Indoor Air Pollution Monitoring System

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***Abstract*—Indoor air pollution is a neglected factor that negatively affects human health and well-being. In this project we address this concern by building a low cost, wireless indoor air quality monitoring system powered by Thread Network. The proposed system continuously monitors key air pollutants (CO2, TVOC, Particulate Matter) along with environmental factors, temperature and humidity. It provides real-time visualization and generates actionable alerts based on thresholds suggested by organizations such as WHO, EPA, RESET, WELL and ASHRAE. Alongside real-time visualization, the proposed system include 24 hour analysis option which provides key insights about the pollutants and indoor environment. Apart from development, this project includes a comprehensive research involving 24 hour data acquisition in a real world environment. To analyze the collected data and identify anomalies, Shewhart Control charts were applied which revealed key insights.**

I. Introduction and Motivation

Indoor Air Pollution is often overlooked but it has a significant impact on human health. People mostly spend most of their time indoors such as offices, private rooms, classrooms etc and when these indoor spaces are not properly ventilated and monitored, they can cause serious short-term and long-term health issues. Poor indoor air quality leads to fatigue, headaches and reduced cognitive performance for all humans and is particularly harmful for infants, elderly and sensitive group people such as individuals with asthma, allergies and other respiratory issues.

With the growing awareness of indoor air quality, there is a need of a low cost, real time and reliable indoor air quality monitoring system in accordance with the established thresholds suggested by the **WHO**, **EPA**, **ASHRAE**, **RESET** and **WELL** that helps people to determine and improve their indoor air quality with simple actionable steps. In our project, we investigate 3 key pollutants which play a major role in air quality, Carbon dioxide (CO2), Total Volatile Organic Compound (TVOC), Particulate Matter (PM1.0, PM2.5 and PM10) along with 2 environmental factors Temperature and Humidity.

II. Related Work

Temperature & Humidity:

- Thermal comfort standards suggest 19-25°C as comfortable range.
- Temperatures above 28°C can cause heat stress among elderly and infants.
- Temperatures below 16-18°C can cause Hypothermia.
- Low Humidity (less than 30-35 %) can cause dry skin, mucous memberanes, increase risk of nose/throat infection, sore eyes and making viruses such as influenza survive long. [2][3]
- Higher Humidity (>60-65 %) triggers major asthma/allergies, promotes mold and dust-mite growth. [2][3]

Carbon-dioxide CO2:

- Elevated CO2 (from human exhalation) itself is generally not toxic but it indicates inadequate ventilation.
- Many controlled studies show that cognitive performance and decision making degrades when CO2 rises from 600-1000 ppm to 1000-1400 ppm. High CO2 can cause headaches, tiredness and drowsiness. [1]
- CO2 itself is not a respiratory but children and asthmatic patients may suffer from build up of other pollutants at high CO2 levels.

Total Volatile Organic Compound (TVOC):

- TVOC are the gases released from human breadth and sweat, paint, glue, cleaning products, cooking smoking etc. [4]
- Short term exposure to elevated TVOC can cause eyes/throat irritation, headaches, nausea or allergic symptoms. [4]
- Long term exposure can cause organ damage and cancer. Low level human produced VOCs can cause cortisol responses. [4]

Particulate Matter (PM1.0, PM2.5, PM10):

- Short term spikes in PM1.0 or PM2.5 can exacerbate asthma, bronchitis and cardiovascular problems in sensitive people.
- Long-term exposures elevates risks of heart diseases, lung cancer and even developmental issues in children. Children with asthma show symptoms at relatively low PM2.5 levels. [5]

Threshold & Guidelines: In our system we will use the following thresholds and guidelines issued by different organizations, to monitor the air quality and alert user when these thresholds are violated.

TABLE I
AIR QUALITY RECOMMENDED THRESHOLDS

Parameter	Good	Normal	Bad	Source
CO_2 (ppm)	<800	801–1000	>1000	ASHRAE [6]
PM2.5 (μg/m³)	<15	16–35	>35	WHO [7]
PM10 (μg/m³)	<45	46–100	>100	WHO [7]
PM1.0 (μg/m³)	<10	11–25	>25	RESET/WELL[8]
TVOC (ppb)	<250	251–500	>500	RESET/WELL[8]
Temperature (°C)	20–23	18–26	<18 / >26	ASHRAE [9]
Humidity (%)	40–60	30–39 / 61–70	<30 / >70	ASHRAE[9]

III. SYSTEM DESIGN

A. Overview

Our system consists of multiple sensor nodes based on nRF 52840 DK, Server Node for data collection from sensor nodes wirelessly via Thread Network, also based on nRF 52840 DK. A laptop running Data Visualization and alert system.

B. Hardware Architecture

Hardware Architecture consists of:

- 3x nRF 52840 DK Boards (2x Sensor Nodes, 1x Server Node)
- **Sensors**:
  - SCD41 (CO2, Temperature, Humidity)
  - CCS811 (eCO2, TVOC)
  - SPS30 (PM1.0, 2.5, 10)
- FT232 UART to Serial
- Laptop

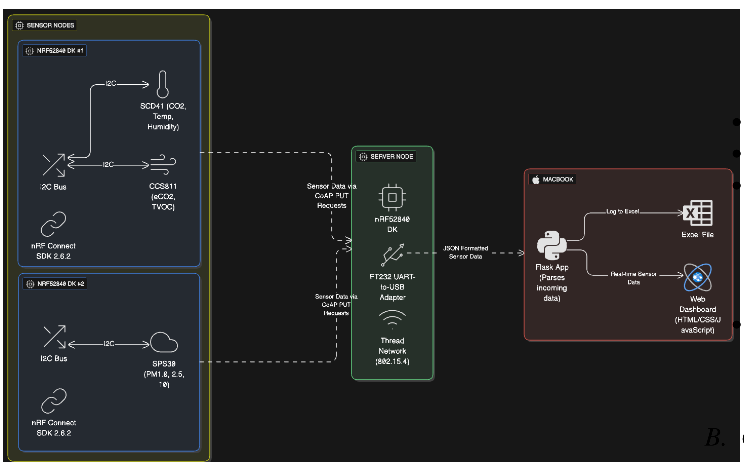

Fig. 1. System Architecture

C. Software Architecture

1) *Sensor Nodes:*

- nRF Development Kits are running nRF Connect SDK 2.6.2.
- Sensor nodes collect environmental data from sensors connected via I2C Protocol.
- After data acquisition, data is formatted into structured JSON string.
- Send JSON formatted data wirelessly to the server node using CoAP over a thread network.

2) *Server Node:*

- Server node initiates Thread Network.
- Server Node receives CoAP packets from the Sensor Nodes via Thread Network.
- It then sends the received data to the Laptop via FT232 UART to Serial.

3) *Laptop:*

- The laptop has a Flask application running that renders the Web Dashboard using HTML, CSS and Javascript.
- Once the data is received at serial, the Flask app logs the data into the Excel file and updates the Web dashboard with the real-time data.

D. Communication Layer

- For communication between Sensor Nodes and Server Nodes, we use CoAP Protocol over wireless 802.15.4.
- The sensor data is sent via CoAP PUT requests from client nodes to a fixed IPv6 Address.
- To transfer data from the Server Node to the client we use wired communication, FT232 UART to serial.

IV. WORKING OF SENSORS

A. SCD41

- The SCD41 uses a technology called Photoacoustic NDIR (Non-Dispersive Infrared). CO2 molecules absorb infrared light causing it to produces sound waves which is detected by a built in microphone. Sensor uses loudness of this sound to calculate the concentration of CO2 in parts per million. SCD41 comes with an integrated temperature and humidity sensor (SHT4X) for compensation and improved accuracy.
- Output Range: 0-40000 ppm
- Specified CO2 Measurement Range: 400-5000 ppm
- Accuracy:
  - ±50 ppm at 400-1000 ppm
  - ±50 ppm at 1001-2000 ppm
  - ±40 ppm at 2001-5000 ppm
- In addition to the WELL Building Standard™, SCD41 provides compatibility with the requirements of RESET® and California Title 24.

B. CCS811

- The CCS811 is a metal oxide (MOX) gas sensor. It contains a tiny heated plate called micro-hotplate with a reactive material on it. VOC changes its electrical resistance and MCU calculates gas concentration. The eCO2 is not the direct measurement of CO2 rather a calculated value based on TVOC.
- eCO2 Output Range: 400-8192 ppm
- TVOC Output Range: 0-1187 ppb

C. SPS30

- SPS30 uses light scattering principle to measure the Particulate Matter. Airborne particles scatter the laser beam inside the chamber. The photodetector measures the scattered light. The scattered light is proportional to the number and size of the particles.

- Mass concentration precision: ±10 %
- Sensirion SPS30 is certified by MCERTS.

V. Data Acquisition

In our project, we collected 24 hours data for analysis.

- **Environment:** The data acquisition setup was deployed in the private room of a student. The setup was placed on the study desk where the student is mostly present. The window was left tilted mostly during data acquisition for ventilation.
- **Sampling Strategy:** The sensor nodes were programmed to collect environmental data 3 times every 15 seconds, average these 3 values and send the averaged value to ther server node. The data acquisition started at 12 PM of June 28th and ended at 12 PM of June 29th.

VI. Basic Data Interpretation

Our proposed system provides 24 hour analysis of the air quality. All the information below has been collected from that analysis.

TABLE II
Recorded Activities and Window Status

Time	Activity Description	Window Status
12:00	Monitoring started	Tilted
12:50	Sprayed deodorant	Tilted
13:12	Hung washed clothes to dry	Tilted
19:16	Left room	Closed
19:23	Briefly returned and left again	Closed
19:45	Brought dinner and consumed	Tilted
20:15	Felt hot, fully opened window	Open
22:00	Cleaned room using a brush	Open
23:30	Went to sleep	Tilted
03:50	Woke up and fully opened window	Open
04:05	Went back to sleep	Tilted
07:30	Woke up and resumed activity	Tilted
08:15	Went to kitchen for Breakfast	Tilted
09:05	Returned to room and resumed work	Tilted
10:05	Felt hot, fully opened window	Open
11:00	Sprayed deodorant	Open
12:00	Monitoring Stopped	Open

A. CO2

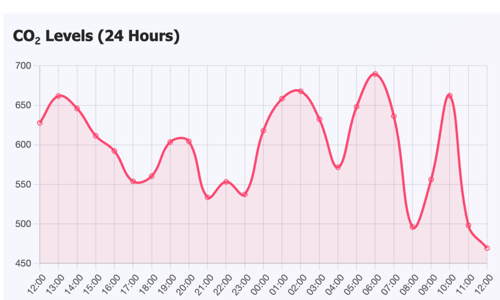

Fig. 2. CO2 Readings - SCD41

- CO2 concentrations averaged around 599 ppm, with maximum of 704 ppm at 06:26 and minimum of 456 ppm at 04:15. Throughout this time, the CO2 concentration remained below the suggested critical threshold of 1000 ppm.
- We see several sudden spikes in CO2 levels when the window was either left tilted or closed, such as between 18:00-19:00, 00:00-02:00, 04:00-06:00 and 08:00-10:00. On to the contrary, CO2 concentration dropped significantly when the window was fully opened, such as 13:00-16:00, 20:00-23:00, 04:00, 08:00 and 11:00.
- These observation suggest that tilted window ventilation is generally sufficient to maintain safe CO2 levels but fully opening up the window periodically can help reduce accumulation of CO2 and maintain better indoor air quality.

B. TVOC - Total Volatile Organic Compound

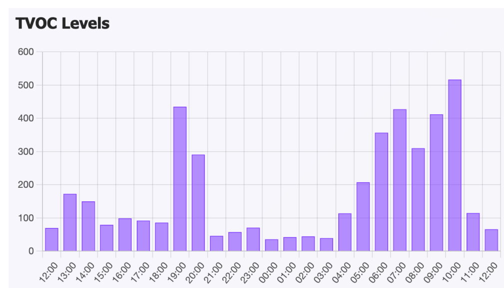

Fig. 3. TVOC Readings - CCS811

- TVOC averaged around 178 ppb, with maximum at 1149 at 20:06 and minimum of 4 ppb at 03:01. TVOC values crossed the WHO recommended safety thresholds of 500 ppb on 124 occassions.
- We see multiple spikes in TVOC levels. The prominent spike between 19:00-20:00, aligns when the student brought in his dinner. This was likely caused by food-related emissions such as oil residues or spices. After that we see some more elevations in TVOC around 06.00 - 10.00 which suggest possible infiltration of TVOC from outdoor sources through tilted window.
- One observation is that when deodorant spraying and floor cleaning which are traditional emitters of VOC, did not show measurable impact on TVOC levels.

C. Particulate Matter

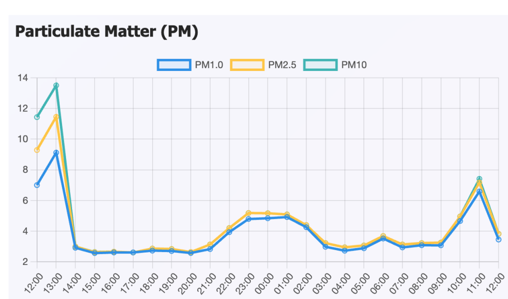

Fig. 4. Particulate Matter Readings - SPS30

- Particulate Matter levels averaged around 3.9 µg/m³ for PM1.0, 4.3 µg/m³ for PM2.5 and 4.4 µg/m³ for PM10. PM levels mostly remained within safety thresholds and only crossed these thresholds 4 times for PM1.0 and 2 times for PM2.5 and PM10. Highest value all PM1.0, PM2.5 and PM10 was recorded 88.5 µg/m³, 123.4 µg/m³ and 159.7 µg/m³ respectively. The minimum values for all PM was 1.3 µg/m³.
- In the chart, we can see a noticeable PM surge around 12.00-01.00 when the student sprayed a deodorant. This validates that aerosol and fine mist products contribute significantly to indoor particulate matter. After that we see sudden drop of PM values which remain stable throughout the day with elevated values around 21.00-03.00 and again at 10.00-11.00 when the student again sprayed deodorant.
- From 21.00-02.00 we see elevated PM levels. At this time there was no major activity by the student and in fact the student was sleeping (from 00.00-03.00). The window was tilted which suggests that outdoor pollution infiltrated the room which elevated PM values overnight. It is important to monitor external air quality when relying on natural ventilation through window as external pollutants can compromise indoor air safety.

D. Temperature & Humidity

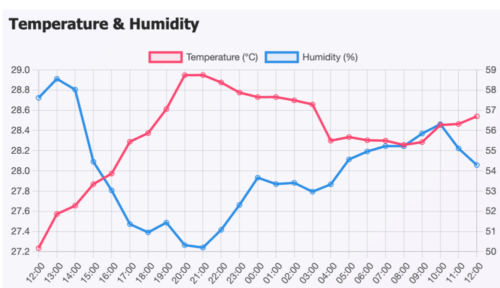

Fig. 5. Temperature & Humidity - SCD41

- During the hot day, the temperature in the room sore to 31.6°C, minimum temperature recorded was 26.3°C and average temperature was 28.4°C.
- Temperature mostly remained above comfort range which was 28°C.
- Humidity remained within the comfort range and averaged at 53.9%.
- It is worth noting that the temperature was affected by the outdoor temperature. Outdoors was a hot sunny day with maximum temperature of 31°C. To keep the temperature with-in the comfort zone, one should consider using a fan or an air conditioner, instead of relying on natural ventilation.

VII. Statistical Data Analysis

To detect anomalies in our collected data, we chose Control Charts, particularly Shewhart Control Chart with 3 sigma limits. Control charts are designed to monitor processes overtime and are perfectly suited for continuous sensor readings. They helped us in distinguishing between commonly caused variation and special caused variation (anomalies). Upper Control Limit (UCL) and Lower Control Limit (LCL) are set as follows:

- UCL = μ +3σ
- LCL = μ -3σ

Where μ is the mean and σ is the standard deviation. Any data point that falls above UCL and LCL is identified as anomaly.

A. CO2 Chart

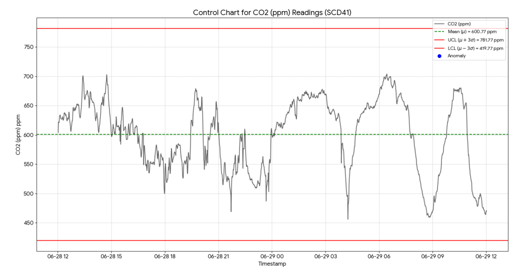

Fig. 6. CO2 - Control Chart

- The above chart demonstrates a statistically stable process. No data point exceeds the control limit.
- No anomalies in the data aligns with real world conditions such as keeping the window tilted or open for most part of the day and night.
- Moreover this also validates that the sensor performed reliably.

B. TVOC

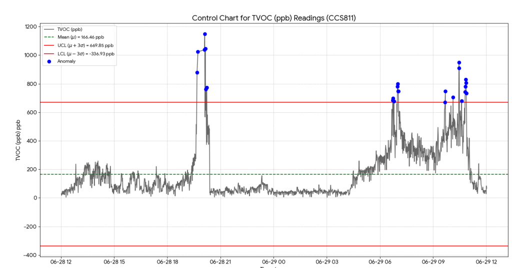

Fig. 7. TVOC - Control Chart

- The TVOC control chart highlight anomaly sets at 3 points, between 19.00-20.00, 06.00-07.00 and 09.00-12.00.
- The first set of anomalies between 19.00-20.00 corresponds to the time when the student brought in and consumed his dinner. VOC emitted from food accumulated in the room and the window was tilted at this time. Tilted window may be have provided insufficient ventilation to disprse this accumulated TVOC.
- The second set of anomalies was recorded between 06.00-07.00 while the student was asleep and no indoor activity

was taking place. The window was tilted during this time which suggests this spike was caused by outdoor air infiltration which was containing VOC or a sensor irregularity.

- The third set of anomalies is seen between 09.00-11.00. This surge is likely due to continuous bioeffluent accumulation while student was sitting and working. Around 11.00 we see a sharp drop in TVOC concentration. This drop coincides with the moment when the window was fully opened, which improved ventilation and reduced VOC concentration.

C. Particulate Matter

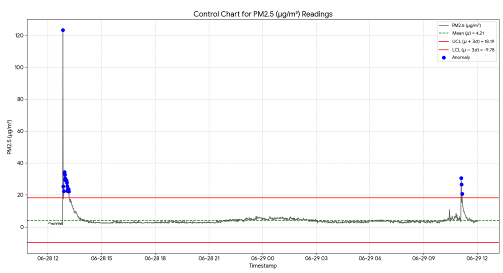

Fig. 8. PM 2.5 - Control Chart

- PM control charts show two anomaly sets. They both align with specific student activities.
- During 12.00-01.00 and 10.00-11.00, the student sprayed deodorant which introduced fine particles in the air, causing spike in PM values.
- These spikes did not last long. PM concentration quickly return to normal because of a well ventilated room. Moreover this confirms that aerosol products like deodorant are significant source of indoor PM but having proper ventilation can mitigate this impact.

D. Temperature & Humidity

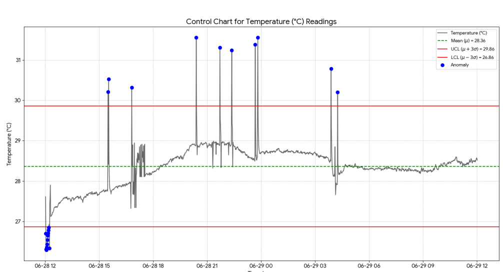

Fig. 9. Temperature - Control Chart

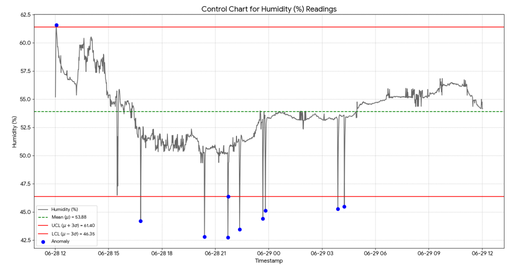

Fig. 10. Humidity - Control Chart

- Temperature & Humidity control charts display multiple individual data points above UCL and below LCL. But these do not form a cluster like TVOC and PM values , which suggest that these might be brief sensor malfunction instead of true environmental anomalies.

VIII. Conclusion

- The proposed system successfully demonstrates how this low-cost and reliable indoor air quality monitoring system is capable of capturing key environmental data using certified sensors and issue alerts and recommendations based on recommended thresholds from organizations such as WHO, EPA, ASHRAE, WELL and RESET.
- Our system offers [10] real-time data visualization dashboard that displays real-time sensor readings and actively issues alerts with recommendations when thresholds are crossed. The 24 hour analysis dashboard offers basic yet key insights of last 24 hours.
- CO2 levels remained within the safe thresholds. Analysis shows that natural ventilation, such as keeping window tilted is sufficient enough to keep the CO2 concentration in safe thresholds. Fully opening the window led to significantly better air quality which suggests that periodic full ventilation is effective strategy for optimal air quality.
- VOC concentration spikes were observed due to human activity such as food intake or prolonged activity. Tilted window was found to be insufficient in reducing VOC levels. Fully opening up the window was found efficient in quickly reducing the TVOC levels, suggesting full window opening or using an air purifier after VOC intensive activities.
- PM Values spike were strongly associated with aerosol products like deodorant. Even after sharp increase in PM values, PM concentration normalize quickly due to good ventilation. Keeping the window tilted was found sufficient to keep the PM values within safe thresholds.
- Irregularities in Temperature and Humidity suggest brief malfunction in SHT4X integrated sensor in SCD41. CO2 values remain stable at points when temperature and humidity data points crosses UCL and LCL.
- While natural ventilation is a simple way of maintaining air quality, one should always consider outdoor air quality while relying on natural ventilation. Bad outdoor air quality can result in poor indoor air quality.

- The system's effectiveness is also validated by Statistical Analysis using Shewhart Control Charts. The anomalies detected at multiple points correlate well with documented user activities and ventilation patterns.

IX. Project Contribution

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TABLE III
TEAM MEMBER CONTRIBUTIONS

Work Product	Contributor(s)	Contribution Summary
Initial Literature Review & Research	Everyone	Basic research on Indoor Air Pollution, related sensors and research questions.
Final/Revised Literature Review & Research	Muzamil	**Assigned** to: Himanshu & Abdul Haq (**no/late response / Content out-of-context**, **Muzamil**: More literature research on other pollutants + revised according to project context, Finalized Safe IAQI Thresholds to be used in the project development.
Software Config Management via Git/GitHub	Muzamil	Maintained and enabled source code traceability via GitHub.
Software Project Plan	Muzamil	Proposed initial problem solution, formulated Functional, Non-Functional Requirements, Initial Architecture, UML Diagrams etc.
Final System Design	Muzamil	Designed and implemented system architecture.
Sensor Integration	Muzamil	Searched for drivers of all sensors, implemented drivers for Zephyr - ConnectSDK v2.6.2.
Embedded Software Development for Data Acquisition	Muzamil	Setup nRF Client boards, developed software for Sensor node, implemented data validation, error handling, measurements error handling (random errors).
Embedded Software Development for Server Node	Muzamil	Setup nRF Server Node and FT232 Connection to Lpatop, Developed embedded software for Server node.
Hardware Contribution	Himanshu & Abdul	Himanshu: Lent me USB Adapter, Abdul Haq: Lent me USB cables for the setup completion.
Data-pipeline	Muzamil	Designed & implemented data-pipeline from data acquition to laptop.
24 hour Data Collection	Muzamil	Collected real-time data from sensors for 24 hours straight for Data Analysis.
Data Visualization (Front-end)	Muzamil	**Assigned to:** Himanshu & Abdul Haq (**no/late response, never received**) **Muzamil**: Developed UI friendly Real-time Data in basic HTML, CSS, JavaScript. Tailored to User Experience.
Data Visualization (Back-end)	Muzamil	**Assigned to**: Himanshu & Abdul Haq (**no/late response, never received**) **Muzamil**: Developed Flask app to receive serial data, parse, store in excel file and update the Real-time dashboard.
Data Analysis - Basic 24 Hour	Muzamil	Added basic 24 Hour analysis Dashboard in Web Dashboard.
Statistical Data Analysis - Shewhart Control Charts	Muzamil	Did statistical analysis with Shewhart Control Charts on 24 Hour collected data.
Final Report (LaTex)	Muzamil	Compiled and wrote the final report.

References

[1] National Center for Biotechnology Information, "Associations of Cognitive Function Scores with Carbon Dioxide, Ventilation, and Volatile Organic Compound Exposures in Office Workers: A Controlled Exposure Study of Green and Conventional Office Environments", PMCID: PMC4892924 PMID: 26502459. [Online] Available: https://pmc.ncbi.nlm.nih.gov/articles/PMC4892924/ [Accessed: Jul. 2, 2025]

[2] ASHARE, "ASHRAE Technical FAQ". [Online] Available: https://www.ashrae.org/File%20Library/Technical%20Resources/Technical%20FAQs/TC-02.01-FAQ-92.pdf [Accessed: Jul. 2, 2025]

[3] Researchgate , "Indoor relative humidity: relevance for health, comfort, and choice of ventilation system". [Online] Available: https://www.researchgate.net/publication/365389064_Indoor_relative_humidity_relevance_for_health_comfort_and_choice_of_ventilation_system [Accessed: Jul. 2, 2025]

[4] Kaiterra, "Understanding TVOC: What You Need To Know About Volatile Organic Compounds". [Online] Available: https://learn.kaiterra.com/en/resources/understanding-tvoc-volatile-organic-compounds [Accessed: Jul. 2, 2025]

[5] Environmental Protection Agency "Particulate Matter (PM) Basics". [Online] Available: https://www.epa.gov/pm-pollution/particulate-matter-pm-basics#effects [Accessed: Jul. 2, 2025]

[6] ASHRAE, "Position Document on Indoor Carbon Dioxide," Apr. 2022. [Online]. Available:https://www.ashrae.org/file%20library/about/position%20documents/pd_indoorcarbondioxide_2022.pdf.[Accessed: Jul. 2, 2025]

[7] World Health Organization, "WHO Global Air Quality Guidelines: PM2.5 and PM10," Sep. 2021. [Online]. Available: https://www.who.int/publications/i/item/9789240034228 [Accessed: Jul. 2, 2025]

[8] ASHRAE Standard 55, "Thermal Environmental Conditions for Human Occupancy," 2023. [Online]. Available: https://en.wikipedia.org/wiki/ASHRAE_55[Accessed: Jul. 2, 2025]

[9] RESET / WELL Building Standards, "Indoor Air Quality: TVOC & PM1.0 Recommendations," 2022.

[10] RESET / WELL Building Standards, "Indoor Air Quality: TVOC & PM1.0 Recommendations," 2022.

[11] Muhammad Muzamil. (2025). indoor-air-quality-monitoring-system [Source code]. https://github.com/muzammilmalik01/indoor-air-quality-monitoring-system