A Wireless Monitoring System to Quantify Indoor-Outdoor Air Pollution in a Building

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***Abstract*—As the world becomes increasingly urbanized and industrialized, the quality of air has become a critical concern for public health. Consequently, various studies involving indoor and outdoor air quality monitoring have emerged and identified airflow as one of the main factors. Even though airflow was deemed a major influence in the dispersion and concentration of pollutants, existing monitoring systems does not consider it when gathering data. To address this issue, the study focused on designing a wireless sensor network for indoor-outdoor air quality and dispersion assessment which can be deployed in different facilities and buildings. This was accomplished through air quality sensors and anemometers which were utilized for measuring pollutants levels, wind speed, and direction. The air quality data of each sensor node were measured and sent to the database server together with the anemometer data. The monitoring system successfully collected air quality levels and wind speed data. Results showed that air flow is a factor in the air quality of a facility. Furthermore, the outdoor environment indicated a worse air quality index in comparison to the indoor environment primarily due to its exposure to more environmental elements. The proposed infrastructure can serve as a stepping stone in the development of a smart building management system.**

***Index Terms*—mesh network, air quality, internet-of-things**

I. Introduction

Air pollution, resulting from the release of harmful substances into the atmosphere, has emerged as a pressing global issue with far-reaching consequences for public health. According to the World Health Organization (WHO), air breathed by 91 percent of the global population each day is polluted leading to approximately 7 million casualties per year [1].

Primary contributors to outdoor air pollution arise from human activities. In Metro Manila, 80 percent of the pollution originated from transportation, with the remaining portion stemming from stationary sources [2]. While pollution outside is more commonly evident due to visible smoke emissions, indoor air pollution also matters as it poses significant threats to well-being of humans with prolonged exposure [3].

There are different sources of pollutants attributed to the degradation of indoor air quality. Combustion products such as fireplaces and gas stoves contribute to release of carbon monoxide and nitrogen dioxide. Building materials such as pressed wood products made using adhesives that generate formaldehyde are also a factor. Other sources include tobacco smoke, asbestos, and biological agents [4].

Air pollutants consist of tiny particles suspended in the air [5]. Due to the continual movement of air, the transfer of these pollutants from one location to another occurs readily [6]. The quality of air can be significantly influenced by airflow, making it one of the crucial factors of pollutant dispersion. Hence, ventilation plays a big part in air quality. Insufficient flow of air can result in the accumulation of pollutants [3].

Numerous studies have explored the dynamics of air quality. Implementation of air quality monitoring systems has been one of the common solutions for indoor environments while air monitoring stations are used for outdoor sensing. Moreover, investigation of air flow as a factor is commonly simulated through computational fluid dynamics. However, measurement of wind speed and direction is administered in the study.

This study aims to construct an IoT-based indoor and outdoor air quality and dispersion monitoring system to measure concentration of pollutants as well as wind speed using multiple sensor nodes that communicate with each other through a wireless sensor network, and anemometers. The study also highlights the relationship of air quality and airflow while providing useful insights on environmental quality.

II. Methodology

A. Hardware Architecture

For each sensor node, the DFROBOT Beetle ESP32-C3 was the microcontroller used. The Sensirion SEN55 sensor was used to measure PM2.5, PM10, temperature, and relative humidity while the M5Stack SGP30 was utilized to obtain CO_2 and TVOC readings; both are interfaced using the I2C protocol. An SD Card Module with an 8GB SD Card is included for data replication and logging. The INA219 chip is used for measuring the power consumption of the node, and a micro-USB breakout board as power supply. The sensor unit is then enclosed in a waterproof case as shown in figure 1.

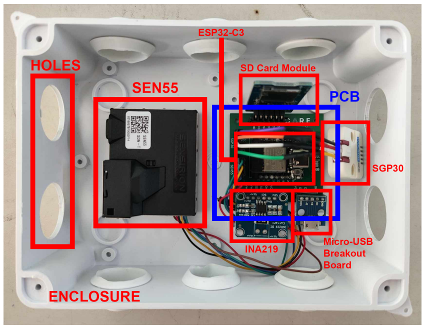

Fig. 1. Sensor node and the included components.

To measure indoor and outdoor gust and average wind speeds, and wind direction, Urageuxy WS0214 WiFi-based Weather Station and Anemometers were utilized and were connected to the Weather Underground cloud service and database.

B. Network Infrastructure

A Wireless Sensor Network (WSN) is implemented using the painlessMesh library that connects the nodes to each other using the built-in WiFi of the microcontroller while abstracting the construction of a mesh topology. Messages can be broadcasted across the mesh or to a specific node identified by its 32-bit chip ID. In addition, painlessMesh allows routing of messages to reach a node even if the sender is not directly connected to that node as long as a path exists [7].

C. Deployment

The system was deployed at the National Engineering Center (NEC) Building at Apacible Street, University of the Philippines - Diliman (UPD), Quezon City, Metro Manila, since it has an open area at its center, as well as a variety of facilities that mimic different real-world and practical situations. Four facilities were observed, one for each floor. They are selected according to usage frequency and its capacity. The variation in the layouts and their purpose was also considered. The audio visual room, administration office, seminar room, and CARE office are the facilities that were involved in the study.

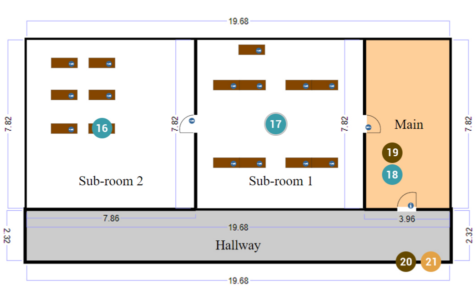

Fig. 2. Deployment floor plan showing the placements of indoor nodes (blue-green), outdoor node (light brown), and anemometers (brown)

The setup involves a mesh network of pollutant sensor nodes and anemometers in every selected room. Each entrance has an indoor and outdoor sensor node accompanied by an anemometer, with each sub room also having additional sensor nodes. A sample setup is illustrated in Figure 2 and 3, The system was deployed for approximately 10 days.

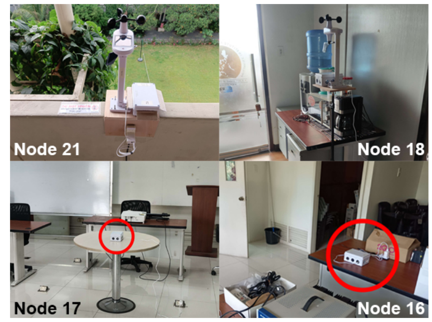

Fig. 3. Deployment setup (top-left: node 21 at outdoors, top-right: node 18 at lobby, bottom-left: node 17 at sub-room 1, bottom-right at sub-room 2)

III. Results

A. Temperature and Relative Humidity

Figure 4 illustrates the differences in temperature across all floors, both inside and outside of the rooms. Generally, outdoor temperatures are higher than indoors due to its direct sunlight exposure, especially evident for the air conditioned facilities during office hours. Moreover, the discrepancy in temperature ranges from 5-15°C however, for the vacant facilities such as the AVR and Seminar Room, the readings have less variations, fluctuating only from 3-5°C. Additionally, at nights, the temperature for all floors settles at 31-33°C, and its inverse relationship with altitude becomes slightly noticeable.

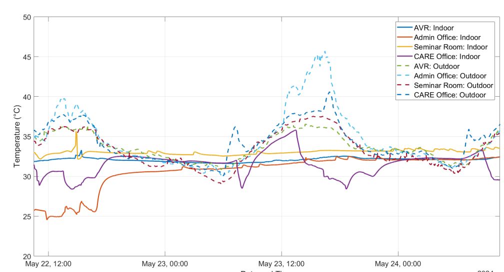

Fig. 4. Indoor and Outdoor Temperature

The relative humidity within the building is presented in Figure 5. It can be observed that its relationship to temperature is inversely proportional. Hence, indoor nodes obtained higher readings. A similar trend to temperature is observed, but in opposite. Humidity outdoors are generally much lower during the day. Its difference to indoor fall within 10-20%. Moreover, the variations per floor followed the temperature pattern. Indoor nodes differ by 5-10%, while outdoors remained closer staying within 2-5%. Lastly, at nights, the relative humidity in the building become less fluctuating, drifting towards 55-60%.

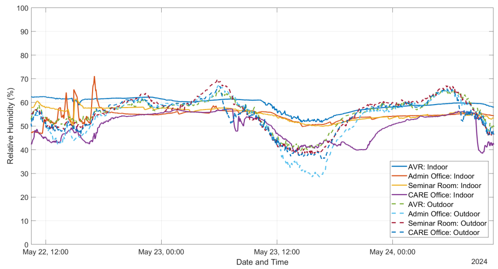

Fig. 5. Indoor and Outdoor Relative Humidity

B. Carbon Dioxide

Humans, as they exhale, are the primary source of CO2 in office setups. Other sources include heating appliances and aerosols. The Admin Office is also relatively compact and closed. With these, from the deployment snapshot from May 26-28, 2024 as shown in Figure 6, indoor CO2 levels tend to be greater than outdoors, likely due to the dense occupancy in the office. It can also be observed that indoor levels increase concurrently with outdoors, as employees frequently enter and exit the office. Furthermore, a weak correlation between Wind Speed and CO2 Levels is noticeable as wind is able to disperse the air, but can also carry the pollutants to the sensing units. Moreover, wind speed tends to increase significantly during day times and settle down to zero during night times.

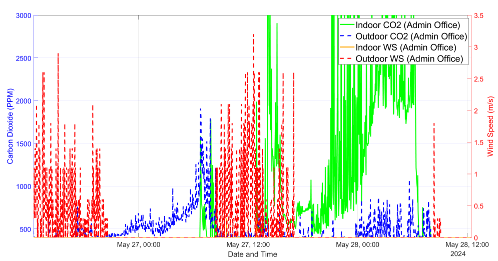

Fig. 6. Admin Office CO2 Levels and Wind Speed

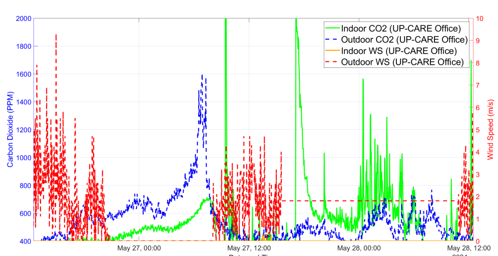

Fig. 7. UP-CARE Office CO2 Levels and Wind Speed

For figure 7, similar trends, particularly the weak wind and CO2 correlation, the concurrent increase of indoor and outdoor levels, and the potential effects of human density to pollution, as in Figure 6 can be seen. The UP-CARE Main Lobby is also compact and closed, with frequent entry and exit of employees.

TABLE I
AVERAGE CARBON DIOXIDE CONCENTRATIONS

Facility	**Average Indoor CO2 (in ppm)**	**Average Outdoor CO2 (in ppm)**
AVR (1st Floor)	541.3626	481.6795
Admin (2nd Floor)	829.6999	494.4044
Seminar (3rd Floor)	448.4401	456.5767
CARE (4th Floor)	602.1843	476.8490

The data in Table I shows that there is no clear relationship between Carbon Dioxide concentration and height. The main contributor to the changes in CO2 concentration is the presence of people within the vicinity of the sensor nodes, as well as human occupancy density. For instance, the outdoor node in the admin office perceived the highest average CO2 concentration since its position encounters the highest foot traffic.

C. Particulate Matter

There is an identical trend between PM 2.5 and PM 10 measurements due to lack of proper sensor calibration as endorsed by the manufacturer. Hence, only instances of PM 2.5 readings were shown together with the wind speed to see its impact on the dispersion of the pollutant.

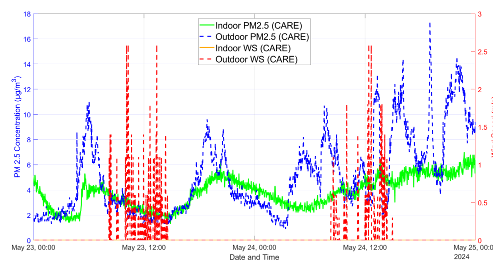

Fig. 8. Admin Office PM2.5 Levels and Wind Speed

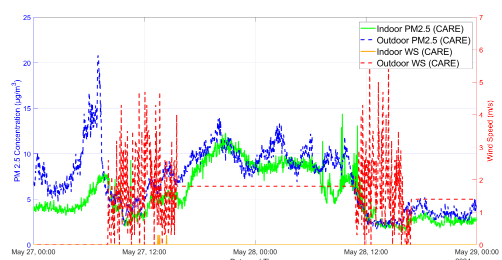

Fig. 9. UP-CARE Office PM2.5 Levels and Wind Speed

Based on Figures 8 and 9, it can be observed that the PM 2.5 levels outdoors are significantly higher because there are people moving near the nodes and it is possible that they carry dust, which is a source of particulate matter. This is very evident in the admin office due to its high usage rate. Moreover, similar pattern from both indoor and outdoor readings can be seen, it is due to people entering the facility as both the nodes are close to the entrance. Furthermore, on some hours of the graph, air flow outdoors has contributed to decrease the concentration because it can carry the pollutant away from the node. Conversely, it can also bring particulate matter towards the sensor causing an increase even with high wind speed. Lastly, the increase in concentration indoors can also be linked to a lack of ventilation as based on the plot, the air is mostly stagnant.

TABLE II
AVERAGE PARTICULATE MATTER CONCENTRATIONS

Facility	**Average Indoor PM2.5 (in $\mu g/m^3$)**	**Average Outdoor PM2.5 (in $\mu g/m^3$)**
AVR (1st Floor)	6.1749	8.2779
Admin (2nd Floor)	6.1163	7.7268
Seminar (3rd Floor)	6.0732	8.8471
CARE (4th Floor)	9.1263	12.2578

In analyzing the average particulate matter concentrations, a trend wherein the average concentration declined as the building is traversed downwards appeared. However, the average PM2.5 concentration outside the AVR neglected this trend since it had a slightly higher average than what is outside the admin office. The initially observed trend also contradicted the expected pollutant concentrations which were anticipated to increase as the height is decreased.

Overall, there are also other factors that contribute to pollutant concentration levels such as the frequency of cleaning the area and how often people come close to the sensor nodes during the deployment.

D. Total Volatile Organic Compounds

TABLE III
MINIMUM, MAXIMUM AND AVERAGE TVOC

Facility	**Indoor TVOC (in ppb)**			**Outdoor TVOC (in ppb)**		
	Min	**Max**	**Average**	**Min**	**Max**	**Average**
AVR	0	215	42.96803	0	60000	187.31
Admin	0	60000	493.7034	0	3299	110.8616
Seminar	0	847	37.28875	0	60000	132.8953
CARE	0	60000	663.1098	0	15411	265.2961

Table III exhibits the minimum, maximum, and average value of total volatile organic compounds in each facility. It can be observed that for the frequently used rooms (e.g. Admin and CARE offices), indoor TVOC level tends to be higher compared to outdoors because the people in these rooms are likely to use aerosol products such as perfumes and air fresheners. Conversely, outdoor TVOC concentration in less occupied rooms (e.g. AVR and Seminar room) is greater than indoors as there are little to no possible pollutant sources. Additionally, elevated levels outside these rooms may be attributed to increased foot traffic and cleaning materials used in the area. Based on these findings, it can be deduced that room occupancy is the primary contributor to TVOC concentration.

IV. CONCLUSION AND RECOMMENDATIONS

The system was able to produce valuable insights regarding the relationship of the pollutants with airflow and their environments. Data indicated that indoor CO2 levels are higher due to closed rooms and stagnant occupant emissions, on top of high occupancy in some indoor facilities. On the other hand, outdoor particulate matter levels are higher due to exposure to surrounding particles.

A wireless sensor network enabled communication among sensor nodes in a mesh network, allowing data transmission even without direct access points. This network feature enhanced air quality monitoring by allowing data to be transmitted and be viewed through a web application or an online dashboard.

Based on the results of the study, future recommendations are: (1) implement networking protocols with automatic sink node election (e.g., ESP-WiFi-Mesh) and use WAPs with stable internet to enhance system resilience, (2) use ultrasonic anemometers indoors to detect slight air movements, (3) employ high-quality sensors like NDIR CO2 sensors and calibrate them for accuracy, and (4) choose better deployment sites to better demonstrate the correlation between indoor and outdoor air quality.

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