{0.5}$ and PM_1 particles per cubic meter are 35,200,000 and 8,320,000 in ISO 9 standards. The developed prototype meets the cleanroom standard of ISO 9. This prototype can be utilized for a wide range of applications, such as the food industry, precision instrument/electronics industry, medical biology, cosmetic industry, and laser color printing for filling lines that require ISO 9 cleanroom standards [41].

7.4. Performance and Efficiency Tests of Air Quality Monitoring and Air Purifier System

The performance testing of air pollution monitoring and air purifier system is necessary to determine the efficiency of the developed prototype. In order to achieve this, three different tests are carried out. The performance of the PMSA003, a low cost and high quality sensor is determined by comparing the PM_{10} concentration obtained from the proposed prototype with the nearby three NAMP (National Air Quality Monitoring Programme) station outputs and the performance comparisons of the results are explained in Sect. 7.4.1. The CADR (Clean Air Delivery Rate) test is important to determine the efficiency of the air purification system. The test procedure and the obtained results are discussed in Sect. 7.4.2. The performance test of air quality monitoring and air purifier system under different air speed conditions are given in Sect. 7.4.3.



(a) (b)

Fig. 7 Concentration of different gas levels under combustion

Table 2 PM sensor outputs with different inputs at 300 s

S. no.	Inputs	Before filtration (Applying inputs)						After filtration					
		Particle mass concentration in (µg/m^3)			Particle number concentration (No. of particles per cubic meter)			Particle mass concentration in (µg/m^3)			Particle number concentration in (No. of particles per cubic meter)		
		PM_1	$PM_{2.5}$	PM_{10}	$PM_{0.3}$ $*10^4$	$PM_{0.5}$ $*10^4$	PM_1 $*10^4$	PM_1	$PM_{2.5}$	PM_{10}	$PM_{0.3}$ $*10^4$	$PM_{0.5}$ $*10^4$	PM_1*10^4
1	Normal air	70	81	82	12,336	3644	330	28	42	50	5034	1592	299
2	Combustion	162	192	222	18,957	5235	411	40	54	65	5084	1324	389
3	Agarbathi smoke	303	395	401	18,324	5631	656	49	69	75	7641	2011	365

Table 3 Gas sensor outputs with different inputs at 300 s

S. no.	Inputs	Before filtration (Applying inputs)					After filtration				
		MQ135—gas levels in (PPM)		MQ2—gas levels in (PPM)			MQ135—gas levels in (PPM)		MQ2—gas levels in (PPM)		
		CO_2	NH_4	LPG	CO	Smoke	CO_2	NH_4	LPG	CO	Smoke
1	Normal air	453.74	73.22	1.25	0.33	4.76	201.91	74.09	0.87	0.26	3.20
2	Combustion	583	154.67	1.26	0.63	7.59	159.34	101.16	0.95	0.30	3.84
3	Agarbathi smoke	642.99	194.36	3.27	0.67	11.79	180.49	74.09	1.26	0.29	3.87

Table 4 Details of the test site and NAMP stations used

Station details		Latitude	Longitude	Distance from test site (km)
Test site	NITPY Admin	10° 59′ 17.98″	79° 50′ 49.09″	–
Station 1	B.Ed. College, Nehru Nagar	10° 56′ 25.62″	79° 50′ 2.03″	5.50
Station 2	Govt. Tourist Home, Kovilpathu	10° 56′ 2.90″	79° 49′ 55.41″	6.34
Station 3	Puducherry Power Corporation Limited (PPCL), Polagam	10° 51′ 11.37″	79° 49′ 55.52″	9.02

Table 5 Performance comparison of PMSA003 and reference stations

NAMP station	Date	NAMP PM_{10} (µg/m^3)	PMSA003 PM_{10} (µg/m^3)	RMSE	RB (%)
Station 1	4.4.2022	20	14.806	5.194	− 25.97
Station 2	4.3.2022	41	36.238	4.762	− 11.6146
	8.3.2022	81	79.696	1.304	− 1.60988
	18.3.2022	70	62.385	7.615	− 10.8786
Station 3	9.3.2022	49	67.299	8.299	37.345

7.4.1. Comparison of the Deployed PMSA003 Sensor Output with Reference Instrument

The PMSA003 is a high-precision particle sensor designed to detect particles as small as 0.3 µm. It utilizes laser scattering technology to detect particles in the air, and it can measure the concentration of particles in two different size ranges: 0.3–0.5 µm and 0.5–10 µm. According to the manufacturer's specifications, the PMSA003 has a high accuracy for detecting particles in the air. The sensor has an error rate of less than 10% for particles larger than 0.3 µm and less than 5% for particles larger than 0.5 µm. It has a high precision of ± 10% for $PM_{2.5}$ and ± 15% for PM_{10} measurements. Also, it has a fast response time of 1 s, which makes it suitable for real-time air quality monitoring.

While the PMSA003 is a reliable particle sensor, it does have some limitations. One of the main limitations is that it can only detect particles in the range of 0.3 to 10 microns. This means that it cannot detect ultra-fine particles that are smaller than 0.3 microns, which can be harmful to human health. The accuracy of the sensor can be affected by various factors such as Relative Humidity (RH), temperature, and airflow. This means that the sensor's accuracy may vary depending on the environmental conditions in which it is being used. It requires periodic calibration to maintain its accuracy, and the calibration process can be complex, time-consuming and it is relatively small, which means that it may not be suitable for applications that require high-volume air sampling. Additionally, the sensor is not able to detect other air pollutants such as nitrogen oxides, sulfur dioxide, and ozone. The PMSA003 sensor has a maximum sampling rate of 10 Hz, which means that it can only provide data at a maximum rate of 10 times per second. So, due to the above-mentioned limitations, the performance of the PMSA003 must be tested with the reference instrument. The related review on the comparison of Plantower sensors with reference instruments are provided next.

The field comparison tests were conducted on Plantower PMS5003, Sensirion SPS30, and Honeywell HPMA115S0 $PM_{2.5}$ sensors using Met One BAM-1020 data in [42]. Both multivariate linear regression (MLR) and nonlinear regression (NLR) models using hourly RHs and original sensor $PM_{2.5}$ data as parameters were able to obtain accurate calibrated hourly PM2.5 values with MNBs (mean normalized biases) less than about ± 10% and MNEs (mean normalized errors) less than about 30% for all three types of $PM_{2.5}$ sensors at all monitoring locations. On the other hand, the MNB and MNE of the calibrated 24-h average $PM_{2.5}$ data for the two models were less than ± 13% and 20%, respectively.

The study in [43] evaluated five PMSA003 sensors in Beijing for 7 months with MEE (Ministry of Ecology and Environment) reference monitor, that are located approximately at a distance of 2 km. High accuracy and inter-sensor correlation were revealed by the correlations between the data from the PMSA003 sensors and MEE reference monitors (R^2 = 0.83–0.90) and among the five sensors (R^2 = 0.91–0.98). When the $PM_{2.5}$ concentration was greater than 250 µg/m^3, the relative bias was at -24.82%. Conversely, during times of high relative humidity (RH > 60%), overestimation and large mistakes were noted. With RH > 75%, the relative bias increased to 14.71%. Poor performance was observed during sand and dust storms, especially for PM_{10} measurements.

In this paper, the field comparison of the deployed PMSA003 output is made with the outputs of nearby NAMP stations on the same day. The NAMP is a program implemented by the Central Pollution Control Board (CPCB) in India to monitor and assess the quality of ambient air across the country. The main objective of the program is to determine the present status of air quality in various cities and to assess the effectiveness of pollution control measures taken by the respective state governments. NAMP also collects data on air pollutants such as sulfur dioxide, nitrogen dioxide, Respirable Suspended Particulate Matter (RSPM / PM_{10}) and Fine Particulate Matter ($PM_{2.5}$). The SO_2, NO_2, PM_{10} data are monitored in three NAMP stations at Karaikal.

It uses the APM 460DXNL, a most advanced PM_{10} sampler, manufactured in India based on cyclone based separation technology. The test site is the Administrative block of the National Institute of Technology Puducherry (NITPY Admin) which is located in Karaikal district of Puducherry Union Territory. There are three NAMP stations which are located within the distance of 10 km from the test site. The coordinates of all the 4 places and the station distances from the test site are given in Table 4.

The NAMP station measures the pollutant level in the air twice per week, and each station will acquire the data on different dates. The data measured at each month will be publicly available after that month's end. For the field comparison, the PM_{10} data measured by PMSA003 and the data acquired on the same day at different NAMP stations are taken. The performance metrics such as Root Mean Square Error (RMSE) and Relative Bias (RB) are used to perform the validation [43].

$$\text{RMSE} = \sqrt{\frac{\sum(\text{Sensor} - \text{reference})^2}{n}} \tag{1}$$

$$\text{Relative Bias} = \left(\frac{\text{sensor} - \text{reference}}{\text{average}(\text{reference})}\right) * 100 \tag{2}$$

Based on Eqs. (1) and (2), the RMSE and RB are calculated and provided in Table 5. As can be seen from Table 5, the sensor measured PM_{10} at station 3 shows very high concentration value and the RMSE, RB are also very high as compared to other stations. Station 3 is located at the industrial area (near the gas turbine power plant) and it is the reason for the high concentration of PM_{10} at that place. For station 1 and station 2, the sensors underestimate PM_{10}, and the relative bias values are indicated in negative.

7.4.2. Determination of Clean Air Delivery Rate of Developed Air Purifier

The CADR test is a standard method developed by AHAM (Association of Home Appliance Manufacturers) to determine the effectiveness of the air purifier system in removing airborne particles such as pollen, dust and smoke from the indoor air, irrespective of the technology being used. In other words, it is a measure used to find how fast the air purifier will deliver the pure air to the environment, higher CADR means the fastest purification. This test method follows a certain procedure, that are adopted by worldwide, and the details are provided in [44]. The Bureau of Indian Standards (BIS) also used the AHAM test procedure for finding the CADR of air purifier developed by our nation. The details of portable electric air purifier specification, performance requirement, test pollutants, CADR test method, marking, grading, and manufacturer's guarantee that are adopted in India were found under the BIS number IS 17531 [45]. The CADR test of the proposed air purifier system is performed in accordance with the AHAM standard procedure and is given next.

7.4.2.1. Test Method A room size of 10 × 10 × 13 cubic feet in LxWxH is chosen as the test chamber. This room is set to fully close with no ventilation and the developed air purifier is placed in the center of the room at nearly 5 feet from the floor. A PMSA003 PM sensor is used as the particle counter to perform this test and placed at 3 feet from the filter system. Initially, the air purifier is set to run for 20 min at its high speed to stabilize the filtering and monitoring unit and then it is switched off. After that, smoke aerosols are used as the test pollutants generated by burning the match crackers for 5 min and this smoke produce the particles in the sizes from 0.3 to 1 µm. A ceiling fan is located above the air purifier to mix the smoke particles around the room, and the purifier's nominal air flow rate is measured as 298.6 CFM (Cubic Feet per Minute) at Normal speed. The digital anemometer is used to measure the air velocity in feet/min. The air velocity is multiplied with prototype surface area ($1.575 \times 1.148\ \text{ft}^2$) to get the air flow rate in CFM. The initial concentration is measured as natural decay (reduction in pollutant concentration due to natural phenomena such as surface deposition, chemical reaction, and agglomeration) for 10 min. Then, the air purifier is switched on and run for 20 min. The total decay (reduction in pollution concentration due to natural decay and air purifier filtration) is calculated. The difference between the total decay and natural decay is found. Then, the CADR is calculated by multiplying this difference with the test room volume.

7.4.2.2. Calculation Steps Theoretically, a first-order decay model describes how pollutant concentrations regress:

$$C_t = C_0 e^{-kt} \tag{3}$$

where C_t = Concentration at time t; C_0 = Initial concentration at $t = 0$; k = Decay constant (t^{-1}); t = Time in (min)

The following formula is used to statistically determine the time-resolved decay constant k using a linear regression of ln (C_{ti}) and t_i:

Table 6 CADR values at different air flow rates

Air flow rate (CFM)	298.6	551.35	809.17	1042.80
CADR (CFM)	141.7	174.25	226.58	280.41

Fig. 8 Natural and measured decay rate at different air flow rates

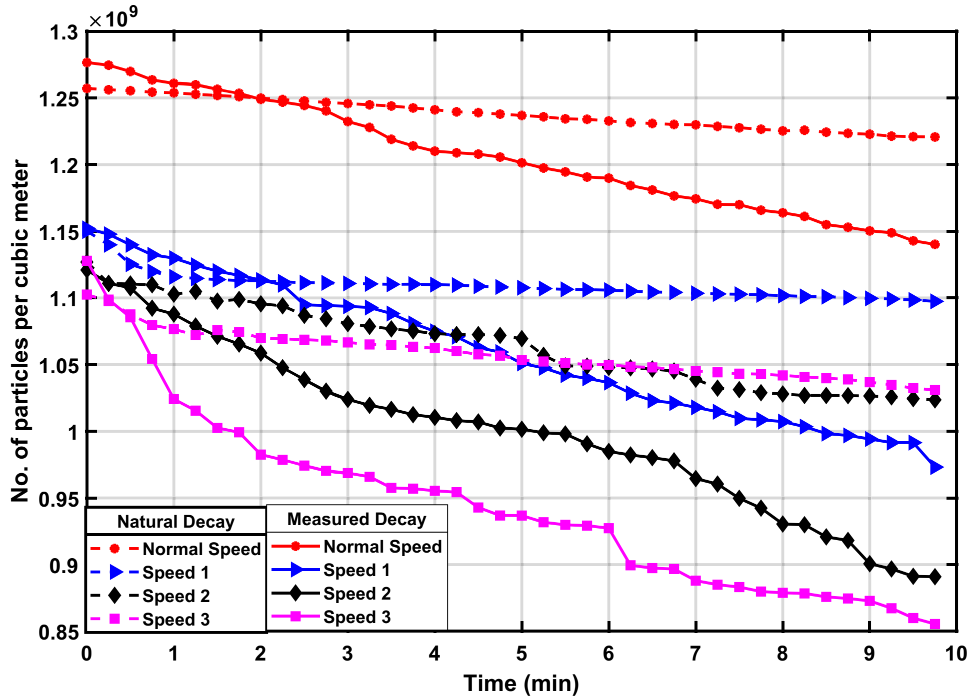


Table 7 Comparison of the proposed system with the existing model

S. no	Air purifier model	Applying space (m^2)	Air flow (ft/min)	CADR (CFM)
1	Philips AC8612	64–109	610–1338	235–535
2	Panasonic F-VJL90C	>100	314–1141	294–412
3	Yadu KJG588G-P5	80–100	–	346
4	Lexy KJ801	60–100	669–1594	282–494
5	Proposed model	100 (tested)	165–576 (tested)	141–280 (tested)

Table 8 Air flow rates at the inlet and outlet of air purifier system

	Normal Speed	Speed 1	Speed 2	Speed 3
Inlet air flow rate in (CFM)	286.76	512.34	786.12	1013.80
Outlet air flow rate in (CFM)	264.97	487.50	742.99	961.23

Table 9 Filtration efficiency (%) of the air purifier system under different air flow rates

S. no.	Air at different flow rates	Filtration efficiency in (%)					
		Particle mass concentration			Particle number concentration		
		PM_1	$PM_{2.5}$	PM_{10}	$PM_{0.3}$	$PM_{0.5}$	PM_1
1	Normal speed	30.48	18.04	10.58	36.13	32	12.65
2	Speed 1	32.81	23.83	13.75	39.06	33.04	16.26
3	Speed 2	36.96	28.18	17.61	41	36.06	25.89
4	Speed 3	42.28	33.54	26.76	49.09	40.29	32.83

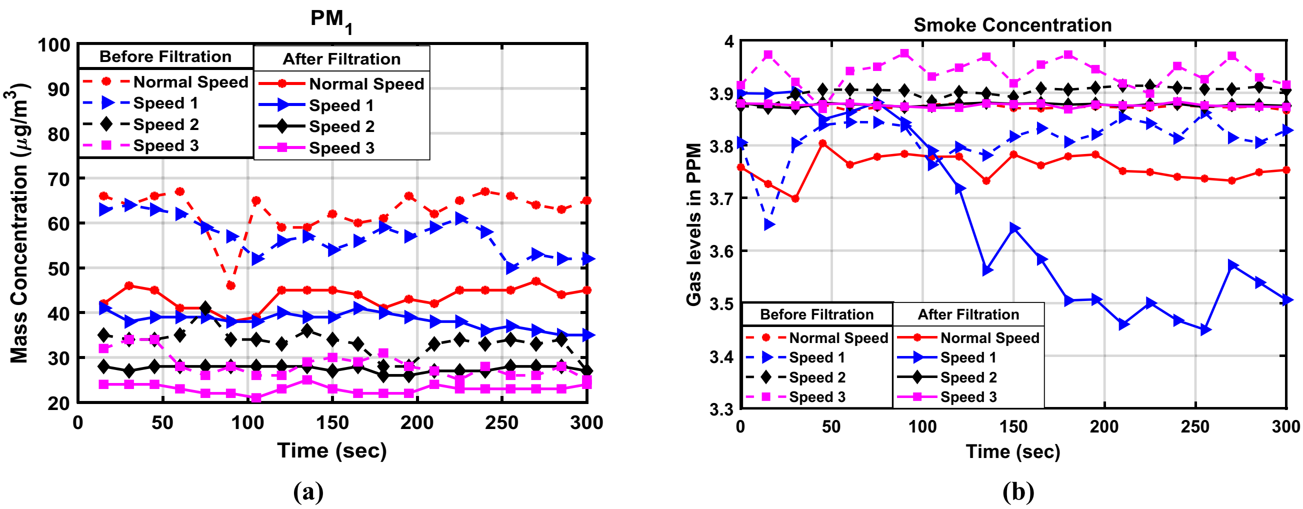


Fig. 9 Concentration of PMSA003 and MQ output at different air flow rate

$$k = \left[\frac{S_{XY}}{S_{XX}}\right] \tag{4}$$

where

$$S_{XY} = \sum_{i=1}^{n} t_i \ln(C_{ti}) - \frac{1}{n}\left(\sum_{i=1}^{n} t_i\right)\left(\sum_{i=1}^{n} \ln(C_{ti})\right)$$

$$S_{XX} = \sum_{i=1}^{n} (t_i)^2 - \frac{1}{n}\left(\sum_{i=1}^{n} t_i\right)^2$$

Based on Eqs. (3) and (4), the formula for calculating CADR is given as per [46]

$$\mathrm{CADR} = V * (k_t - k_n) \tag{5}$$

where CADR = Clean Air Delivery Rate (CFM); V = Volume of the test room (ft^3); k_t = Total decay rate (min^{-1}); k_n = Natural decay rate (min^{-1}).

The test was repeatedly done at different air flow rates, such as 551.35 CFM (Speed 1), 809.17 CFM (Speed 2), and 1042.80 CFM (Speed 3) to determine the CADR test performance at different air speeds. The obtained results (No. of particles per cubic meter as a function of time) are shown in Fig. 8 and CADR values at different air flow rates are tabulated in Table 6.

Figure 8 shows the deviation of measured and natural decay rate at four air flow rate conditions. It represent the decaying of pollutant concentration due to natural phenomena and air purifier on condition (denoted as measured decay in Fig. 8) over the time in minutes and the total decay is the summation of natural decay and measured decay. It is observed from Fig. 8 that the increase in air flow rate should increase the filtering of the pollutant concentration as measured decay at speed 3 (pink) shows rapid decay as compared to other low air flow rates. Similarly, the natural decay is showing slow decay at all the air flow rates as compared to the measured decay.

In Table 6, both the air flow rate and CADR are represented in terms of CFM (The unit explanations for both the parameters are provided in Sub Sect. 7.4.2.1). It is evident from Table 6 that the increase in air flow rate increases the CADR value that is the efficiency of the filtration is increased. As per AHAM [44] the smoke CADR will range from 10 to 450 CFM and the proposed air purifier system achieved the desired CADR at the air flow rates considered. The maximum allowed air flow rate to conduct CADR is 600 CFM [47]. So, the CADR at speed 2 and speed 3 will not be considered, as the air flow rates exceed the limit. The optimum air flow rate and CADR of the developed air purifier are 298.6 CFM and 141.7 CFM, if it is used in the normal environment. The CADR obtained at air speed 1 can also be used, if the environment comes with high pollutant concentration.

Table 7 shows the CADR comparison of the proposed system with the existing models [27]. The available air purifier models are chosen for comparison based on the room size tested. Our proposed model's airflow rate is minimal compared to the other existing systems. So that it provides a low CADR value. Once the air flow rate is increased, the proposed model achieves a high CADR value and performs well like other systems.

7.4.3. *Performance Test of Air Quality Monitoring and Air Purifier System Under High Air Speed Conditions*

7.4.3.1. Testing of Air Flow at Both the End of Prototype The Air flow rate measured at inlet and outlet of the air purifier system under different air speed conditions from low to high are provided in Table 8. It is clear from Table 8 that the air flow rate at the inlet is always higher than the outlet of the system. The pressure associated with the air filter used, should reduce the air flow rate at the outlet of the system. Also, the air flow reduction rate is higher when the flow rate is increased from low to high speed.

7.4.3.2. Testing of filtration efficiency The filtration (single pass) efficiency of air purifier system is determined by finding the particle concentration both at the inlet and outlet of the system [48]. This test measure the particle mass concentration and the number concentration at both inlet and outlet of the system for 10 min during each air flow rate. The overall filtration efficiency is calculated based on the Eqs. (6) and the results are provided in Table 9.

$$\text{Efficiency } \eta(\%) = \left(1 - \frac{\mathrm{PM_{OUT}}}{\mathrm{PM_{IN}}}\right) * 100 \tag{6}$$

Table 9 shows the filtration efficiencies of air purifier at different air flow rates based on the particle mass concentration and particle number concentration measured at both the before filtration and after filtration of the system. As can be seen from Table 9, it is found that filtration efficiency of the purifier system increases, when the air flow rate is increased from normal speed to speed 3 at both mass concentration and number concentration of the PMSA003 output. Also, the minimum filtration efficiency is observed at high particles both in mass concentration and number concentration output.

7.4.3.3. Testing of Air Quality Monitoring System The performance testing of air quality monitoring system under different air speed conditions from low to high air flow rates is required to determine the effect of high air flow in measuring the concentration of both gas and particles. The air monitoring system comprises of MQ sensor such as MQ2, MQ135, and PMSA003 PM Sensor. This test is performed under the smoke of match crackers, which produces the particles ranges from 0.3 to 1 µm sizes. Figure 9 shows the concentration plot of PM_1 (PMSA003) and smoke (MQ2). As can be seen from Fig. 9a, the particle concentration is reduced if the air speed is increased from low to high level and the same is achieved for other concentration. In contrast to the above, the measuring concentration of MQ sensor is increased at high air flow rates. During the high air flow, the MQ sensors are expected to measure high gas concentration. The higher gas concentrations are measured at the higher air flow conditions and this is true for all the MQ sensor gas concentrations measured. The Conclusion and future work are provided next.

8. Conclusion and Future work

The IoT-enabled air pollution monitoring and air purifier prototype are designed. The monitoring unit consists of two sets of MQ sensors (MQ2 and MQ135) and PM sensors. MQ sensors sense the presence of gases such as CO, CO_2, NH_4, LPG, and smoke. These sensors are connected to the GPIO pins of the Raspberry Pi microcontroller. The PM sensor uses the UART protocol to establish the connection to the microcontroller. The control (filtering) unit contains three types of filters for step-by-step filtration of air pollutants. Two exhaust fans are placed at the front and rear ends of the prototype setup. The designed prototype is tested under normal air, combustion, and agarbathi smoke inputs. An IoT-based sensing network is developed using a Raspberry Pi controller and sensors for finding the concentration of various gaseous pollutants present in the atmosphere and sending the sensor readings via the cloud to further analyze it. The proposed prototype is able to sense gases CO_2, NH_4, LPG, CO, and smoke and filters particles of all sizes from very small (very close to 0.3 µm) to bigger (around 10 µm) effectively. The developed prototype is suitable for ISO 9 cleanroom standard applications. The developed prototype costs about Rs.15000/-, which is lower than the existing air pollution prototypes in the market. The CADR test, the field comparison of PMSA003 sensor against NAMP stations, and the performance test of both the air quality monitoring and air purifier system are done under the high air speed conditions.

This prototype uses two MQ sensors. But there is a provision to add multiple sensors with a wide range of gas detection capabilities. To achieve green energy standards, this prototype can be powered by renewable and alternative power sources. The addition of one or more HEPA filters or a nano-filter after the current filters in the designed prototype improves the filtering capability of the purifier and helps to meet better ISO cleanroom standards. The development of filters' fault detection and cleanliness detection technique can also be included to enhance the lifetime and performance of the designed air purifier.

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