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Article

A cost-effective IoT-based intelligent indoor air quality monitoring

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SUMMARY

Air quality monitoring has become a critical issue for human beings as it is related to living quality. Poor air quality harms human health, worsening respiratory diseases, increasing heart risks, impacting brain health, and endangering vulnerable populations. Various countries legislate air quality norms related to air monitoring and measurement standards. Nonetheless, most of the monitoring stations for air pollution are set up outdoors and monitor sources of air pollution and greenhouse gases in larger regions, neglecting the importance of indoor air quality (IAQ). Thus, monitoring the IAQ for better healthcare has become necessary. However, low-cost sensors are often associated with design compromises that hamper data reliability. Although scientists have extensively studied IAQ, the practical application of low-cost devices in indoor environments has yet to be investigated. We explored the effectiveness of a low-cost IAQ experimental monitoring device by studying the quality of the results gathered from the reference monitor unit. We hypothesized that the advanced technology and sensors would provide accurate and valid data to make the low-cost IAQ monitor feasible for widespread usage. Our goal was to provide an intelligent, movable, and cost-effective indoor air quality monitoring unit which has been designed to simulate users' indoor routes and detect air quality in real-time. Since, the main factor affecting the accuracy and validity of the measurements results from its orthogonal design. Our results revealed a low-cost monitoring device can be used with efficient design and by using sensors that are highly accurate which are low-cost for accurate and valid readings.

INTRODUCTION

The World Health Organization (WHO) has set the air quality guideline for annual exposure to particulate matter under 2.5 µm ($PM_{2.5}$) to be less than 10µg/m³, which is the definitive and strictest global standard (**Figure 1**) (1). Furthermore, WHO and ongoing research indicate that $PM_{2.5}$ exposure should be as close to zero as possible, especially considering the impacts on childhood development (1). $PM_{2.5}$ is a common pollutant that reaches high levels indoors (2). $PM_{2.5}$ is one of the most dangerous pollutants due to its small size. It can be absorbed into the blood, causing adverse effects on organs (2,3). International organizations stress the impact of air pollution and estimate that environmental air pollution kills an estimated seven million people worldwide every year (2). Reports also estimate that air pollution kills more people annually than global pandemics ever will (3,4). Comunian et al. observed a positive correlation between the spread of the pandemics and air pollution (5). Moreover, atmospheric PM could create a suitable environment for transporting the virus at greater distances than previously considered for close contact (5,6).

The need for reliable air quality monitoring in indoor environments is critical due to the plethora of potential pollutants that might arise in high concentrations in indoor environments. Conventional indoor air quality (IAQ) monitoring approaches that use high-cost, complex, stationary devices have limited data access, application flexibility, and overall affordability (7). In recent years, low-cost sensor technology has made remarkable advances, providing an opportunity to change this status quo (8). Low-cost indoor air quality monitors will promote wide use with the realizability and increase in validity data. Despite this, the reliability of low-cost sensor data is often questioned due to design flaws and the need for frequent recalibration. However, the increasing number of studies and projects using non-conventional literature based on low-cost sensors has led to scattered information and a need for studies on sensor performance and calibration/validation. Standardizing performance assessments and implementing credible validation processes through sensor calibration/validation analysis could help address these gaps (7).

To bridge this gap, our study aimed to develop a novel indoor air quality (IAQ) monitoring device capable of simultaneously collecting and calibrating seven crucial air quality parameters in real time: $PM_{0.3}$, $PM_{0.5}$, PM_1, $PM_{2.5}$, PM_5, PM_{10}, and temperature (C). Employing the Arduino IDE, we designed the device using a PMS5003 air particle dust sensor, an ESP8266 Wi-Fi Internet of Things (IoT)

Figure 1: Airborne particulate matter size breakdown. Size shown from a human hair strand (180 µm) down to an atom (0.1 nm µg/m³).

module, and MQ135 vapor/gas microsensors. Evaluating the experimental-grade device's performance and utility, we compared its measurements with those of a commercial-grade air quality monitor, the Kaiterra Laser Egg. The experimental device was successfully designed and constructed during this project, producing results comparable to those of the reference commercial-grade air quality monitor. Remarkably, this study represents the first of its kind, concentrating on low-cost IAQ monitoring devices, encompassing calibration, validation, and performance assessment. Utilizing the Wi-Fi standard of the Institute of Electrical and Electronics Engineers (IEEE 802.11) for connectivity offers advantages like reduced communication delays and lower system costs. However, it can increase energy consumption, affecting device autonomy. To address this, we employed the Espressif Systems Product (ESP) 8266-12F module as an efficient and low-cost, ultra-low-power solution for Wi-Fi-enabled devices. Mesquita et al. suggested that the ESP8266-12F module demonstrated suitability for battery-powered IoT applications with a 1000mAh battery and seconds-scale transmission intervals (9). To further enhance the performance of the low-cost air quality monitor, we designed a printed circuit board (PCB) during the project, contributing to increased device efficiency. A well-designed PCB can improve signal integrity, reduce noise, and provide more accurate sensor readings (10,11). Furthermore, it can reduce the device's size and weight, making it more portable and user-friendly. Additionally, a good PCB design can improve the device's reliability and durability, reducing the need for frequent repairs or replacements (12,13).

Our research aimed to contribute to the advancement of reliable and cost-effective IAQ monitoring devices by presenting specific study details. The results shed light on the value of real-time air quality monitoring through this platform, enabling occupants to take necessary measures for air quality improvement. This stands in contrast to the limitations of many commercially produced air quality measuring devices, often restricted to hourly or weekly averages (8). Technologically advanced but low-cost sensors are being evaluated for their ability to provide accurate data that can be verified against a reference indoor air quality monitor. Earlier studies have revealed that design flaws could compromise data validity (9,10). We used our innovatively designed and developed experimental device for the experiment, eliminating the problem associated with low-cost sensors' lack of data reliability due to flaws in their design. Near real-time data capture enhances the accuracy of the results from the sensors and reduces data reliability issues (15). During the device's design stage, the two primary requirements are the low-cost sensors' sensitivity to ambient pollutant concentrations and the second calibration of the sensors.

RESULTS

The proposed air quality measuring device was designed as a low-cost efficient device to detect indoor air quality experimental device used an orthogonal design with effective low-cost particle sensor and temperature sensor to test the effectiveness comparing a commercially available air quality monitor. The reference instrument used in the study was the Kaiterra laser egg, which uses an optical sensor that counts individual particles in the air, similar to the sensor used in the experiment device as the device is also IoT enabled.

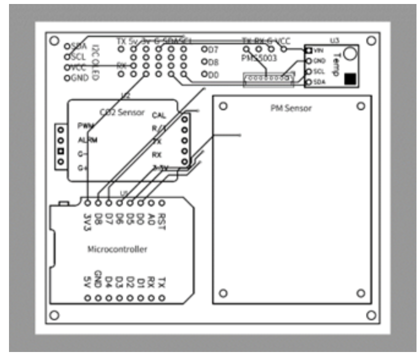

Figure 2: Schematic capture of the designed PCB for the air quality monitor. WithEasyEDA a web-based PCB design tool.

Furthermore, the device is calibrated using cloud-based data from the manufacturer. The experimental device used an innovative design schematic to mount components on a printed circuit board (PCB) was decided on the printing and mounting of components. (**Figure 2**).

Before the test both the reference and experimental devices were accurately calibrated/validated together, and air quality data were collected twice a day for two weeks (morning and evening). The experimental and referral devices were used simultaneously, and PM_1, $PM_{2.5}$, PM_{10} values were obtained from the reference and the experimental device (**Figure 3**). The results obtained from the sensors were transmitted to the IoT platform via the Internet.

Data collected from the experimental IAQ device and the reference device, which consisted of 28 data observations for each of the devices, showed that the results of the devices were similar (**Figure 4**). We found that there was no significant difference in the mean air quality measurements between the experimental device and the reference monitor: 31.32 ± 2.27 μg/m³ vs. 31.11 ± 3.10 μg/m³, respectively (*t*-test, *p*=0.739). Test results revealed that the effectiveness of the low-cost IAQ device closely correlated with the reference instrument.

Reference measurements were made on ambient air continuously with the test device kept side by side. Readings were from the particle sensor in a closed-door living room environment. Readings from the device and the IoT platform

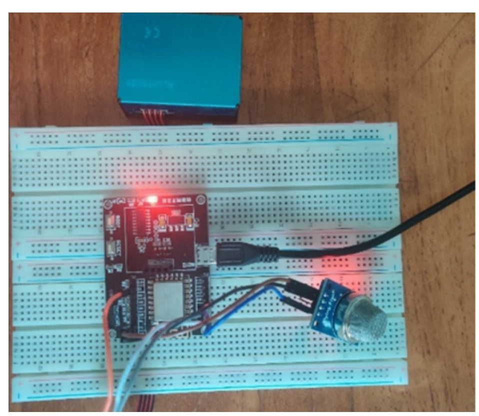

Figure 3: Prototype of the microcontroller and the PMS5003 particulate monitoring sensor. Testing and code testing for serial output for results.

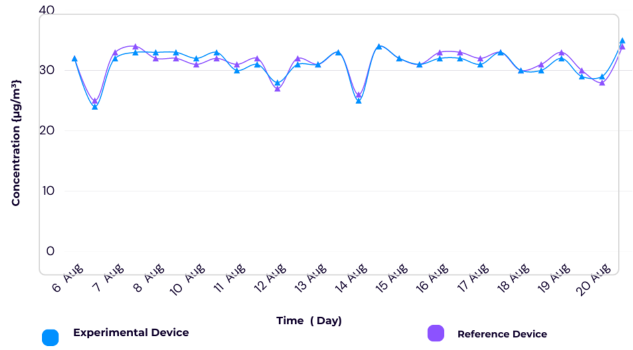

Figure 4: PM concentrations of the two-reading. Experiment and Reference devices for two weeks.

also indicated that the room pollutant level of the ambient indoor environment was moderately polluted during the second reading in the evening based on the air quality index reading above AQI of 50 and $PM_{2.5}$ above one (8,14). Our results show that the advanced technology and sensors provide accurate and valid data to make the low-cost IAQ monitor feasible for widespread usage. Typical airflow rates for low-cost air quality meters can range from 50 to 500 mL/min (13). Due to the experimental design, intake for air flow was optimized by the orthogonal design and air intake place to the particle sensor to enable air flow rate of 500 mL/min.

The development of an IoT-based IAQ monitoring device and its components, including the sensor selection, was done while considering the minimum cost and maximum measurement accuracy. Low power consumption sensors were selected so the measurement device could also be used with batteries when necessary. The unit cost of the devices developed for IoT-based air quality measurement is $33 (**Table 1**). Therefore, the low-cost research-grade device developed for air quality measurement, with its portability, scalability, and modular features, can offer a reliable and effective solution for air quality measurement systems compared to existing commercial solutions (18). The technical specifications of reference commercial air quality sensors with prices ranging from $96 to $132, indicating that the proposed IAQ monitoring device has a significantly lower cost compared to its commercial counterparts that make similar measurements (**Table 2**).

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Component	Cost ($)
ESP8266-12E Chip	5.00
PMS5003	15.00
MQ-135	2.00
BMP280	1.00
PCB	4.00
5V/10Ah Power Bank	5.00
Power Supply Cable15V	1.00
Total	33.00

Table 1. Cost details of the components and sensors used for the IoT-based IAQ monitoring device.

DISCUSSION

Indoor air pollution has received wide attention during the global Covid-19 pandemic as it harms people's health. Commercially available air quality monitors are not in wide use due their high cost. Our goal was to design and build an efficient low-cost indoor air quality monitor that can provide accurate and valid data similar to a commercially available air quality monitor. Our results demonstrated that the near real-time data from the tested sensors displayed particulate matter ranging from 0.3 µm to 10.0 µm. The data from the sensors were transmitted to the IoT platform, which allowed us to aggregate, visualize, and analyze live data streams. Sensors in the device were calibrated, and data were validated through a reference instrument before testing. The smallest detectable microparticles of 0.3 µm were the most abundant and abundance decreased as the size of the particles increased. The Kaiterra Laser Egg retail cost is approximately $132 compared to the experimental device built for this experiment, which cost $33. We validated the experiment data with the reference instrument daily and confirmed the results for two weeks twice a day (morning and evening). Based on the readings from the experimental and reference devices through the IoT platform readings demonstrated indoor testing location to be moderately polluted. As a solution to the pollution in the room air condition (AC) units in the room was fitted with an additional external filter on top of the AC mesh filter, which showed reduction in the pollutant level dramatically.

Once the data reliability was verified and satisfactory, the collected data was used for sampling for better calibration methods, behavior patterns of airborne pollutants. The use of low-cost air quality monitors offers numerous advantages over their expensive high-end counterparts that use the same sensor technology. Firstly, low-cost AQMs are more cost-effective, making them accessible to a broader range of individuals and communities (11). This, in turn, allows for increased monitoring coverage, especially in low-resource settings. Secondly, low-cost AQMs are easy to use and offer real-time monitoring, allowing immediate action if pollutant levels exceed recommended limits, just like commercially available devices (11,12). Additionally, low-cost AQMs can be customized to suit specific monitoring needs. In contrast, commercially available AQMs justify their high cost through their proprietary algorithm with similar sensors. For instance, the Kaiterra Laser Egg AQM requires the use of the company's cloud-based calibration software, limiting the device's portability. Users depend on the company to update device calibration remotely, thus, limiting the usability of the monitor as the locations are limited and updated frequently (9). In addition, there are privacy concerns about data collection from devices. The proposed measurement system can provide precise information about the instantaneously changing pollutant concentrations. Furthermore, the experimental

Brand	Retail Price	PM size/sensor
Kaiterra Laser Egg	$132	0.3-2.5 µm

Table 2. Technical specification of commercially available air quality used as the reference device.

device is much cheaper and expandable, and sensors for different pollutants can be added. Additionally, long-term data recording (over 1 year) can be stored in the cloud server, and it allows for an adjustable contaminant threshold. Recently sensor technology has improved dramatically with sensitivity for satisfactory reading of pollutant concentrations. However, calibration challenges persist as the sensors are prone to cross-sensitivities with other ambient pollutants (15,16).

With further enhancements and developments, additional sensors such as temperature, humidity, or other airborne health hazard detectors can be integrated. We have also tested a more accurate sensor for CO_2, Sense Air S8, which uses infrared to measure CO_2. The growing popularity of low-cost devices to monitor IAQ ecosystems can be used to understand indoor air pollutants' behavior and potentially reduce the impact of related health care. We would also like to enhance monitoring capabilities to generate triggers and alert the inhabitants regarding the deteriorating air quality levels indoors. Inhabitants could then respond to improve the air quality by increasing indoor ventilation and replacing air filters.

There are several limitations that should be acknowledged when interpreting the reported findings. Firstly, the study only utilized a single new device as a reference monitor, without considering its long-term durability and consistency. Nonetheless, given that most studies last from 15 minutes to several days, conducting a two-week study is expected to yield reliable results (14,15). However, mitigate the limitation using two reference units can be used, Secondly, the absence of a standard calibration methodology presents a significant constraint in drawing conclusive insights about the sensors/devices used. Since calibration is essential to the sensors prior testing for consistent data gathering and for repeatability of the experiment. Limitation can be mitigated by documenting a step process of calibration and calibration both devices prior to each testing and reading. According to Zamora et al., monthly calibrations demonstrated the highest accuracies, although comparable accuracy levels could be achieved with just one or two calibrations (16). Consequently, it is crucial to regularly conduct onsite calibrations for both the low-cost sensing technology and the reference instrument, even if a prior calibration was performed in the laboratory. Moreover, to ensure the experiment's robustness, it is recommended to use instruments for comparison that employ governmental references for monitoring indoor air quality (10).

This study's main outcomes suggest that some low-cost sensors/devices exhibit good performance and can be utilized in indoor environments. Nonetheless, qualitative air quality understanding can still be gained from a significant part of the low-cost sensing technology evaluated in the study, providing valuable insights into indoor air quality management and personal exposure (15). As a ready-to-use and tool, it can alert end-users to high levels of pollutants and enable them to implement simple mitigation measures. However, caution is advised as it may not match the reference instruments' quality when measuring extreme levels (15,16). Performance indexes, settings, and conditions in the laboratory or field play a fundamental role in the performance of air quality monitoring technology (17). To ensure ongoing advancements in low-cost environmental sensing technology, future research efforts should concentrate on evaluating the long-term performance of these devices, creating quality control algorithms to minimize errors and eliminate bias, and establishing standards and guidelines for testing.

MATERIALS AND METHODS

Particle Sensor was carefully selected after extensive research for cost-effective sensors without compromising the quality that can measure relevant air quality parameters such as temperature, humidity, CO_2 concentration, and particulate matter ($PM_{2.5}$ and PM_{10}).
The use of Wi-Fi standard institute of Electrical and Electronics Engineers (IEEE 802.11) for connectivity provides shorter communication delays and lower system costs, but it can be energy-consuming, impacting device autonomy. In this study, the Espressif Systems Product (ESP) 8266-12F module was used as a efficient and low-cost, ultra-low-power solution for Wi-Fi-enabled devices. Mesquita, et al. postulated that the ESP8266-12F module showed suitability for battery-powered IoT applications with a 1000mAh battery with seconds-scale transmission intervals (9).

The PCB design was undertaken to suit a orthogonal design with compact sensor mounting and also addressed the components' placement by increasing the airflow intake efficiency without compromising compactness PCB design was done using EasyEDA a web-based PCB design tool with schematic capture. The tool also helps to do PCB layout, and simulation. Arduino programed microcontroller ESP8266-12E and PMS5003 particle sensor which can be powered using a battery or power supply was mounted on deigned PCB.

In designing the PCB and components placement, extra care was taken to monitor the airflow to the device to improve accuracy ensuring an optimal airflow rate of 500 mL/min. Airflow to the inlet is critical for a good air quality monitor device because it ensures that the air being sampled is representative of the ambient air in the surrounding environment (19). If the airflow is adequately controlled and calibrated, it can lead to accurate readings and accurate data (16). A stable and controlled airflow is important to ensure that the air sample collected by the device is representative of the air in the environment being monitored (15,16). For the air flow monitoring, the BT-100 handheld Anemometer was used. The data collection period was two weeks twice a day (morning and evening), to gather a representative sample of air quality data and a reference air quality monitor. Data analysis tools Seaborn in Python were used to visualize and analyze the collected data. Results were evaluated by comparing the indoor air quality data to standards and benchmarks of the monitored environment.

Hardware components and costs

The hardware components consist of two modules and a power source, which includes Plantower PMS5003 $PM_{2.5}$ laser scattering air particle detector, ESP8266 IEEE 802.11 (Wi-Fi) IoT Module, andBMP280 module -Temperature, Pressure, and Altitude. The orthogonally designed monitor was added as a communication platform to capture data in near real-time and to add IoT capabilities to the device. The testing was carried out using each individual sensor with "Android Studio IDE" Java programming language code communicating via ESP8266-12F to validate results.

We combined and interfaced sensors that detect fine particles (PMS 5003) with ESP8266 WiFi module using computer programming code, specifically using Arduino for

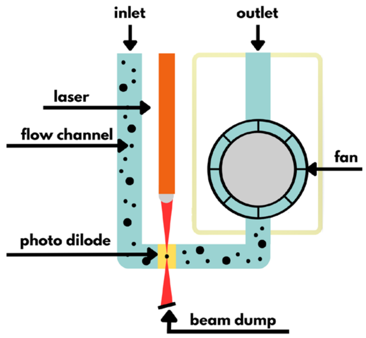

Figure 5: Air quality measurements using particle matter. Light scatter working principle.

the project. PMS 5003, used to measure PM_1, $PM_{2.5}$, and PM_{10} values, is a sensitive sensor produced by Plantower, which calculates the number of suspended particles in the air using the laser scattering principle. PMS 5003 is a laser scatter particle sensor that counts the number of particles that pass through a laser beam to determine the concentration of particulate matter in the air. Emitting a laser beam, it measures the scattering of light from particles in the air. A photodetector detects the scattered light, and the signal is processed to determine the size and concentration of particles in the air (**Figure 5**). The PMS5003 particle sensor uses a laser to measure and contains a small fan to maintain a constant airflow across the sensing chamber. It is a sensor with PM detection capabilities with an operating range between 0.3 μm~10 μm, −10~+60°C, and 0~99 rH% relative humidity. The sensor is 50×38×21 mm in size with a maximum consistency error of ±10%@100~500μg/m³ based on the device's datasheet (11,15, 20). It is used in many commercially produced air quality measurement systems due to its stable and accurate measurement features (19,20).

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