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Hanin Othman, Rahman Azari & Tamy Guimarães

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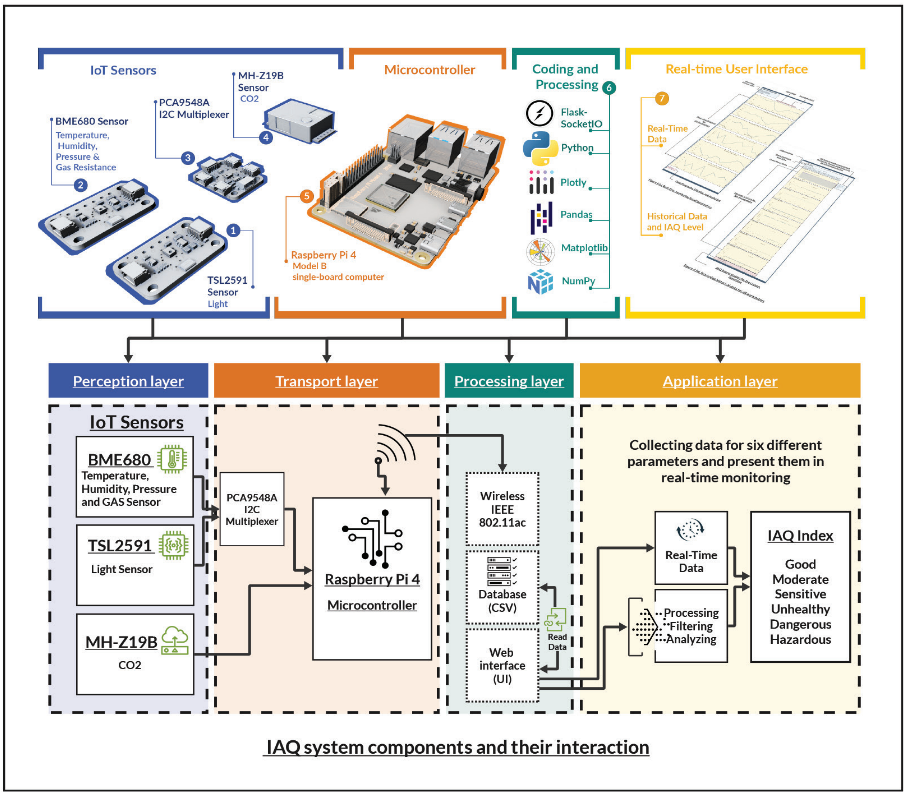
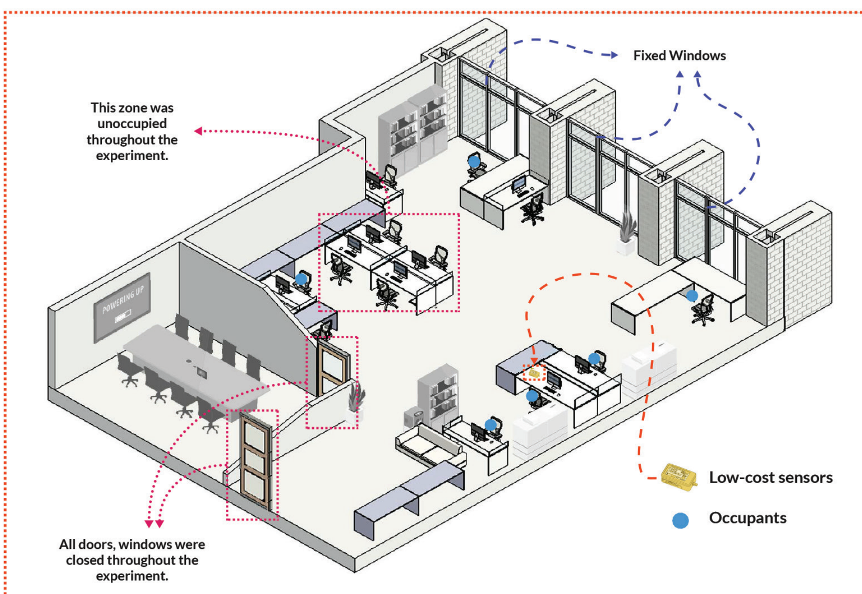
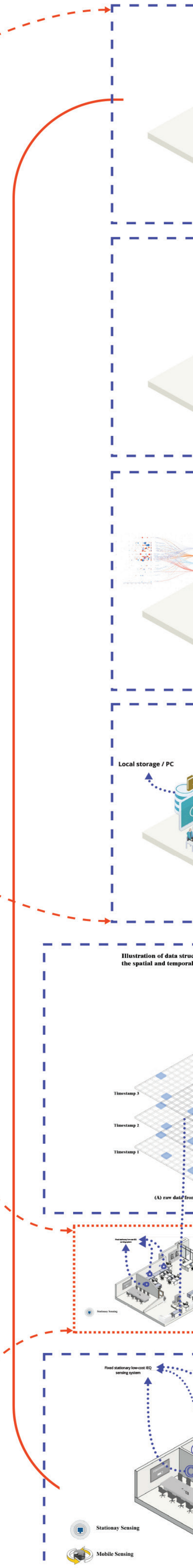
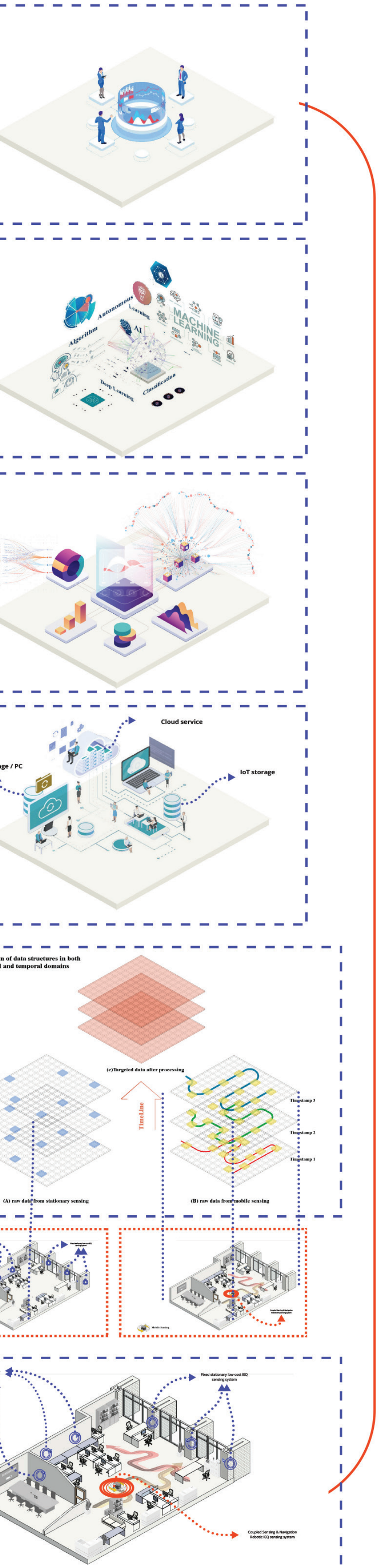

IoT Sensors
Microcontroller
Coding and Processing
Real-time User Interface
BME680 Sensor
Temperature, Humidity, Pressure & Gas Resistance
PCA9548A I2C Multiplexer
MH-Z19B Sensor CO2
TSL2591 Sensor Light
Raspberry Pi 4 Model B single-board computer
Flask-SocketIO
Python
Plotly
Pandas
Matplotlib
NumPy
Real-Time Data
Historical Data and IAQ Level
Perception layer
Transport layer
Processing layer
Application layer
IoT Sensors
BME680
Temperature, Humidity, Pressure and GAS Sensor
TSL2591
Light Sensor
MH-Z19B
CO2
PCA9548A I2C Multiplexer
Raspberry Pi 4
Microcontroller
Wireless IEEE 802.11ac
Database (CSV)
Read Data
Web interface (UI)
Collecting data for six different parameters and present them in real-time monitoring
Real-Time Data
Processing Filtering Analyzing
IAQ Index
Good
Moderate
Sensitive
Unhealthy
Dangerous
Hazardous
IAQ system components and their interaction


Fixed Windows
This zone was unoccupied throughout the experiment.
All doors, windows were closed throughout the experiment.
Low-cost sensors
Occupants


Local storage / PC
Stationay Sensing
Mobile Sensing



Hanin Othman
Pennsylvania State University

Rahman Azari
Pennsylvania State University

Tamy Guimarães
Pennsylvania State University

Low-Cost IoT-based Indoor Air Quality Monitoring

Indoor air quality (IAQ) is gaining significant interest as an essential determinant of human health, productivity, and well-being, necessitating the development of environmental sensing systems with cost-effective air-quality monitoring setups. In this article, we report on our ongoing research addressing the problem of limited access to affordable IAQ monitoring solutions. We aim to design, develop, and prototype a small, low-cost IAQ monitoring system that could serve as an Internet-of-Things (IoT)-based network for sensors for building postoccupancy evaluation. In this endeavor, we constructed a stationary multisensing device capable of real-time monitoring and visualization of six IAQ indicators with the potential to connect to similar devices in the built environment. Additionally, we explore the integration of the IoT to store, visualize, and analyze the data.

Keywords: Indoor Air Quality (IAQ), Internet of Things (IoT), Low-cost Sensing, Real-time Monitoring

Introduction

Air pollution is estimated to cause 8 million deaths worldwide yearly, and 99% of the global population breathes air that does not meet the guidelines set by the World Health Organization (Manisalidis et al. 2020; WHO Data. n.d.), which has hostile effects on human health and well-being (Coulby et al. 2020b; Manisalidis et al. 2020; Kumar et al. 2021; Sun et al. 2023). Amid the COVID-19 pandemic, respiratory health concerns have elevated the importance of monitoring and optimizing indoor environmental conditions (Peladarinos et al. 2021). Poor indoor air quality (IAQ) exacerbates respiratory issues and raises equity and fairness concerns for communities more vulnerable to air pollution, heightening health risks (Anand and Phuleria 2022; Holden et al. 2023). This emphasizes the urgent need for fair and comprehensive strategies to address IAQ issues, especially in anticipation of future pandemic scenarios, necessitating the development of cost-effective monitoring solutions in response to the rise of small-scale, low-cost systems (Barot et al. 2020; Coulby et al. 2020b). However, the potential hindrance posed by the cost and complexity of monitoring devices has made implementing such solutions less feasible (Coulby et al. 2020a), as current practices in IAQ sensing are based mainly on locally installed stationary sensors, leading to multifaceted complexities. This approach is expensive, involving many sensors, limited spatial coverage, the need for regular maintenance, and an inability to adapt to building changes (Quintana et al. 2021). Encouraging low-cost sensors for IAQ monitoring is imperative due to their advantages. The new low-cost Internet of Things (IoT) sensors have valuable applications, including real-time concentration characterization, IAQ issue mitigation, enhanced spatial resolution, reduced uncertainty, real-time warning systems, facilitated personal exposure assessments, and improved building control for energy efficiency.

Moreover, the collected data can inform building efficiency measures, leading to cost savings and reduced emissions, making it economically compelling. These systems also play a crucial role in providing air supply data, optimizing IAQ management, and promoting associated health benefits. Despite the relatively low cost of deploying sensor networks, challenges emerge regarding ongoing maintenance and data processing expenses, often surpassing the initial hardware costs. The holistic budgetary considerations encompass additional hardware prerequisites and setup and installation expenses (Xiang et al. 2013; García et al. 2022; Qin et al. 2023). Some researchers emphasize the critical challenge of resolving the tradeoff between quality and cost in IAQ sensor development. Calibrating low-cost sensors, crucial for sensor developers and engineers, presents notable challenges, especially in addressing frequent calibration requirements (Saini et al. 2021). Despite sensor aging leading to drift, impacting long-term stability, and diminishing operational lifespan, IoT sensor systems promise to revolutionize high-resolution spatial-temporal IAQ sensing, offering numerous anticipated benefits (García et al. 2022; Saini et al. 2021; Coulby et al. 2020b).

The research aims to design and prototype a low-cost, real-time multisensing IAQ monitoring system suitable for Internet-of-Things (IoT) integration to assess indoor built environments in the face of thermal comfort and poor IAQ challenges. The IoT-based air-quality monitoring systems consist of affordable sensors equipped with communication devices to monitor the space's air quality in real time with fine temporal and potential spatial resolution. It provides facility managers, building owners, and space users with the information needed to operate mechanical conditioning and air purification systems to address the prohibitive cost of the current sophisticated IAQ monitoring practices (Afolaranmi et al. 2018; García et al. 2022; Schalm et al. 2022).

This study investigates the following research questions: "How can we develop a low-cost IoT-based real-time multisensing system for IAQ assessment, and how can we visualize and interpret the collected data in a user-friendly approach?" The research addresses a critical need for affordable and accessible solutions for IAQ monitoring and adding light sensors under investigation of IAQ, particularly in indoor environments where occupants spend a significant amount of time.

A comparative analysis based on an ongoing PhD research project was conducted to thoroughly grasp the current state of the art, examining similar products used in recent studies. This analysis delved into similar products utilized in recent studies, exploring various vital aspects such as the type of collected data, network technology, IoT platform adoption, data storage systems, sensor types, approximate prices, and each study's limitations.

Articles for review were sourced from respected databases, including the Web of Science and SCOPUS, which are renowned for indexing significant journals in our field. These databases included articles published between 2013 and 2023.

The systematic selection process employed vital terms such as "Internet of Things," "Indoor air quality," and "Sensors" for filtering. An inclusion criterion focused on articles exploring the integration of low-cost IAQ monitoring and sensing with IoT. A total of 42 articles on stationary sensing published since 2014 were identified through meticulous searching within titles, abstracts, and published keywords. Among these, 20 articles were directly relevant to our topic, with a notable 68% published between 2019 and 2023, indicating a growing interest in this subject in recent years. Table 1 provides a reasonable analysis of the selected works.

The studies reviewed face limitations that affect their effectiveness in IAQ monitoring. These limitations include scope constraints, as some studies focus solely on one specific IAQ indicator (Yang et al. 2014; Salamone et al. 2016; Ray 2016; Mahanth and Karishma 2017; Marques et al. 2019; Peladarinos et al. 2021; Al-Okby et al. 2022a; Kuncoro et al. 2022), neglecting a broader assessment of other pollutants (Kim et al. 2014; Folea and Moiş 2015; Marques et al. 2018; Salamone et al. 2017b; Moiş et al. 2018; Mylonas et al. 2019; Sung et al. 2019; Coulby et al. 2021). Additionally, many studies lack robust data analysis methodologies or don't provide interpretation for IAQ data, limiting their utility in taking actionable decisions (Yang et al. 2014; Kim et al. 2014; Mahanth and Karishma 2017; Marques et al. 2019; Coulby et al. 2021; Kuncoro et al. 2022). Reliability issues due to sensor calibration inadequacies, communication challenges affecting real-time data transmission, and limitations in scalability and compatibility further obstruct the deployment and adoption of these systems (Kim et al. 2014; Marques et al. 2018; Al-Okby et al. 2022b).

Short monitoring times (Marques et al. 2018; Ray 2016; Marques et al. 2019; Coulby et al. 2021; Al-Okby et al. 2022a; Kuncoro et al. 2022), insufficient validation and testing, and spatial distribution limitations also hinder the effectiveness of IAQ monitoring solutions (Salamone et al. 2017b; Marques and Pitarma 2016; Coulby et al. 2021). The focus would be reducing energy consumption instead of thermal comfort or indoor air quality (Coulby et al. 2020a; 2021; Broday and da Silva 2022; Al-Okby et al. 2022a; Peladarinos et al. 2021). Building a sensing prototype can overcome the limitations and gaps in the existing studies. It could offer cost efficiency and customization options not typically available in commercial devices, allowing customization to meet specific requirements and constraints not addressed by existing solutions. The cost-effectiveness of this prototype allows for the deployment of multiple sensors, providing more comprehensive coverage of indoor environments. This approach enables users to gain insights into IAQ conditions across different spatial locations within a building, which may not be feasible with traditional fixed sensors due to installation procedures, maintenance, calibration, and cost constraints.

The provided system boosts sensor coverage, integrating multiple sensors, including CO_2, temperature, humidity, barometric pressure, VOCs, and light sensing. This provides a comprehensive view of indoor environmental conditions and an interpretation of air quality through the IAQ index. This breadth of sensing capability surpasses that of many existing systems, which often focus on one or a subset of these parameters. Additionally, the proposed system ensures real-time data detection by leveraging Flask-Socket IO for real-time communication and data accessibility through seamless integration with the latest low-cost IoT sensors.

The technical contribution provides an interpretation and explanation for the user on the IAQ situation so that they can take direct action based on the air quality situation through the IAQ index. This study utilizes a unique coding framework that has yet to be used through various libraries and coding tools for comprehensive data processing, filtering, storage, and analysis. By leveraging Flask-SocketIO, a real-time web framework, for real-time communication and the WebSocket protocol, the system enables continuous data streaming to the storage server simultaneously, facilitating immediate access to IAQ information from anywhere at any time within the network. This overcomes a significant limitation of many existing solutions, which rely on local data storage while needing more capability for real-time remote monitoring or relying on an online cloud with a specific monthly subscription. By addressing the critical factors of cost, sensor coverage, real-time data accessibility, and user-friendliness, the proposed system represents a paradigm shift in DIY IAQ monitoring, offering a more comprehensive, affordable, and accessible indoor environmental management (IEM) solution.

Several key objectives advance an understanding and management of IAQ. First and foremost, the aim is an accurate and reliable IAQ monitoring system. Secondly, a pivotal aspect of this research involves the integration of multiple sensors to ensure comprehensive data collection. We capture various environmental parameters by incorporating different sensors to determine indoor status. This multifaceted approach is crucial in understanding the indoor environment holistically. Thirdly, the overarching goal goes beyond focusing solely on detecting pollutants to explain the IAQ situation using an IAQ index. The IAQ index is a measure used to assess the quality of the air inside buildings. This involves considering many factors, analyzing them simultaneously, and capturing data with high temporal resolution to provide a comprehensive understanding of IAQ. With the integration of advanced sensors capable of delivering accurate and nuanced measurements, we can enhance our grasp of the dynamic interplay of various environmental factors. Through these objectives, this research aspires to contribute to the evolution of IAQ monitoring technologies, paving the way for more effective and insightful solutions in IEM.

Furthermore, indoor spaces are typically assessed from a single location, resulting in a low spatial density of IAQ measurements. This limitation restricts the ability to draw comprehensive conclusions about the health and well-being of individuals across different areas within space. In pursuit of increased spatial density and longitudinal monitoring, researchers suggest that it may be necessary to accept a tradeoff between precision and accuracy of measurements. Therefore, this study serves as an initial step towards addressing the challenge of spatial coverage in IAQ monitoring, aiming to provide a more holistic understanding of indoor air quality. Following the validation of the device in a controlled calibration room environment and comparing the data with reference device data, the subsequent phase of our project will focus on the development of spatial mapping and analysis of IAQ dynamics using multiple stationary devices.

Related Work

Air quality, thermal comfort (temperature, humidity), air pressure, volatile organic compounds (VOCs), and light stand out as the most assessed aspects of indoor environmental quality (IEQ) (AlHorr et al. 2016; Afolaranmi et al. 2018; Andargie et al.2019). The advancements in IoT technology, driven by its cost-effectiveness and accessibility, have created the opportunity to use a diverse range of IEQ and IAQ instruments and configurations (Saini et al. 2021; García et al. 2022). Manufacturers and the broader IoT user community support these advancements by offering setups, techniques, and code libraries and facilitating seamless integration among sensors, microcontrollers, and other IoT infrastructure through several platforms and forums (Afolaranmi et al. 2018; Coulby et al. 2020a; Arduino n.d.; Adafruit n.d.; Autodesk n.d.).

The focus is on IAQ and light as part of the IEQ monitoring. Adding the light sensor to the monitoring system broadens the scope of data collection, allowing for additional insights such as ambient light opacity and enhancing the user's visual experience. This comprehensive approach helps monitor and improve the effectiveness of IEM (Salamone et al. 2017a; Hsu et al. 2022).

Table 1. A comparative analysis of the selected works.

Authors	Data collection	Research limitation
(Yang et al. 2014)	CO_2	- Limited scope of IAQ indicators. - No data storing. - No analysis or interpretation for IAQ prediction.
(Kim et al. 2014)	(O_3, PM, CO, NO_2, SO_2, VOC and CO_2), temperature, humidity.	- Communication distance and power consumption. - Wireless traffic interruptions. - Limited battery capacity. - Environmental exposure and maintenance. - No data analysis.
(Folea and Mois 2015)	CO_2, Air temperature and relative humidity	- Limited scope of IAQ indicators. - No analysis or use for IAQ prediction. - Sensors need calibration and further testing.
(Salamone et al. 2016)	Thermal	- Limited generalizability to larger spaces. - Focuses on smart lamp using a DIY approach. - No indication for any IAQ monitoring.
(Marques et al. 2018)	Air temperature, humidity, carbon monoxide, carbon dioxide	- Limited scope of IAQ indicators. - Short monitoring time. - Limitations in terms of network range and reliability. - No analysis or interpretation for IAQ prediction. - Acknowledgment of open issues related to IoT. - Potential limitations in scalability and compatibility.
(Ray 2016)	Particulate matter	- Limited scope of IAQ indicators. - Short monitoring time. - Data flow might cause a burden in the server's memory.
(Salamone et al. 2017b)	Air temperature and relative humidity + energy consumption	- Limited scope of IAQ indicators. - The sensors need precalibration and validation. - Irregularities in the detection. - Possibility of errors due to sensors with incompatible characteristics are combined.
(Mahanth and Karishma 2017)	CO and CO_2	- Limited scope of IAQ indicators. - Lack of validation of the accuracy or reliability - Limitations in scalability - No interpretation for air quality.
(Marques and Pitarma 2016)	Temperature, relative humidity	- Limited scope of IAQ indicators. - Laboratory test environment. - Quality traceability, sensors response time and systems throughput evaluations need to be conducted.
(Moiş et al. 2018)	Temperature, relative humidity, VOC	- Limited scope of IAQ indicators. - The proposed solution may not provide measurements as detailed and accurate as traditional monitoring stations. - The work focuses mainly on optimizing the power consumption. - The sensor network's reliability needs improvement. - The sensors need precalibration and validation.

Network technology	IoT platform	Data storage	Sensors + Approximate prices
ZigBee5 protocol	Not used	Not Mentioned (NM)	3765$ as follow: IAQ-CALC, TSI - 2765$ Gilair-5, Gilian - USD $1000
ZigBee5 protocol	Not used	NM	383$ as follows: TGS2600 -UDS $122 T6613 - USD $100 TGS2602 – USD $20 GSNT11 – USD $10 TGS5042 - USD $30 MiCS-2610 - USD $10 SO2-AF - USD $60 GP2 Y1010AUF - USD $15 DHT11- USD $16
Wireless Sensor Network (WSN)	Data displayed locally on an LCD	NM	143$ for: COZIR - USD $121 TSL2561 - USD $6 DHT11- USD $16
Not Mentioned (NM)	Not used	NM	DHT11 - USD $16 LED IR and LED module
Wi-Fi	Using Web application	SQL server	PMS 5003 - USD $25 ESP8266 Wi-Fi - USD $10
Wi-Fi	ThingSpeak platform	Cloud server	DHT11 - USD $16
Bluetooth	Not used	Local server	HIH6130 - USD $15 DHT11 - USD $16
Wi-Fi	Not used	SQLite Database	Carbon Dioxide Sensor COZIR-A - USD $121 Carbon Monoxide Sensor - MQ7 - USD $6
WSN	Twilio, a cloud communication platform	SQLite Database	Bosch BME680 - USD $12 The DFRobot Gravity BME680 - USD $20 FireBeetle ESP8266 - USD $10
Wi-Fi and BLE	Libelium platform	Cloud server	Around USD $162 CCS811 (CO+TVOC) - USD $20 SHT21 (T+RH) - USD $9 OPT3001(LIGHT) - USD $15 CYBLE-022001-00 - USD $22

Table 1. A comparative analysis of the selected works. (continued)

Authors	Data collection	Research limitation
(Marques et al. 2019)	CO_2	- Limited scope of IAQ indicators. - Short monitoring time. - The sensors need precalibration and validation. - Accuracy and reliability of sensors need to be tested. - No interpretation for the collected data.
(Mylonas et al. 2019)	CO_2, Air temperature and relative humidity	- Lack of information on the calibration of sensors. - Inability to control humidity levels throughout the experiment. - Study not aimed at ranking or recommending a specific sensor. - No single dominant factor was identified in the experimental evaluation. - Accuracy and reliability of sensors need to be tested. - The sensors need precalibration and validation.
(Sung et al. 2019)	Air temperature, relative humidity, and CO_2	- Focus on thermal comfort index and energy saving, while neglecting the sensors' accuracy, validity, and performance. - Network transmission problems. - Address the thermal comfort index not the IAQ data interpretation.
(Coulby et al. 2021)	CO_2, VOC, Air temperature and relative humidity	- High-cost sensing devices. - Short monitoring time. - Low spatial density for environmental monitoring. - There is a need for more research to assess the suitability of sensors for ventilation monitoring. - Accuracy and reliability of sensors need to be tested. - No interpretation for the collected data.
(Peladarinos et al. 2021)	Particulate matter	- Limited scope of IAQ indicators. - Use of simulation tools to compare theoretical results with real-life experiments. - The sensors need precalibration and validation.
(Al-Okby et al. 2022b)	VOC, NO_2	- Limited scope of IAQ indicators. - Chamber experiment. - The sensors need precalibration and validation. - The study did not discuss the cost-effectiveness or scalability of the sensor. - Accuracy and reliability of sensors need to be tested.
(Riffelli 2022)	CO_2, Air temperature and relative humidity	- Limited scope of IAQ indicators. - There is a need for more data to efficiently use artificial intelligence algorithms for predictive modeling. - Accuracy and reliability of sensors need to be tested.
(Al-Okby et al. 2022a)	TVOC	- Limited scope of IAQ indicators. - Short monitoring time. - Accuracy and reliability of sensors need to be tested.
(Kuncoro et al. 2022)	PM2.5	- Limited scope of IAQ indicators. - Short monitoring time. - Accuracy and reliability of sensors need to be tested. - No interpretation for the collected data.

Network technology	IoT platform	Data storage	Sensors + Approximate prices
Wi-Fi	Not used	SQLite Database	MHZ-19 CO_2 sensor - USD $34 ESP8266 Wi-Fi - USD $10
NM	Not used	NM	All sensors cost around USD $1976; 7 sensors prices between USD $513 and $70
Wi-Fi	Not used	NM	NM
Wi-Fi	NM	Cloud server	USD $1555 as follows: Onset HOBO® MX1102 (CO2 and eCO2) - USD $630, IQAir Air Visual Pro (PM2.5) - USD $300, Onset HOBO® MX1104 (Light intensity, temperature, humidity) - USD $300, Omega HHSL-101 (noise levels) - USD $325
Long Range (LoRa)	The THINGS—network server	InfluxDB with a Grafana server	Sensirion SVM30 - USD $25 Renesas ZMOD4410 - USD $84 BOSCH BME680 - USD $25 Sensirion SPS30 - USD $44 Omron B5W-LD0101-1/2 - USD $15
Wi-Fi	NM	NM	MOX gas sensor - USD $22
Wi-Fi	NM	API service and SQL database	CO_2 K-30 sensor - USD $70 Enviro+ board - USD $62 contains: Air temperature BME280 sensor Humidity BME280 sensor Illuminance sensor - USD $12
Wi-Fi	InfluxDB	Influx database	SGP40 gas sensor - USD $15, SGP30 Gas Sensor - USD $17
Wi-Fi	NM	Adafruit server	ESPS30 sensor - USD $30, ATWINC1510 - USD $10

The literature survey demonstrates numerous experiments developing sensors that are cost-effective, energy-efficient, and highly accurate (Saini et al. 2021; Schalm et al. 2022). Many of these experiments were conducted in controlled laboratory environments, where precision is achieved with fewer sensors, enabling the observation of larger sample sizes within shorter measurement periods (Wei et al. 2018; Samad et al. 2020; Ganev et al. 2020; Liu et al. 2020; Schalm et al. 2022). This proves beneficial in addressing budget constraints. However, a disparity exists between data collected from real-world settings and the controlled environment conditions (European Commission Joint Research Centre 2017; Karagulian et al. 2019; Liu et al. 2020). In addition, research indicates that laboratory-detected data, under controlled conditions, displays enhanced correlations for all identified gaseous pollutants compared to data gathered in intricate real-world environments, which are marked by variations in the composition and concentration of different factors (Castell et al. 2017; Sá et al. 2022). There is a growing emphasis on developing low-cost IEQ and IAQ measurement tools that utilize microcontrollers and multiple low-cost sensors. This approach is accurate, reliable, user-friendly, and cost-efficient due to its open-source electronics platform and versatile laboratory equipment, which presents it as an alternative solution for long-term high-cost monitoring, particularly for developing communities where traditional high-cost monitoring systems may be less accessible or economically feasible (D' Ausilio 2012; Wan et al. 2016; Jeon et al. 2018; Afolaranmi et al. 2018; Barot et al. 2020; Rafsanjani et al. 2020; Coulby et al. 2020a; Bae et al. 2021; Mataloto et al. 2021; Calvo et al. 2022; Metwally et al. 2022; Mitro et al. 2022). The focus on versatility and affordability can potentially increase access to quality air monitoring in regions that face challenges in deploying expensive monitoring infrastructure.

Low-cost Sensors (LCS)

The recognition of air quality issues has progressed alongside rapid technological advancements, transforming into the availability of low-cost sensors (LCS) that enable users to access online real-time information about IAQ. The demand is well matched with the capabilities of LCS, offering high-density temporal coverage data (Chojer et al. 2020). These devices measure a variety of common indoor air pollutants, presenting valuable applications for the occupants (Lewis et al. 2018). Such applications include identifying potential emission sources within households, managing and mitigating IAQ issues, implementing real-time warning systems, and assessing personal exposure (Lewis et al. 2018; García et al. 2022). Real-time sensing, facilitated by the deployment of these sensors in large numbers, provides a significant opportunity to supervise and control the new generation of buildings and holds the potential to revolutionize the management of critical air pollutant concentrations (García et al. 2022).

IAQ primarily involves monitoring pollutants and examining factors, ranging from physical elements such as temperature, humidity, and particulate matter (PM) to chemical components, including CO_2, CO, formaldehyde, volatile organic compounds (VOCs), and PM (Yang et al. 2014; Abraham and Xinrong 2014; Salamone et al. 2016; Marques and Pitarma 2016; Mahanth and Karishma 2017; Coulby et al. 2021; Marzouk and Atef 2022). This study focuses on the following factors in this phase to establish our system using LCS:

1. CO_2 Sensors

Various CO_2 sensing systems currently used in practice have been developed, including nondispersive infrared (NDIR) sensors that emerged as the go-to reference standard for measuring CO_2 due to their low cost, accuracy, and long-term stability (Neethirajan et al. 2009; Wu et al. 2010). The sensors include a detector that measures the infrared light released by a source passing through a gas based on the principle that CO_2 concentration is proportional to light absorption (Wu et al. 2023). The sensors are widely used in measuring atmospheric CO_2 concentrations, owing to their stability and resilience against interference from other air components, including pollutants (Coulby et al. 2021; Wu et al. 2023). The durability of NDIR sensors makes them reliable for atmospheric CO_2 measurement, with an analytical accuracy within 2% of the reading, as highlighted in studies (Wang et al. 2005; Kwon et al. 2009; Yasuda et al. 2012; Yang et al. 2014; Marques and Pitarma 2016; Coulby et al. 2021).

2. Gas Sensors

Due to advancements in semiconductor technology, low-cost sensors have evolved into open-platform systems. These systems integrate various sensors, such as electrical conductivity (EC) and NDIR sensors, with a metal-oxide-semiconductor (MOS) module. This allows for detecting diverse gases in the air by measuring the changes in electrical resistance caused when metal oxide is exposed to the air (Clements et al. 2017; Zhang and Srinivasan 2020).

In contrast to various studies that utilized multisensor arrangements for measuring air pollutant concentrations (Alkandari and Moein 2018; Jose and Sasipraba 2019; Pu'ad et al. 2020; Zhang et al. 2021), this approach takes a forward-looking step. This research focuses on real-time data collection and simultaneously assesses IAQ levels. Moreover, it involves interpreting the significance of the collected data and developing an internal web platform. This platform allows for the real-time presentation of data online within the internal network, enhancing accessibility and usability.

3. Light Sensors

The growing awareness surrounding indoor environments has led to the emergence of diverse IEQ monitoring systems. IEQ, as a comprehensive concept, encompasses IAQ, thermal comfort, lighting quality, and acoustic comfort, which collectively influence the health, comfort, and different performance of occupants (Piasecki et al. 2017; Kim et al. 2018; Hou 2016).

Light is among the most evaluated building parameters (Geng et al. 2017). Some studies explore the application of various light sensors, including low-cost light sensors, through comparative analysis of TSL2561, BH1750, TEMT6000, and Light-Dependent Resistor (LDR) sensors (Beyaz and Gül 2022; Babakhouya et al. 2023). Each sensor is tailored to specific use cases based on its characteristics. The TSL2561 is a light-to-digital converter with a wide measurement range, suitable for assessing sunlight intensity (Adafruit n.d.). In contrast, the BH1750 is a digital light sensor measuring light or sunlight intensity within a specified small area (Adafruit n.d.). The Light-Dependent Resistor (LDR) is a passive electronic component that determines light intensity by adjusting its resistance based on exposure (Setya et al. 2019). Like the LDR, the TEMT6000 is an ambient light sensor emulating human eye detection. It is commonly utilized for automatic brightness adjustment in electronic devices or systems, operating as a silicon epitaxial planar phototransistor for detecting visible light (Beyaz and Gül 2022). Employing affordable light sensors allows for precise and efficient light measurements, opening avenues for the automation of lighting systems and improving the overall user experience (Füchtenhans et al. 2021).

Materials and Methods

This section addresses the architecture and components of the proposed low-cost IAQ monitoring system, including hardware and software design, and reports on the implementation, initialization, data collection, and data analytics process. This setup is a four-layer IoT architecture. The hardware configuration used in this setup consists of a Raspberry Pi microcontroller, a CO_2 sensor (MH-Z19B), a multigas sensor (BME680), a light sensor (TSL2591), and an Adafruit PCA9546 Multiplexer (Figure 1). The overall hardware cost of the proposed system is less than \$100, as detailed in Table 2.

The architecture of widely used IoT systems typically consists of three to five layers (Wu et al. 2010; Yang et al. 2011; Madakam et al. 2015; Al-Fuqaha et al. 2015; Elbashir and Ali 2019). The conventional three-layer architecture includes a perception layer (containing physical sensors), a network layer (through which collected information is transferred via wired or wireless channels), and an application layer (responsible for executing intelligent management of the IoT services to meet customer needs).

Figure 2 illustrates the four-layer architecture we adopted for this project and provides insights into the components of the device. The perception layer is responsible for sensing the physical environment and includes the BME680 multigas sensor, the TSL2591 light sensor, and the MH-Z19B CO_2 sensor. The transport layer facilitates data transportation from the perception to the processing layer by utilizing the Raspberry Pi 4 with Wi-Fi capabilities to ensure data transfer between components. The processing layer controls data storage, analytics, and filtering through various Python libraries. It also stores the data locally in a comma-separated values (CSV) file, performs IEQ computation, and stores the output data after processing and filtering. The data is sent to the CSV file and a browser user interface (BUI), serving as a dynamic and real-time responsive web interface in the application layer. The application layer ensures the delivery of services to the user, providing a user interface and dashboard for displaying sensor values and IAQ calculations.

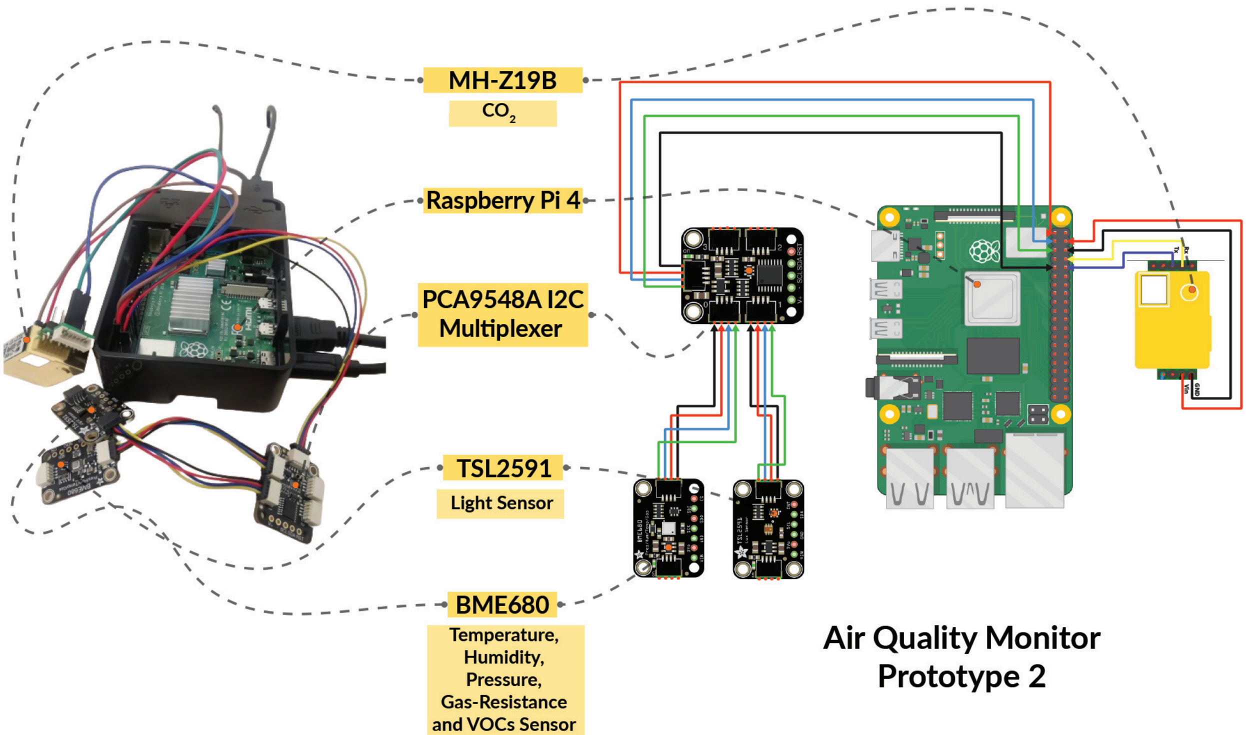
MH-Z19B is a CO_2 sensor built upon NDIR technology designed explicitly to detect CO_2 particles in the air in concentrations ranging from 0 to 5000 parts per million (ppm) and independently of oxygen levels, meaning the sensor's readings are not influenced by the concentration or presence of oxygen in the air to ensure accurate readings (Winsen Electronics n.d.). MH-Z19B incorporates a temperature compensator and provides Universal Asynchronous Receiver-Transmitter (UART) type output (Coulby et al. 2021), weighs only 5 grams (0.18 oz.), has dimensions of 33 mm (1.29 in.) by 20 mm (0.78 in.) by 9 mm (0.35 in.), and requires a power supply ranging from 4.5 to 5 volts to operate effectively (Winsen Electronics n.d.).

To achieve optimal operating conditions, MH-Z19B requires a three-minute preheating period each time to power it on or restart with 3.3 volts. The power input should not be interrupted during data collection (Winsen Electronics n.d.; Moumen et al. 2016; Rodriguez-Huerta et al. 2019; Coulby et al. 2021).

For additional parameters, the BME680 multigas sensor was considered a cost-effective and reliable multisensor capable of detecting temperature, relative humidity, barometric pressure, and VOCs as a direct indicator of IAQ (Jose and Sasipraba 2019; Marques and Pitarma 2019; Folea and Moiş 2020; Peladarinos et al. 2021; Salamone et al. 2022). This sensor employs Inter-Integrated Circuit (I2C) and UART ports as distinct communication protocols, ensuring compatibility with various systems. It also operates on a low-voltage power supply, making it suitable for small battery-powered setups. Specifically designed for gas sensing, the BME680 includes a compact small Metal Oxide (MO) sensor that is 30 mm (1.18 in.) by 22 mm (0.86 in.) (Bosch n.d.). This heated MO changes resistance based on VOCs in the air and can detect gases and alcohols such as ethanol, alcohol, and CO_2. Moreover, the sensor incorporates an onboard Infinite Impulse Response (IIR) filter, which safeguards sensor readings against transient changes in conditions. For instance, a sudden door slam causing momentary pressure changes will be filtered out by the IIR, preventing inaccurate readings influenced by such transient events (Jose and Sasipraba 2019; Ganev et al. 2020; Wall et al. 2021; Luculesc et al. 2022; Vishnubhatla 2022).

For light monitoring, we used the TSL2591, a lighting sensor measuring optical intensity within a wireless network that facilitates the real-time tracking of IEQ. This sensor excels in providing accurate measurements and is known for its cost-effectiveness, user-friendly operation, and robust performance, as highlighted in studies (Yong 2011; Hrbac et al. 2013; Tiele et al. 2018; Adafruit n.d.). The TSL2591 light sensors capture the light intensity and convert it into digital data transmitted to the sink node through the I2C bus. To ensure accuracy, the TSL2591 reads analog inputs of light intensity and utilizes an empirical formula, converting the data into a digital format before being sent to the microcontroller for transmission (Yong 2011; Hrbac et al. 2013; Carpenter 2015; Tiele et al. 2018).

Raspberry Pi 4 is the central processing unit and the system's brain due to its robust capabilities and versatility. The Raspberry Pi 4 provides the processing power needed for data collection and serves as an ideal hub for this research's low-cost IEQ monitoring setup by offering an array of ports and connectors. This minicomputer is equipped with a standard 40-pin GPIO header, Broadcom BCM2711, Quad-core Cortex-A72



◁ Opening Figure. A framework for integrating IoT with a mobile system for indoor air quality (IAQ) sensing in built environments. (Credit: Authors for all figures)

△ Figure 1. The hardware setup consists of a Raspberry Pi microcontroller with all three sensors, which allows the system to collect IEQ data of six parameters: CO2, temperature, relative humidity, barometric pressure, VOCs, and light.

(ARM v8) 64-bit SoC @ 1.8GHz, 8GB LPDDR4-3200 SDRAM, 5.0 GHz IEEE 802.11ac wireless, Bluetooth 5.0, BLE, Gigabit Ethernet 2 USB 3.0 ports, and 5V DC via GPIO header (Rochim et al. 2020; Zhang et al. 2021; Raspberry Pi n.d.).

Operating on Debian Linux, the sensing system includes a sensor network and wired serial connection that transmits data to the middleware (the transport and processing layers) for storage and interpretation. Using the Raspberry Pi single-board computer, sensor nodes execute code to refine and consolidate data obtained from connected sensors. Processed data is stored in a CSV file and presented in a real-time visualization facilitated through text and dynamic diagrams within the internal network. The sensor nodes, connected to a web page through a wireless serial connection, receive information. The system's architecture enhances measurement accuracy and incorporates autocalibration mechanisms for improved performance. It is also accessible from any device through the internal building network.

The Indoor Air Quality (IAQ) Index

The Pollution Standard Index (PSI) is the reference for this project, adopted by the Environment Protection Agency (EPA) (K and Kumar 2022). The IAQ index in the proposed system is assessed as part of its broader IEQ monitoring capability. It is determined by various indicators sensed by the BME680, which detect VOCs through adsorption on its sensitive layer, reacting to various gases commonly found in indoor air, such as ethanol, methane, formaldehyde, and benzene. This capability allows the BME680 sensor to identify sources like paint, furniture, garbage, and activities such as cooking, eating, breathing, and sweating that contribute to elevated VOC levels.

In its raw signal state, the BME680 outputs gas sensor resistance values reflecting changes due to varying gas concentrations—higher concentrations of reducing VOCs lead to lower resistance and vice versa. The raw values transform an Air Quality Index (IAQ Index) through intelligent algorithms embedded in the sensor code (Bosch n.d.) to account for factors beyond VOC concentration (e.g., humidity).

The primary parameters for IAQ Index are humidity and gas concentrations, with humidity contributing up to 25% and gas concentrations up to 75%. The algorithm considers optimal conditions when humidity is 40%, resulting in a 0% contribution to the IAQ Index. Deviations from this level towards 0% or 100% humidity gradually contribute to the IAQ Index. Gas concentration contribution follows a linear relationship, with output scaled between 0% and 75% based on the BME680 sensor's minima and maxima. The combined measurements are converted into a quantitative IAQ Index ranging from 0 to 500, where 500 indicates 'hazardous' air quality and descriptive values categorize interim stages from 'good' to 'hazardous' air quality (Shihab 2023), shown in Figure 3.

The stored data includes individual sensor readings, monitored data, IAQ Index, and time series for both individual sensor readings and the IAQ Index displayed on a graphical user interface (GUI) through a web page. The code reads data points every three seconds for accurate monitoring. Initial

Table 2. Specification of the hardware setup.

Sensor	IEQ	Sensors-Pins	Volts	Accuracy and range	Price (as of December 2023)
MH-Z19b CO_2 Sensor	CO_2	Serial port (UART)	5V	± (50ppm + 5%).	USD $20
TSL2591 Light Sensor	Luminosity	Digital (I2C) interface	3.3-5V	Dynamic range (Lux): 0.1 to 40,000 Lux	USD $6.95
PCA9546 Multiplexer	Multiplexer	Digital (I2C) interface	-	-	USD $3.95
BME680 Multigas Sensor	Temperature, humidity, pressure and gas sensor	Digital (I2C) interface	3.3-5V	-40–+85°C, 0–100% r.H., 300–1100 hPa	USD $18.95
Raspberry Pi 4 Model B	Microcontroller	Standard 40 pin GPIO header	5.1V at 3.0A	Not application	USD $35

minute data are excluded due to abnormal peaks caused by signal pulses, but the sensors stabilize and self-calibrate afterward for reliable readings. The algorithms automatically calibrate during operation, adapting to typical sensor operating environments. Based on recent measurement history (adjustable up to four days), this calibration ensures consistent IAQ Index performance (Hu et al. 2015; Kang and Hwang 2016; Jose and Sasipraba 2019; Bosch n.d.).

Results and Discussion

For data processing and analysis, all data are collected at a sampling rate of 30 seconds. An initial data collection, dependent on time intervals of 1-second and 5-second, yielded no observed differences in the indicators of interest. Consequently, the analysis extended to a 30-second time interval for data collection, which yielded comparable results to the smaller time intervals. However, shorter time intervals are recommended for postoccupancy data collection, and the measurement period covered 14 days at the Hamer Center office at Penn State University. The experiment occurred in a south-facing shared office, regularly occupied by multiple users (up to five to six users simultaneously), as shown in Figure 4.

Occupants had no control over windows or heating and cooling systems. Peak operating hours were typically from 10 a.m. to 7 p.m., Monday to Friday. Due to the positions of the desks, no direct light from computer monitors reached the light sensors, capturing a blend of natural daylight and ambient artificial lighting from LED bulbs. Data from all LCS were consolidated into a single database, with the device strategically placed in the most frequently occupied zone, above a computer desk, throughout the experiment period. Despite the case study limitations due to the experiment setup, the system provided highly accurate predictions for the IAQ and light.

Our system is designed to be versatile and efficient regarding software and coding. Our code, written in Python, utilizes various libraries and coding tools for comprehensive data processing, filtering, storage, and analysis. Python (a free and open-source programming language) was used for its flexibility and ease of integration with the Raspberry Pi capabilities. The software and programming details are described next and summarized in Figure 5.

The Data Processing Logic

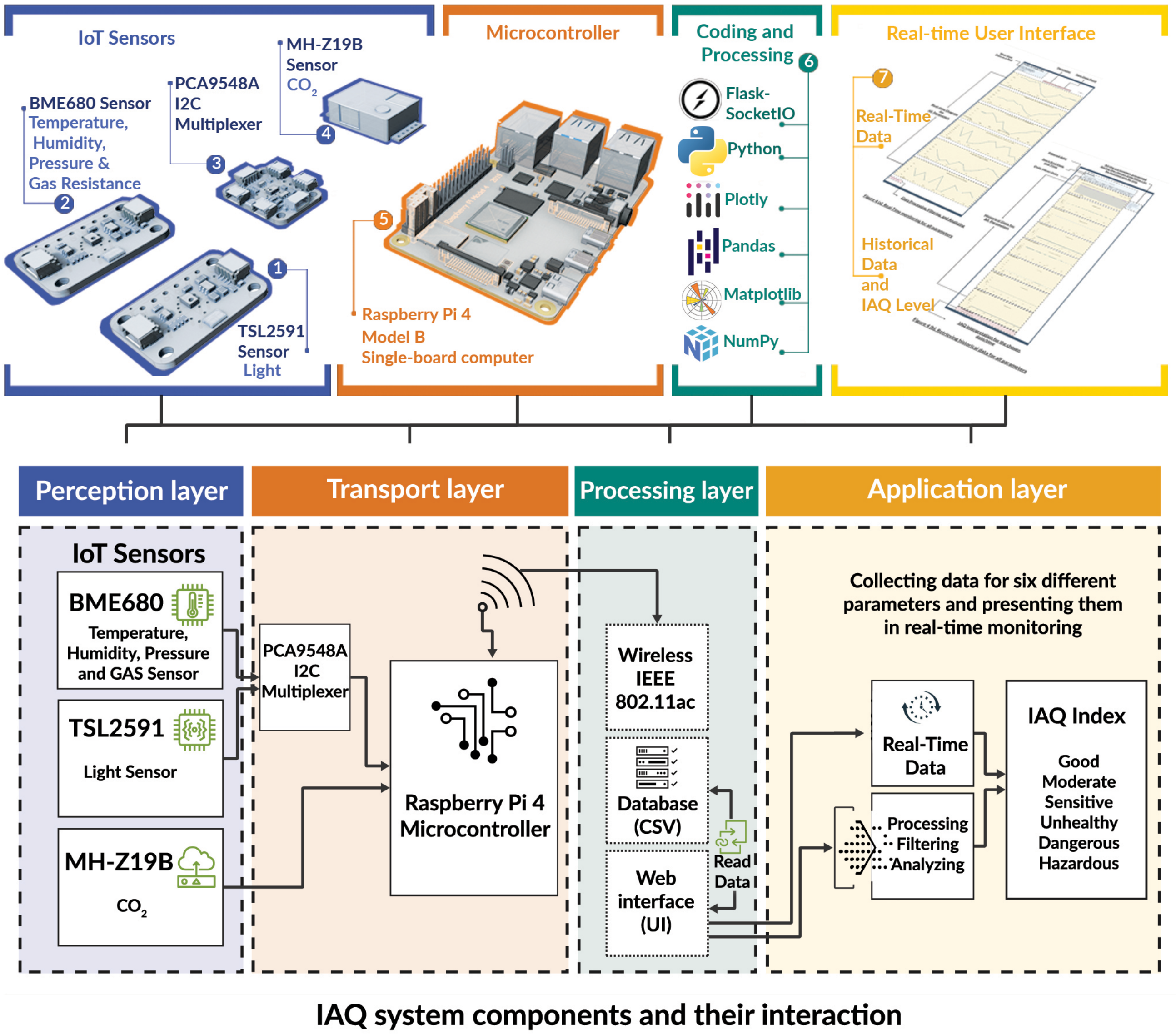
The Python script employed for data analysis utilizes Pandas for data structuring and manipulation within tables. It facilitates the import of numerical readings into Excel or CSV databases (Panda n.d.). Plotly generates diagrams for various parameters (Plotly n.d.), NumPy for advanced mathematical operations (NumPy n.d.), and Matplotlib for diverse graphical representations (Matplotlib n.d.). These tools calculate the IAQ Index, enabling comparisons of trends across different dates and times. In terms of error handling, code comments, and documentation, the script is extensively documented to aid future developers in understanding the logic and functionality of the data processing operations.

Real-time Data Update

A Flask-SocketIO was used for real-time communication and the WebSocket protocol. Flask-SocketIO is a web framework for Python that adds support for handling real-time, bidirectional communication between clients and the server. It is built on the WebSocket protocol, which provides full-duplex communication channels over a single TCP connection. It allows for low-latency communication and is well-suited for real-time applications. It enables real-time communication between web browsers and servers over a single, long-lived connection. This is especially useful for applications requiring instant updates or interactions (Gelens et al. 2015; Abbas et al. 2020).

Web User Interface

The interface extends beyond Python, incorporating HTML and JavaScript for an intuitive and responsive application layer.

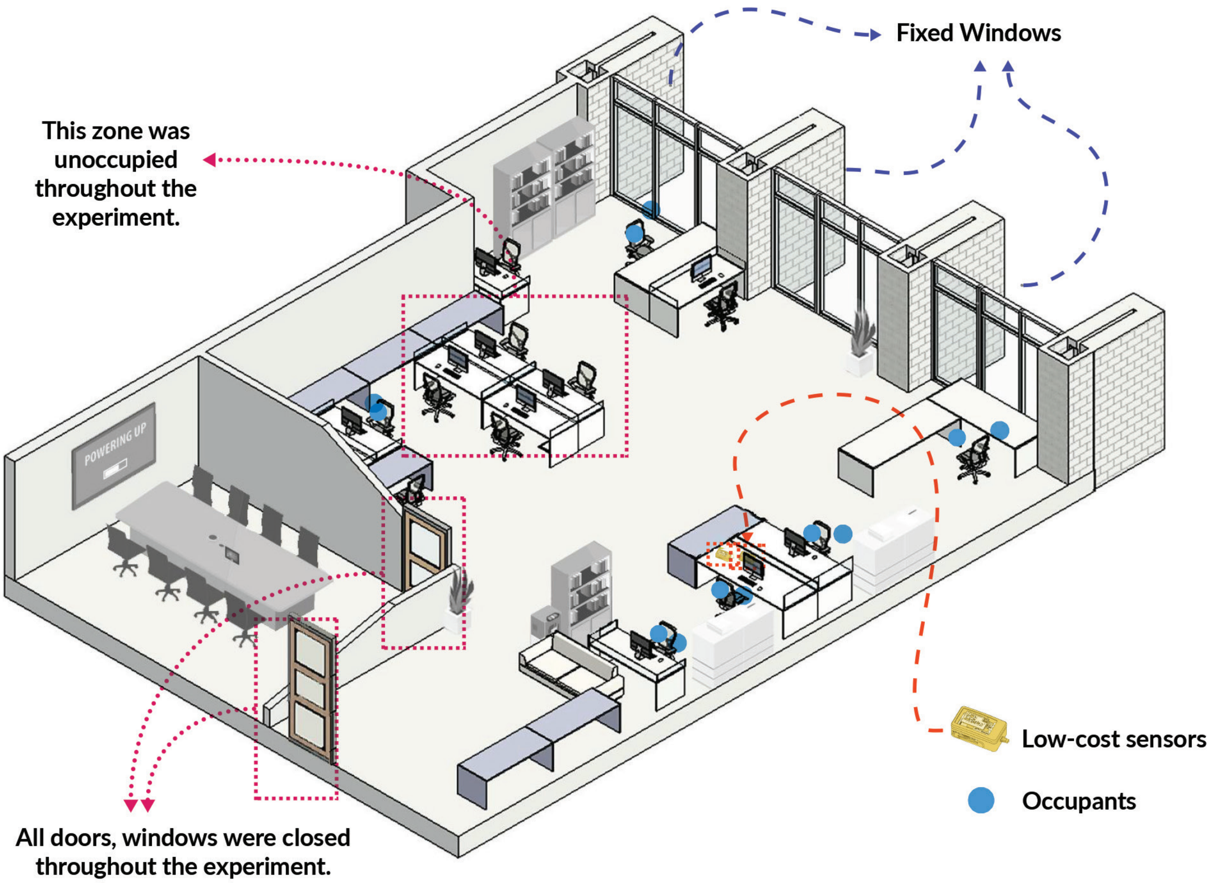


△ Figure 2. The IEQ system's overview includes hardware and software elements and the interaction among the four layers in the system's architecture. The perception layer is dedicated to sensing the physical environment, with the Raspberry Pi serving as the transport layer, facilitating data transfer from the perception layer to the processing layer.

Indoor Air Quality Index

Good	Moderate	Sensitive	Unhealthy	Dangerous	Hazardous
0 - 50	51 - 100	101 - 150	151 - 200	201 - 300	301 - 500
Air quality is satisfactory, and air pollution poses little or no risk.	Air quality is acceptable. Maybe a risk for some people, particularly those who are unusually sensitive to air pollution.	Members of sensitive groups may experience health effects	Some members of the general public may experience health effects	The risk of health effects is increased for everyone.	Health warning of emergency condition

△ Figure 3. Categorization and color codes for indoor air quality (IAQ).



△ Figure 4. Visual representation of the monitored space highlighting sensor installation locations.

The interface enables seamless interaction with IAQ data in real-time and historically. The structure of the web interface is divided into two pages using HTML and JavaScript. Graphs presenting IAQ and parameter levels are generated in real time as diagrams and text, with historical data represented graphically. The parameter data is generated on the chosen date and starting and ending times, and then the IAQ chart is produced accordingly. The web interface's modularity is evident in its ability to visualize up to 15 real-time data points simultaneously, as shown in Figure 6 (a) and (b). Additionally, by the end of the web page, an interpretation of the status of the indoor air quality situation is produced based on the provided IAQ Index in Figure 3.

Data Storage

Using Panda, the Python script responsible for data analysis, also involves data storage operations. It establishes a structured data format, manipulates data within tables, and imports numerical readings into CSV databases. Historical data is stored in files, contributing to the system's capacity for retrospective analysis. In the future, more advanced databases, such as SQLite should be used.

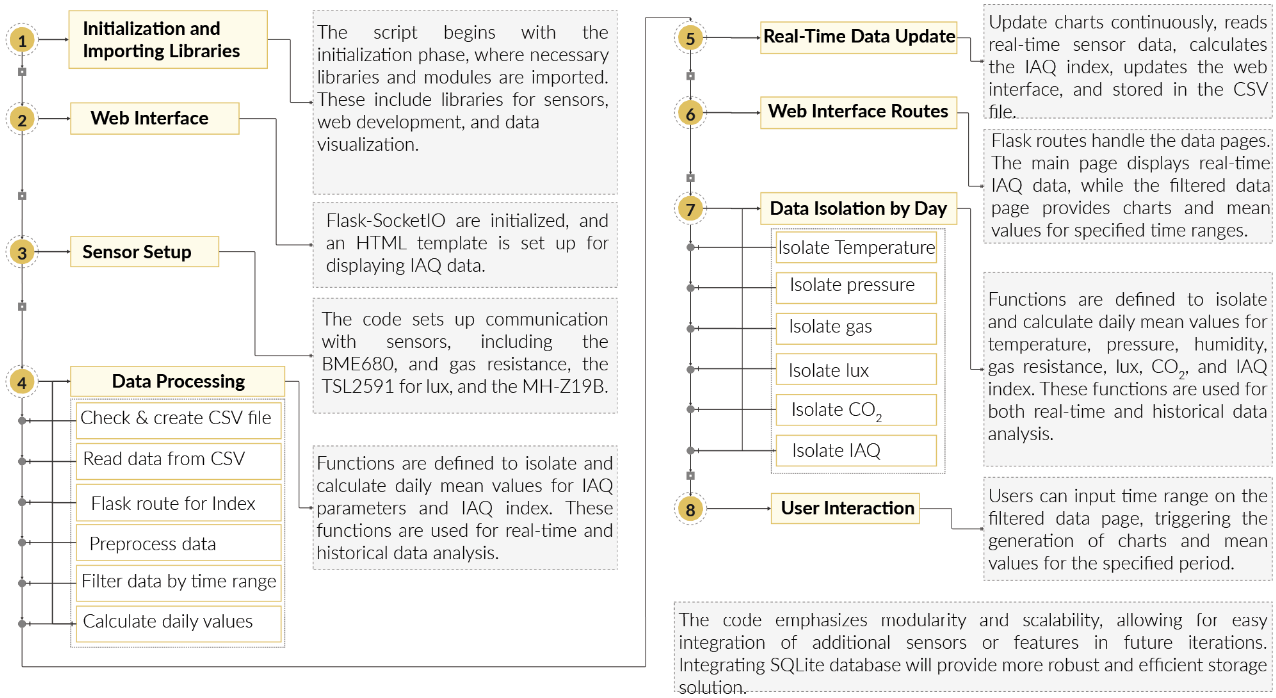
Scalability and Modularity

The coding approach prioritizes modularity and scalability, facilitating the seamless integration of additional sensors or features in future iterations. Regular monitoring and updates to the codebase ensure optimal performance and adaptability to evolving IAQ monitoring requirements.

Conclusions and Future Outlook

This article proposes an IoT-based real-time sensing system featuring a hardware prototype for data acquisition and Web compatibility for seamless data access. The system monitors CO_2 levels, temperature, relative humidity, barometric pressure, qualitative air quality, and light sensing. Leveraging the capabilities of the Raspberry Pi 4 and a combination of sensors proved an innovative solution for IEQ assessment.

The system, focusing on affordability, real-time monitoring, and IoT integration, contributes to the ongoing evolution of IAQ monitoring solutions. In addition to data collection and visualization, the proposed system ensures timely alerts through the web interface when the indoor environment exceeds IAQ thresholds, allowing for IAQ enhancement within the living environment. It also boasts flexibility and expandability, allowing users to incorporate additional sensors and parameters



△ Figure 5. Flowchart outlining the major phases and components of the provided Python code for the IAQ monitoring system.

according to their needs. The next phase of this research will extend the system's capabilities by adding other types of sensors and parameters.

The system's novel contribution lies in developing a standalone integrated solution incorporating an internal storage database, networking protocol, and web user interface, all without subscription to online platforms. This approach significantly reduces costs, making real-time monitoring more accessible and affordable. By adopting a low-cost, open-source approach, the system offers a valuable resource for enhancing IEQ monitoring in diverse settings.

The current approach's limitations include using a simple format as a database. Thus, employing an IoT platform will simplify the process of managing and analyzing large volumes of data and provide a range of visualization tools, enabling users to review the collected data directly through its platforms.

This research marks a preliminary step toward establishing a comprehensive framework for integrating IoT into mobile IAQ sensing in built environments. Priority is placed on validating and testing system performance, including comparison with reference monitors and controlled calibration. Meticulous testing ensures reliability across various conditions and environments.

The future involves expanding the experiment's setup to include multiple stationary prototypes equipped with IAQ sensors. This extension aims to provide robust, real-time monitoring with enhanced spatial coverage, leveraging IoT capabilities. By addressing the limitations of conventional setups, such as spatial distribution and data accuracy, we aim to improve overall IEQ measurement density. The trajectory of this research seeks to go beyond assessment, focusing on active intervention and refinement. Network deployment, enhanced data analytics, integration with building management systems, and controlled testing will significantly contribute to IEM.

Data Statement

The code supporting this study's findings is available from the corresponding author, Hanin Othman, upon reasonable request.

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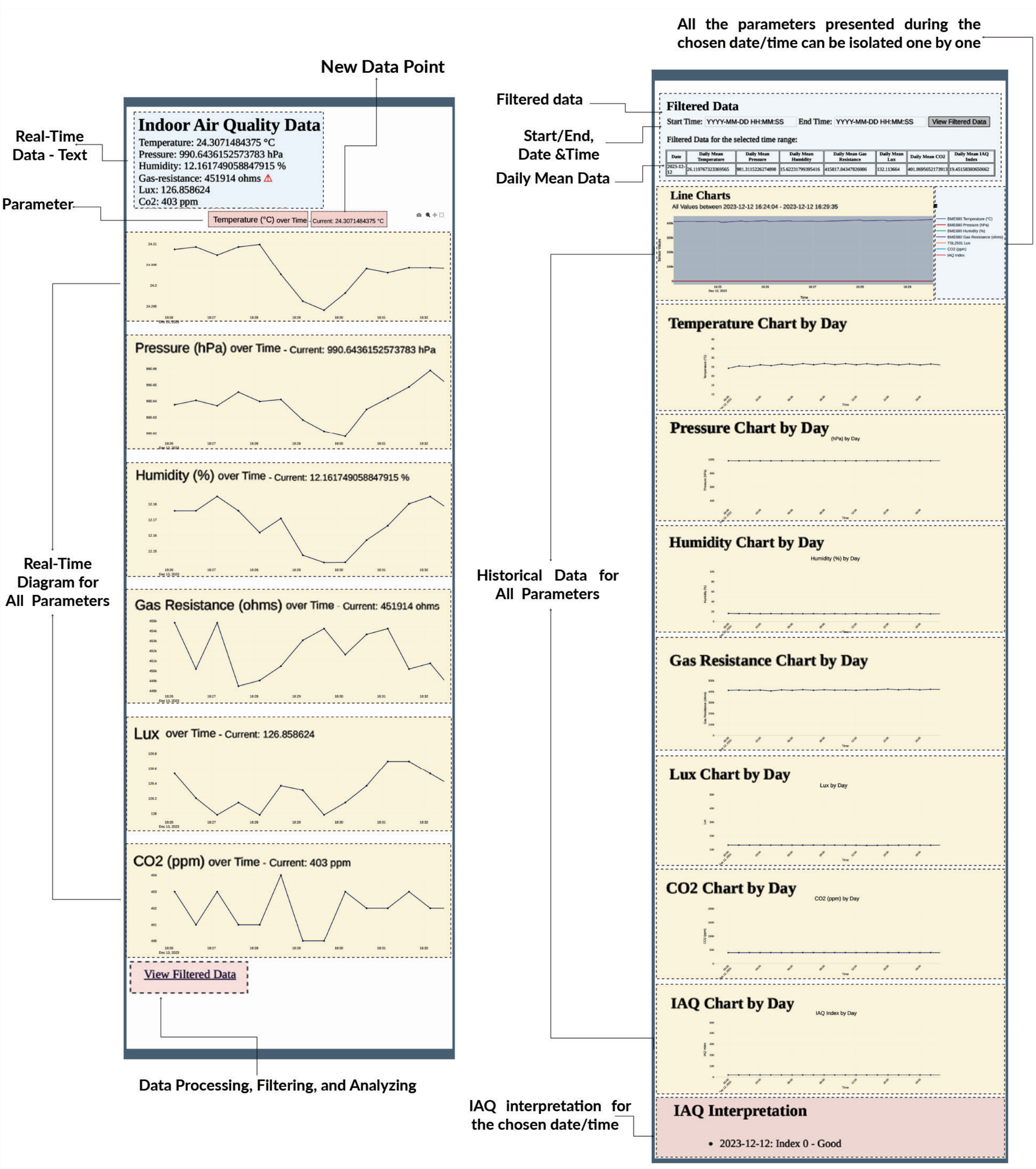

(a). Real-Time monitoring for all parameters

(b). Retrieving historical data for all parameters

△ Figure 6. Graphical format visualization using the web application: (a) real-time user interface to visualize all the collected data in simultaneous monitoring; (b) a second user interface to recall the historical data from the database storage.

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Hanin Othman is a PhD Candidate at Penn State University. Her research interests include advanced sustainable building technologies, built environment quality, low-cost sensors, and smart systems. Othman's previous work, "The Role of Urban Morphology on Outdoor Thermal Comfort: The Case of Al-Sharq City—Az Zarqa," in *Urban Climate* (2020), garnered attention in understanding the impact of urban design on outdoor thermal comfort.

Rahman Azari is an Associate Professor of Architecture and Affiliate Associate Professor of Architectural Engineering at Penn State. Azari's research areas lie at the nexus of architecture, environmental sustainability, and urban resilience, funded by private and governmental agencies, including the US Department of Energy.

Tamy Guimarães is an Assistant Professor of Mechanical Engineering at Penn State. She was born in Brazil and graduated with a bachelor's in Energy Engineering from Universidade Federal do ABC. She studied abroad for a year at UC Davis, where she fell in love with experimental research. She received her PhD from Virginia Tech in 2018 and lived in Munich, Germany, until 2021.