Impact of Sensor Placement on Indoor Air Quality Monitoring: A Comparative Analysis

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ABSTRACT: This study investigates the impact of sensor placement on the accuracy and responsiveness of indoor air quality (IAQ) monitoring focusing on particulate matter concentrations. Measurements were conducted in a controlled environment using three intercalibrated sensors positioned at different locations: a wall-mounted sensor installed at 1.2 meters above the ground, a sensor placed at the inlet of an air purifier, and a sensor located at breathing height in the center of the room. A particle source was introduced at four different points within the room to simulate varying pollution scenarios. The results revealed that the wall-mounted sensor exhibited delays of up to 200 seconds in detecting peak pollutant concentrations compared to the sensor near the air purifier. Additionally, the wall-mounted sensor consistently recorded lower pollutant levels compared to the other two sensors. The findings underscore the critical importance of strategic sensor placement for accurate and real-time IAQ monitoring. Placing sensors closer to breathing zones and pollution sources provides data that more accurately reflects human exposure risks. The study concludes that wall-mounted sensors may not provide real-time air quality data in dynamic indoor environments. Further research, including computational fluid dynamics (CFD) simulations, is recommended to optimize sensor placement strategies.

INTRODUCTION

Indoor air quality (IAQ) is a critical component of public health, affecting productivity, comfort, and well-being. Poor IAQ can result in significant health impacts such as respiratory diseases, headaches, fatigue, allergies, and cognitive impairment. These issues are exacerbated by the fact that modern humans spend the majority of their time indoors. Indoor air pollution levels are often two to five times higher than outdoor air due to confined spaces and sources like furniture, electronics, and human emissions (1).

The increasing awareness of the adverse health effects of air pollutants has driven the need to monitor indoor air quality status. Indoor sensors are indispensable for IAQ monitoring because they provide continuous and real-time data, ensuring that indoor spaces remain safe and comfortable, especially in commercial and public buildings where large numbers of people are present (2). Advances in sensor technology have enabled the development of low-cost, highly sensitive devices capable of detecting various air pollutants (3). Accurate sensor readings are essential for maintaining healthy indoor environments and provide practical guidelines to adjust HVAC systems and their energy use (4,5). However, the accuracy of IAQ sensors is highly dependent on their placement within a space, as environmental factors, airflow patterns, and other variables can significantly affect sensor performance. Hence, the strategic positioning of sensors plays a critical role in ensuring accurate and real-time IAQ data collection (4).

Studies have shown that improper sensor placement can lead to data inaccuracies, which may compromise the overall IAQ monitoring strategy (3,5). For example, placing a sensor too close to a pollution source or an air vent can result in over- or under-estimation of pollutant concentrations.

Related studies:

Yun & Licina (4) explored the importance of strategically placing stationary air quality sensors in office environments to monitor better personal exposure to pollutants like CO2, PM2.5, and PM10. Controlled experiments found that proximity to occupants and ventilation strategies significantly influence exposure detection accuracy. They showed placements near the occupant's breathing zone, can improve the prediction of inhalation exposure, especially during different activity levels. Rackes et al. (3) simulated the impacts of the placement of CO2 and volatile organic compounds (VOCs) sensors, their accuracy, and the numbers required for effective IAQ monitoring in four typical offices. The spatial variation of concentrations for both sensors was not large, (standard deviation CO2= 3–10% and VOCs= 21% when its emissions sources were highly variable across the space). Errors due to sensor accuracy were found to be more significant than the spatial distribution of sensors, suggesting that improving sensor quality is more critical than increasing the number of sensors. Azizi et al. (5) examined the effects of 18 bundled multi-sensor devices (CO2 and passive infrared (PIR) radiation) positioned in three single-occupant offices (six sensors in each office) on the sensor data. They found the PIR sensors on the ceiling resulted in unreliable data, with 60% accuracy. Installing sensors under office desks can boost accuracy to 84%. Filios et al. (6) focused on using virtual sensing and machine learning techniques to continuously adjust gas sensor locations in two indoor settings (with HVAC and naturally ventilated room). The method reduced the need for excess hardware and improved real-time air quality assessment by predicting less valuable sensor data. Their results demonstrated that improvements in data coverage and machine learning inputs could enhance prediction accuracy. Xiang et al. (7) proposed a hybrid network combining stationary sensors for accuracy and mobile sensors for coverage. Using pollutant prediction models, their approach reduces network error by 40.4% and improves exposure measurement accuracy by 35.8% compared to stationary networks. Borodinecs et al. (2) evaluated the importance of proper ventilation in ensuring accurate CO2 sensor measurements in indoor spaces and found the sensors perform reliably in mechanically ventilated buildings, but inaccuracies in naturally ventilated spaces, particularly where room occupancy fluctuates. Cheng et al. (8) optimized temperature and CO2 sensor placement for multi-zone thermal comfort and IAQ monitoring using building information modeling (BIM), computational fluid dynamics (CFD), and genetic algorithms (GA). The study emphasizes that traditional sensor placement guidelines are insufficient for capturing critical spatial variations, and more sensors, especially in areas like corridors without HVAC systems, are needed to enhance thermal comfort and indoor air quality.

Despite the growing attention to IAQ monitoring, there is still a lack of studies that explore the placement of sensors indoors in conjunction with simulation surveys. To our knowledge, only three studies (2,4,5) have experimentally investigated this topic. By combining experimental data, computational fluid dynamics (CFD) simulations, and advanced optimization algorithms, this study provided new insights to this extent. We evaluated the effect of positioning of particle and gas sensors (total VOCs) on their accuracy and reliability in different office settings. The CFD method has become one of the most used tools in optimizing the placement of IAQ sensors. By simulating different airflow conditions, CFD models can identify zones where pollutant concentrations are likely to be higher or lower, guiding the placement of sensors for more accurate measurements. This is particularly important for particle sensors, as particulate matter follows complex airflow paths, often settling in areas that are not immediately obvious (8). Furthermore, CFD models can simulate the impact of various factors such as ventilation rates, temperature gradients, and occupant movement on indoor pollutant distribution. This allows for more precise sensor placement, ensuring that the sensors capture a representative sample of the indoor air environment (9). Bulot et al. have investigated the performance of the sensor elements themselves, including their accuracy for different particle types. Significantly they find that certain sensors have a significant time delay, up to 90 s, built into the device (10).

One could characterize error in terms of a time delay between the change of concentration in the breathing zone and the measurement point. Another error would be if there was a constant offset in concentration, for example, if the sensor was placed next to a source of pollution or clean air. Both types of error will be discussed in this article. To better understand the question of sensor placement we carried out a study in which sensors were placed at different locations.

Several guidelines have been set in place for IAQ monitoring. They mostly include placing the monitors in the height of a typical breathing zone and away from openable doors and windows. The US EPA guide states that the ideal placement would be at a height of 0.9 – 1.8 m and away from pollution sources and sinks. Rapid changes in temperature and relative humidity should be avoided near the sensors and one should make sure the sensors are not tucked away behind furniture(11).

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Materials and Methods

Study Environment and Data Collection

The study was conducted in a controlled environment—a sealed room with a volume of approximately 82.2 m³, located at the H. C. Ørsted Institute at the University of Copenhagen. FIGURE 1 shows the setup room. The room was undisturbed during the study, and baseline conditions were recorded before air purifier activation. PM1 and PM2.5 concentrations were measured using time-stamped readings at regular intervals. Sensors were first placed 1 cm apart to correlate proximity and were intercalibrated according to the results.

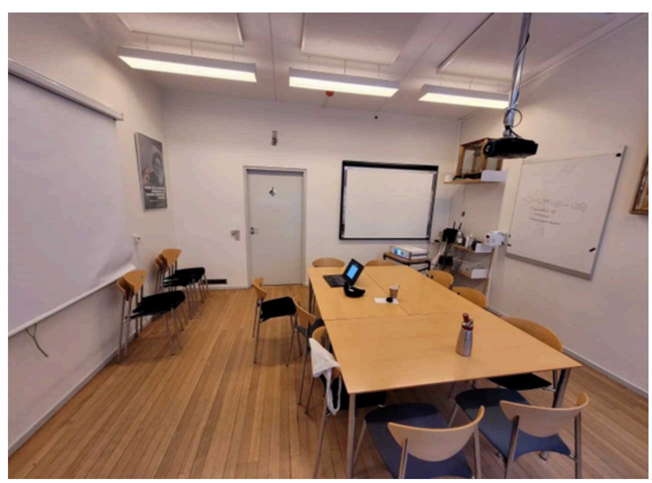

FIGURE 1. Room setup in this study.

Three intercalibrated particulate matter sensors were used to count particle concentrations simultaneously. The locations of the sensors are highlighted by the red circles in FIGURE 2.

- Wall-mounted sensor: Installed at a standard height of 1.2 meters above the ground for monitoring air quality.

- Device sensor: Placed at the inlet of an air purifier, where real-time air quality data is expected to reflect conditions as air enters the device for filtration.

- Center sensor: Placed at breathing level in the room center.

FIGURE 2. Locations of the sensors

The particle sources (incense) were placed at four different points 1, 2, 3, and 4 as shown in FIGURE 3.

Data were analyzed by comparing the PM1 and PM2.5 concentration trends between the wall-mounted, center, and device sensors. Delays between sensors were noted, particularly between the wall-mounted and center sensors.

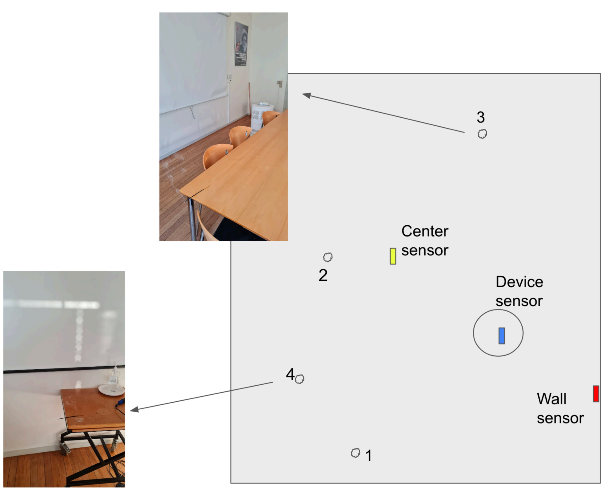

FIGURE 3. Locations of the particle source in the room

Results and Discussion

PM1 and PM2.5 Concentration

The background numbers were very similar for all three sensors. After a few minutes to record the background, the particles were released at point 1. FIGURE 4 shows the particle concentrations at the three locations when the pollution source was placed at Point 1. The device and center sensors showed more similar readings than the wall-mounted sensor. The horizontal axis shows time in minutes.

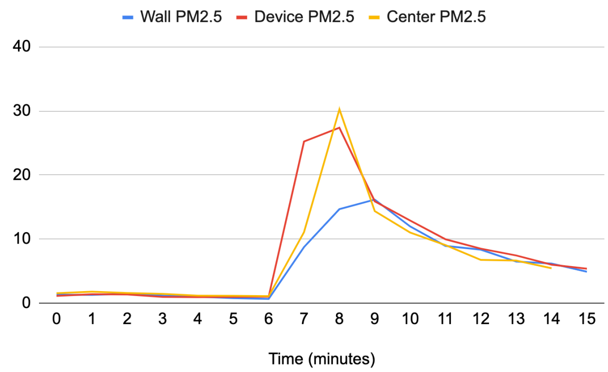

FIGURE 4. Measured particle concentrations (µg/m³) by the three sensors at Point 1

All three sensors showed similar numbers where the particle source was placed at Point 2, as shown in FIGURE 5. However, the device sensor is still more aligned with the center sensor. The horizontal axis shows time in minutes.

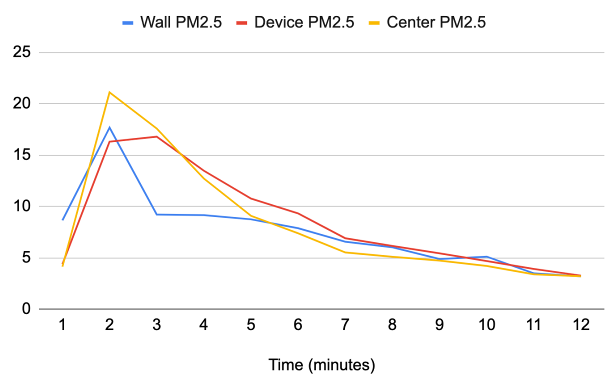

FIGURE 5. Measured particle concentrations (µg/m³) by the three sensors at Point 2

FIGURE 6 shows the PM2.5 concentrations measured by the three sensors, with the particle source located at Point 3. The readings from both the device and the center sensor peak at approximately 20 µg/m³, while the wall sensor registers a peak of around 12 µg/m³.

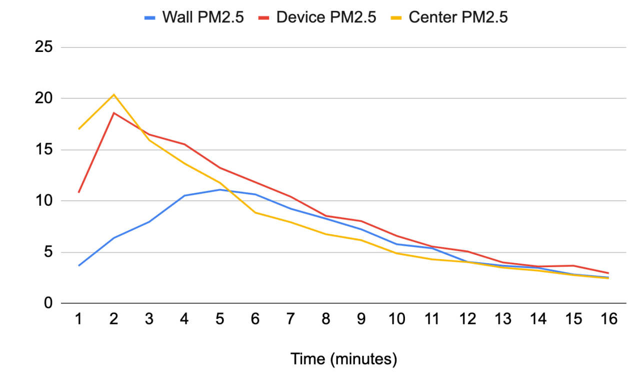

FIGURE 6. Measured particle concentrations (µg/m³) by the three sensors at Point 3

The concentrations when the particle source is at Point 4 are shown in FIGURE 7. The device and the center sensor showed a pick of around 15 µg/m³, while the wall sensor shows a pick of about 5 µg/m³, i.e. one-third of the exposed concentration.

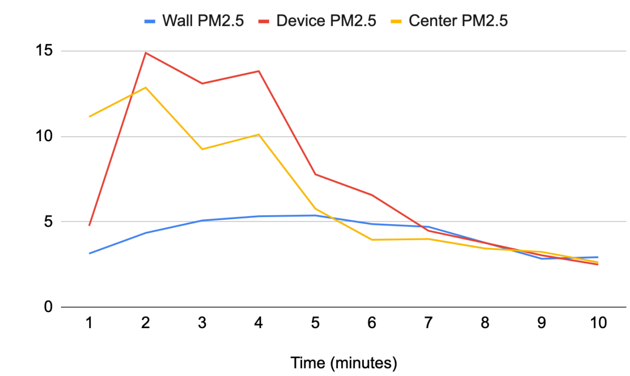

FIGURE 7. Measured particle concentrations (µg/m³) by the three sensors at Point 4.

Discussion

The study's findings underscore the critical importance of sensor placement in IAQ monitoring. Although useful for long-term installations, wall-mounted sensors may not provide real-time sensitivity in environments with rapidly changing air quality. The wall-mounted sensor shows both concentration differences and time delay regarding the particle concentrations. All measurements show more than a 30% discrepancy between the peaks of the wall sensor maximum numbers and the maximum numbers of the two other sensors, except for Point 2 measurement, where the point source is near the center of the room.

The peak concentration of the wall sensor, when the particle source was at Point 4, had a delay of more than three minutes. Detecting pollution fast results in reacting fast to remove the pollution by removing the pollution source, using a local air purifier, using the central ventilation system, or staying away from the polluted area. Device sensors, placed at the inlet of air purifiers, offer a better solution for immediate tracking of air quality and pollutant levels.

Two main phenomena cause on dispersion of pollutants in the air. One is diffusion and the other is turbulence. The turbulence effect is minimal near the walls, due to the boundary layers. This effect can be seen here as well for the wall sensor. The pollutants that can reach the sensor at the wall are less than the pollutants at the center and the device. After several minutes all sensors show similar numbers since the mixing happens during this time. The air purifier fan adds turbulence to the room which helps to have mixing. More CFD simulation studies can be done to scrutinize this condition.

A room is not a well-mixed reactor and concentrations will vary depending on the location of pollution sources and ventilation. But the concentration in the breathing zone is the most important concentration to be determined accurately, since this is directly linked to pollution exposure. These results indicate that future IAQ monitoring systems must carefully consider the location of sensors to ensure timely and accurate pollutant detection. Placing sensors, far from the walls, closer to breathing zones and pollutant sources yields data that more accurately reflects human exposure risks.

Conclusion

This study highlights significant differences in air quality data obtained from wall-mounted and device sensors. The findings suggest that the sensor placed at the inlet of the air purifier provides more accurate and immediate readings, particularly in environments with fluctuating air quality. In contrast, the wall-mounted sensor may introduce delays, reducing their effectiveness for real-time monitoring. These results have important implications for designing indoor air quality monitoring systems, where sensor placement should be prioritized to ensure accurate assessments of human exposure to pollutants. More studies are needed to visualize the relationship between the concentrations of wall-mounted particle sensors, ventilation exhaust sensors, and the sensor placed at a local air purifier inlet. This could be done by using CFD simulations.

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