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ARAŞTIRMA MAKALESİ **RESEARCH ARTICLE**

Field Testing of Low-Cost PM Sensors in Animal Production Facilities

Düşük Maliyetli PM Sensörlerinin Hayvansal Üretim Tesislerinde Test Edilmesi

Seyit UGUZ[1], Pradeep KUMAR[2], Shalini TIWARI[3], Young CHANG[4], Xufei YANG[5]*

Abstract

The measurement of particulate matter (PM) in animal housing environments is crucial for ensuring the health and well-being of both animals and human workers. High concentrations of PM can lead to respiratory issues, reduced productivity, and compromised animal welfare. The affordability and compact design of low-cost PM sensors present an opportunity to enhance spatiotemporal resolution in PM measurements. However, these low-cost sensors have certain limitations and require characterization in dusty environments such as animal production facilities. This study examines eight low-cost PM sensors (PMS5003, PMS7003, OPC-R2, OPC-N3, Gravity, SDS011, GP2Y1010, and PPD42) for their performance in monitoring PM_1, $PM_{2.5}$, and PM_{10} concentrations in animal houses. It details sensor components, hardware integration, and field deployment, along with preliminary testing in farm office and production room environments. A GRIMM 11-D aerosol spectrometer was used as the reference monitor. The OPC-N3 sensor showed high linearity against the reference monitor in the office, with R^2 values higher than 0.97, but this correlation dropped to 0.40-0.59 in the production room due to increased particle concentration affecting sensor sensitivity. Meanwhile, the PMS7003 sensor excelled in PM_1 measurements with an R^2 value of 0.90, performing well in production settings, in contrast to its performance in the office. The SDS011 sensor also demonstrated good performance in production environments. Preliminary results suggest that while these sensors effectively measure PM levels under certain conditions, their performance varies significantly depending on environmental factors such as dust concentration, temperature, and relative humidity. The necessity for rigorous field testing and calibration is emphasized to enhance the reliability and accuracy of these sensors in monitoring indoor air quality in agricultural settings. Further research and field testing are essential to validate sensor performance and ensure their effectiveness across diverse environmental conditions.

Keywords: Particulate matter, Low-cost sensors, Air quality, Animal houses, Measurement

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Öz

Hayvan barınakları iç ortamında partikül maddelerin (PM) izlenmesi hem barındırılan hayvanların hem de çiftlik çalışanlarının sağlık ve refahının sağlanması için oldukça önemlidir. Yüksek düzeyde organic partiküllere ve kirletici gazlara maruz kalan çiftlik çalışanları, yaşlandıkça solunum yolu hastalıklarına daha duyarlı hale gelmektedirler. Düşük maliyetli sensörlerin ekonomikliği ve kompakt tasarımı, PM ölçümlerinde uzamsal-zamansal çözünürlüğü artırmak için bir fırsat sunmaktadır. Bu çalışmada, hayvan barınaklarından salınan PM_1, PM2.5 ve PM10 konsantrasyonlarının izlenmesi için düşük maliyetli PM sensörlerinin geliştirilmesi ve geliştirilen sistemin ön denemelerinin yapılması amaçlanmıştır. Çalışmada, düşük maliyetli 8 adet PM sensörlerinin (PMS5003, PMS7003, OPC-R2, OPC-N3, Gravity, SDS011, GP2Y1010, PPD42) donanım, sensör bileşenleri ve kurulum süreçlerinin yanı sıra hayvansal üretim tesislerinde ofis ve barınak ortamında ön testleri ve referans PM ölçer ile karşılaştırması yapılmıştır. OPC-N3 sensörü, ofis ortamında referans monitörle yüksek korelasyon göstermiştir (0.97-0.98) ancak bu korelasyon barınak iç ortamında 0.40-0.59 değerlerine düşmüştür. Bunun sebebi ise barınak iç ortamında artan partikül konsantrasyonlarının sensor hassasiyetini etkilediği düşünülmektedir. Bu arada PMS7003 sensörü PM_1 ölçümlerinde yüksek korelasyon değeri ile (R^2: 0.90) ile ofis ortamının aksine barınak iç ortamında daha iyi bir performans göstermiştir. SDS011 sensörü de barınak iç ortamında daha iyi performans göstermiştir. Ön sonuçlar, bu sensörlerin belirli çevre koşulları altında PM seviyelerini etkili bir şekilde ölçerken, performanslarının toz, sıcaklık ve bağıl nem gibi çevresel faktörlere bağlı olarak önemli ölçüde değiştiğini göstermektedir. Hayvansal üretim yapılarında iç mekân hava kalitesinin izlenmesinde bu sensörlerin güvenilirliğini ve doğruluğunu artırmak için detaylı saha testleri ve kalibrasyonunun gerekliliği vurgulanmaktadır. Düşük maliyetli PM sensörlerinin performansının doğrulanması ve farklı çevresel koşullarda etkinliklerinin arttırılması için daha fazla araştırma ve saha testi yapılması gerekmektedir.

Anahtar Kelimeler: Partiküler madde, Düşük maliyetli sensör, Hava kalitesi, Hayvan barınakları, Ölçme

1. Introduction

Indoor air quality in animal production facilities is a critical concern due to the potential health impacts on both animals and humans. Particulate matter (PM) emanating from animal husbandry, particularly in poultry and pig houses, poses significant challenges in maintaining air quality standards (Silva, 2023; Guo et al., 2022; Zhang et al., 2022). PM is categorized into three types based on particle size: PM_{10}, which consists of inhalable particles with diameters of 10 µm or smaller, $PM_{2.5}$, which comprises fine respirable particles with diameters of 2.5 µm and smaller, and PM_1, which includes extremely fine particles with diameters less than 1 µm (Lowther et al., 2019). These distinctions are essential for understanding the potential health impacts of various sizes of PM in the environment. Exposure to PM has been linked to an increased risk of lung cancer (Tsameret et al., 2024) and cardiovascular disease (Laltrello et al., 2022) and is associated with elevated daily mortality rates (Bist and Chai, 2022). In response to these health implications, regulatory bodies worldwide have implemented regulations and guidance to assess and control PM levels. Studies have emphasized the importance of measuring both PM number and mass concentrations within animal houses to develop effective reduction techniques and evaluate their actual performance (Cambra-López et al., 2011).

Past research highlights the need for real-time PM monitoring inside animal confinement buildings. However, professional instruments such as TEOM, DustTrak, and HAZ-DUST, while effective, come with several drawbacks. These include (1) high costs, which may be prohibitive for smaller farms; (2) operational complexity that requires specialized training; (3) the necessity for regular maintenance; and (4) limited accessibility. Additionally, these instruments may not offer real-time data at a desired temporal resolution, lack sufficient portability for field deployment, and are often designed for ambient PM monitoring with lower PM concentrations than typically found in animal houses. These factors limit their extensive use in commercial animal production facilities. Moreover, these instruments usually require intricate calibration and specific power conditions (Arulmozhi et al., 2024).

To overcome these challenges, low-cost sensors (LCSs) have garnered attention for their ability to facilitate personalized monitoring at a fraction of the cost of federal reference methods (FRMs) and federal equivalent methods (FEMs). LCSs offer flexibility in field deployment due to their compact size and minimal maintenance requirements. These sensors provide high-resolution data at minute or even second intervals, enabling the detection of transient PM emission events (Holstius et al., 2014; Gao et al., 2015; Li et al., 2018). Laboratory evaluations have demonstrated moderate to high correlations between LCSs and FRMs/FEMs, indicating their suitability for use across a wide range of concentrations and environmental conditions (Samad et al., 2021). LCSs have been proposed to estimate PM concentrations in broiler houses (Yasmeen et al., 2019), but no systematic assessments have been reported to date. Combined with advanced data processing technologies, LCSs may offer an affordable solution for assessing both animal and human exposure to PM and effectively mitigating PM pollution in animal houses.

LCSs have been increasingly deployed in both ambient and indoor settings, offering valuable insights into PM dynamics (Jayaratne et al., 2018). The evaluation and calibration of data collected by low-cost PM sensors in different environments have been a focus of recent research, aiming to enhance the accuracy and reliability of sensor measurements (Huang et al., 2022). The application of LCSs for PM measurements has been explored in various studies, including laboratory assessments (Manikonda et al., 2016), residential areas (Kortoçi et al., 2022; Mahajan and Kumar, 2020), and rural areas (Johnson et al., 2018). These studies highlight the versatility and potential of LCSs in diverse indoor environments. Several low-cost PM sensors, including models from Shinyei, Alphasense, and Plantower, have been tested in various environments and for different PM size fractions. However, gaps remain in the literature regarding their calibration and performance assessment, making it challenging to validate data quality across studies. For example, Delgado et al. (2020) faced challenges validating SDS011 sensors due to unsuitable testing environments. In contrast, Afroz et al. (2024) achieved an 80% accuracy with SDS011 sensors using a correction factor in a Canadian egg farm environment, though they noted decreased reliability at night. Yasmeen et al. (2019) used Dylos 1700 sensors in broiler houses, applying conversion factors to estimate PM concentrations. These findings highlight the ongoing need for evaluation and standardization of low-cost PM sensors to improve their accuracy and reliability across different research settings.

The effectiveness and accuracy of LCSs in animal houses, often hindered by dusty conditions, present significant challenges for maintaining sensor performance and ensuring reliable data. This research paper explores development and installation of low-cost PM sensors for measuring PM_1, $PM_{2.5}$, and PM_{10} concentrations for specific needs of confinement animal houses. Additionally, LCSs were rigorously tested and validated through preliminary tests and comparisons with a reference monitoring device. This study aims to foster animal welfare, the health of both animals and farmers, and the sustainable advancement of the agricultural sector by providing a cost-efficient, real-time PM monitoring solution for animal production facilities.

2. Materials and Methods

2.1. Sensor selection

Eight PM sensors were selected for field assessment, as listed in *Table 1*. Notably, although all these sensors are marketed as LCSs, they fall into two distinct price ranges. All sensors, with the exception of the OPC-N3 and OPC-R2 models, are priced below 50 USD each. OPC-N3 and OPC-R2 sensors are substantially more expensive but remain priced below 600 USD per unit. According to our discussions with animal producers in the United States, air quality sensors priced under 1000 USD are considered acceptable if they provide satisfactory field performance. In contrast, DustTrak, a professional instrument for real-time PM monitoring, costs over 7,000 USD per unit. All the selected LCSs use light scattering for PM detection. Based on the detection principle, these sensors can be classified into two categories: optical particle counter (OPC) and nephelometer. An OPC can count and allocate individual particles into multiple size ranges, allowing it to derive their mass concentrations; while a nephelometer estimates the mass concentration of all particles in an optical chamber based on their collective light scattering. Additional information on their detection principles can be found in Yang et al. (2022). A brief introduction to each of the tested sensors is given below:

- **Plantower PMS5003** is a widely used LCS for air quality monitoring, recognized for its capability to measure real-time PM_1, $PM_{2.5}$, and PM_{10} concentrations (Kobziar et al., 2019). It employs laser scattering to categorize airborne particles into six size bins: >0.3 µm, >0.5 µm, >1.0 µm, >2.5 µm, >5.0 µm, and >10 µm. The sensor then calculates PM concentrations for three size ranges: 0.3–1.0 µm, 1.0–2.5 µm, and 2.5–10 µm. The PMS5003 boasts high counting efficiency: 50% efficiency at 0.3 µm and 98% at 0.5 µm and larger sizes (Dobson et al., 2023). **Plantower PMS7003**, a newer model from the same manufacturer, features a smaller footprint and consumes less power compared to the PMS5003. It supports both binary and ASCII output modes, making it compatible with various data acquisition systems and microcontrollers (Badura et al., 2019).
- **Alphasense OPC-N3** classifies airborne particles with diameters ranging from 0.35 to 40 µm into 24 size bins, and calculates PM_1, $PM_{2.5}$, and PM_{10} concentrations based on particle counts in their respective size bins. **Alphasense OPC-R2** is a simplified version of the OPC-N3, featuring a more basic optical module and flow channel design. It classifies particles in a diameter range of 0.35 to 12 µm into 16 size bins. Both sensors are equipped with a fan to ensure consistent airflow through the optical chamber, which enhances the reliability of their measurements. These sensors are widely used in air quality monitoring applications due to their precision and robustness (Sousan et al., 2021; Correia et al., 2023; Raheja, 2023).
- **BJHike Gravity** is part of a series of environmental sensors designed for compatibility with Arduino and other microcontroller platforms. These sensors are typically used for air quality monitoring, detecting PM concentrations in the environment (Singh et. al., 2022). While specific details are not available, the sensor appears to use a design similar to the Plantower PMS5003, based on a visual inspection of their interiors.
- **Nova SDS011** is a PM sensor designed for air quality monitoring, capable of detecting both fine and coarse particles in the air. It measures $PM_{2.5}$ and PM_{10} levels using laser scattering technology, providing real-time and accurate assessments of PM concentrations. Known for its rapid response and stability within a compact design, the SDS011 is well-suited for use in portable devices or fixed air quality monitoring stations. It is commonly employed in both indoor and outdoor environments to evaluate air quality (Liu et al., 2019; Soms and Soms, 2021).
- **Sharp GP2Y1010** is an optical sensor designed to detect dust or smoke particles greater than 0.5 µm. It utilizes an infrared emitting diode (IRED) as the light source and a phototransistor to detect the light scattered by dust particles in the air. This sensor provides an analog output voltage that correlates to the density of dust particles,

enabling its use in air purifier systems and for monitoring air quality in indoor and semi-outdoor environments (Ghamari et al., 2022; Wang et al., 2015). **Shinyei PPD42**, also intended for dust or smoke particle detection, employs a similar design to the Sharp GP2Y1010 but has a more limited detection range (>1 µm; up to 28 particles/cm³). Both sensors are passive and do not include a fan to force air through the optical chamber.

Table 1. Low-cost PM sensors selected in this study

Manufacturer	Model	PM measured	Type	Unit price* (USD)
Plantower	PMS5003	PM_1, $PM_{2.5}$, PM_{10}	OPC	$30
Plantower	PMS7003	PM_1, $PM_{2.5}$, PM_{10}	OPC	$32
Alphasense	OPC-N3	PM_1, $PM_{2.5}$, PM_{10}	OPC	$550
Alphasense	OPC-R2	PM_1, $PM_{2.5}$, PM_{10}	OPC	$450
BJHike	Gravity	PM_1, $PM_{2.5}$, PM_{10}	Likely OPC	$45
Nova	SDS011	PM_1, $PM_{2.5}$, PM_{10}	Likely OPC	$35
Sharp	GP2Y1010	Total particles	Nephelometer	$15
Shinyei	PPD42	Total particles	Nephelometer	$14

* It is the price at which a sensor was acquired.

2.2. Test system construction

2.2.1. System Integration

Due to the significantly higher cost of the OPC-N3 and OPC-R2 compared to other sensors, separate test systems were constructed for each model (*Figure 1b*). Each system utilized an Arduino Mega 2560 R3 microcontroller to measure PM_1, $PM_{2.5}$, and PM_{10} concentrations from the OPC-N3 or OPC-R2 sensor. The PM concentration data, along with timestamp information from a real-time clock (RTC) module, were saved to a microSD card and simultaneously displayed on an LCD screen. Additionally, the system included a Wi-Fi module, which is currently unused but could enable real-time data submission to a cloud server in the future.

The remaining six PM sensors shared a common test system (*Figure 1a*). This system also used an Arduino Mega 2560 R3 microcontroller to collect PM concentration data from the sensors, which employed various communication protocols. An RTC module provided timestamp information. To simplify the setup, this system did not include a WI-FI module or an LCD screen. However, due to the higher power demands of the six sensors, a dedicated DC power supply board was employed to ensure an undisrupted power supply. *Figure 1* shows the system design of six sensors (a) and OPC-N3/OPC-R2 (b).

2.2.2. Packaging

Six sensors including PMS5003, PMS7003, GP2Y1010, Gravity, PPD42, and SDS011 sensors were enclosed inside a plastic box with a length, width, and height of 13 x 6 x7 cm, making the sensor compact and suitable to fit indoors and outdoors. The OPC-N3 and OPC-R2 sensors were enclosed inside a plastic box with the dimensions of 20 x 13 x 8 cm. This setup, housed in a waterproof box and powered by a DC power supply adapter or alternatively a 10.000 mAh standby battery, was collocated next to a reference monitor for testing.

The enclosure models to be printed were designed in the Autodesk AutoCAD 3D modeling software. The sensor enclosures were designed with two parts, the first one is the bottom part that holds the sensor, microcontroller, LCD screen, and battery. The second part is the enclosure cover, which is attached to the bottom part with screws. The 3D models, shape, and parameters of these parts are shown in *Figure 2.*

Then the designed model is exported in ".STL" format. STL, short for "stereolithography," is a file format developed by 3D Systems for its CAD software, widely adopted for 3D printing, rapid prototyping, and computer-aided manufacturing. The format predominantly captures the surface geometry of three-dimensional objects but lacks the capability to encode color, texture, or other common CAD model attributes (Hoque et al., 2018). The Flashforge CreatorPro 3-D Printer (FlashForge Creator Pro, FlashForge Corporation) was used for printing the sensor enclosures. The polylactic acid (PLA) 3D Printer Filament (Filament diameter: 1.75 mm) was used as the printing material. The sensors integrated into the printed enclosures are shown in *Figure 3*. *Figures 3a*, *3b*, and *3c* show the OPC-R2, OPC-N3, and six sensors, respectively.

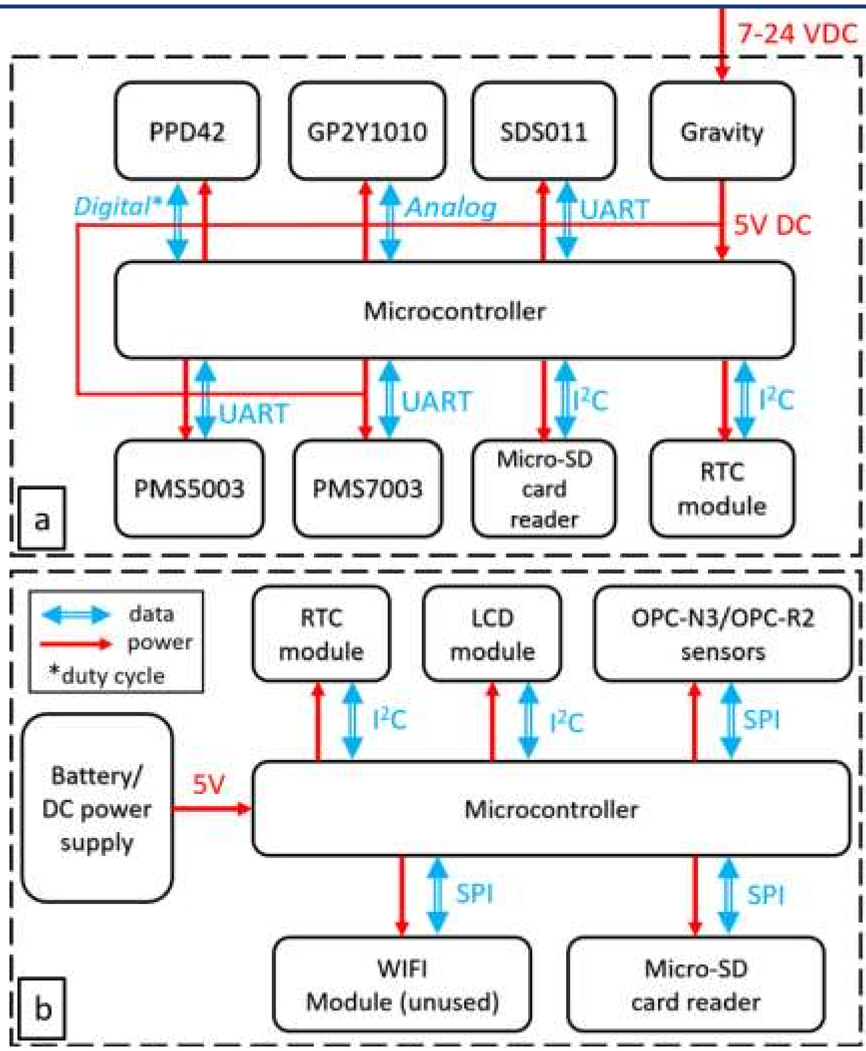

Figure 1. System design of six sensors (a) and OPC-N3/OPC-R2 (b)

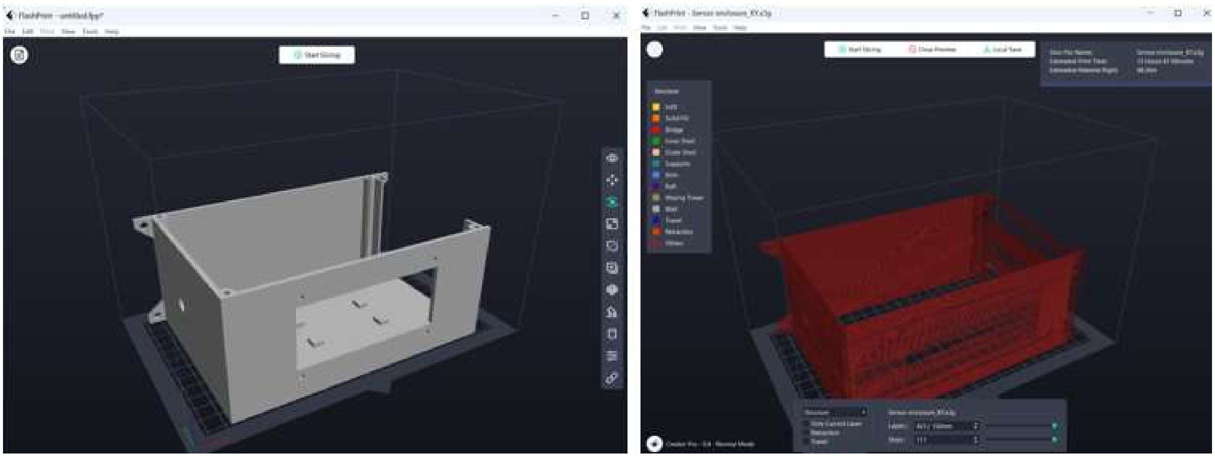

Figure 2. The designed 3D Model

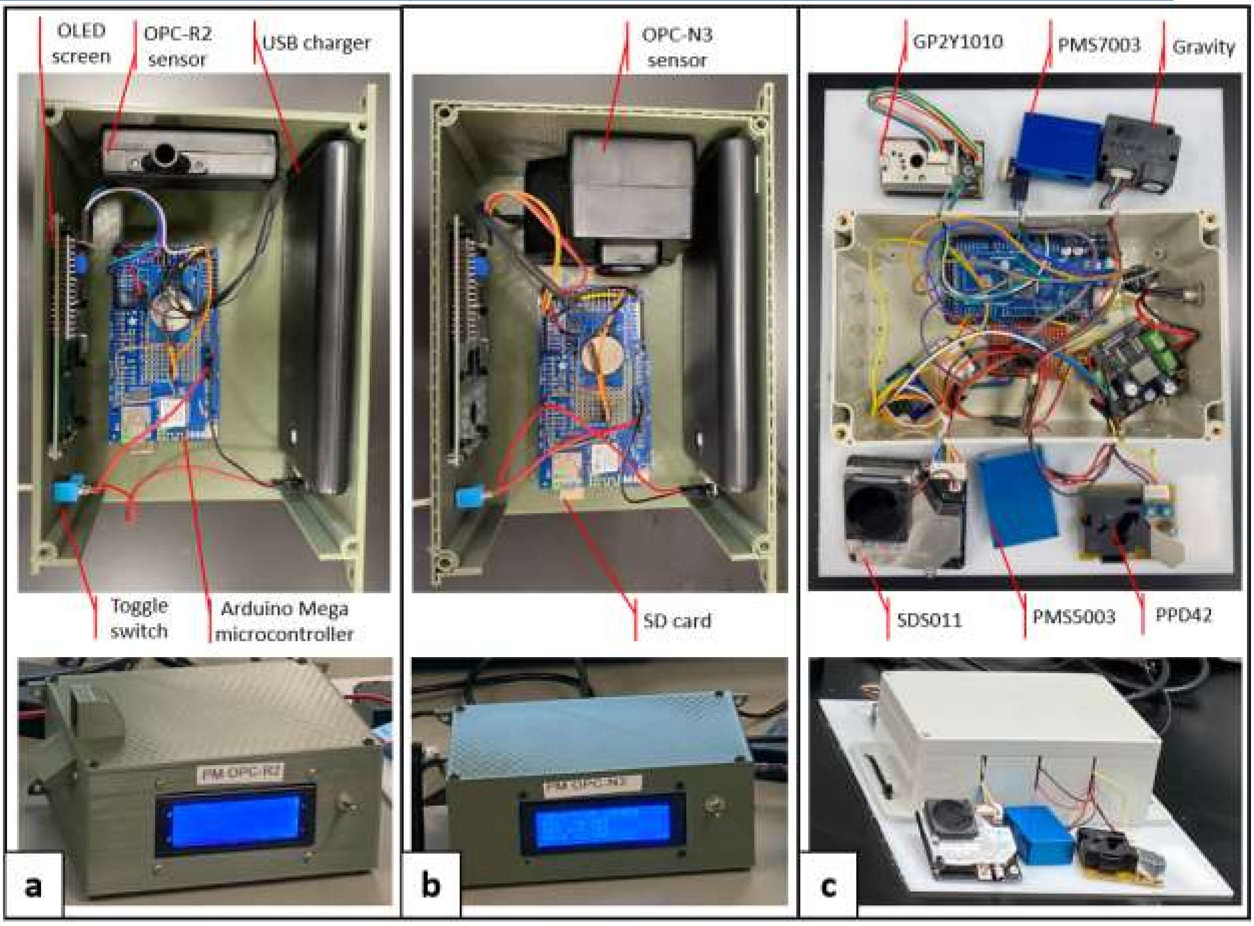

Figure 3. Interior view of the low-cost PM monitors

2.3. Preliminary test measurements

A preliminary test was initially conducted inside a barn office before moving to a wean-to-finish production room. This study developed low-cost PM sensors and validated them in a 1,200-head pig pen at South Dakota State University (SDSU). Field evaluations in both office and barn environments utilized the GRIMM and LCS to assess the sensors' performance. All devices measured PM_1, $PM_{2.5}$, and PM_{10} at the same location, while a temperature/humidity sensor monitored indoor conditions. Measurements were conducted at the Offsite Wean-to-Finish Production Barn, 12 miles south of the SDSU campus. The barn, which houses 1200 wean-to-finish pigs in two identical rooms of 52 pens each, is mechanically ventilated and features systems for remote monitoring and data logging. Sensors were positioned 1.2 m above ground level and about 3.5 m ft from the central exhaust fans. Eight different low-cost PM sensors were tested over seven days to evaluate their performance. Sensors recorded PM concentration every five minutes, and data were processed into hourly averages for comparison. Temperature and humidity were also monitored using a HOBO (MX1101, Onset) sensor. The field experiment setting is depicted in *Figure 4*, conducted at the SDSU Swine house in Brookings, SD, USA.

To analyze trends in PM concentration, the GRIMM 11-D aerosol spectrometer—a portable particle counter categorizing particles from 0.253 to 35.15 µm—served as the reference. It counts particles using a diode laser with a 30 mW output and 655 nm wavelength. Among various monitoring devices, the GRIMM monitor has emerged as a reliable tool for assessing PM levels in confined animal facilities. This device is particularly adept at measuring different PM size fractions, including PM_1, $PM_{2.5}$, and PM_{10}, which are critical for understanding the potential health risks associated with airborne particulates. The GRIMM monitor's effectiveness has been validated in various settings, including broiler farms and laboratory animal facilities, where it has been used to track PM concentrations and assess their impact on animal health (Fernández et al., 2018; Shen et al., 2018). The ability to continuously monitor PM levels allows for timely interventions to mitigate exposure risks, thereby enhancing the overall air quality in animal housing. As highlighted in recent studies, the integration of such monitoring systems is essential for developing comprehensive strategies to manage indoor air quality and ensure the welfare of both animals and workers (Guo et al., 2022; Lovanh et al., 2016).

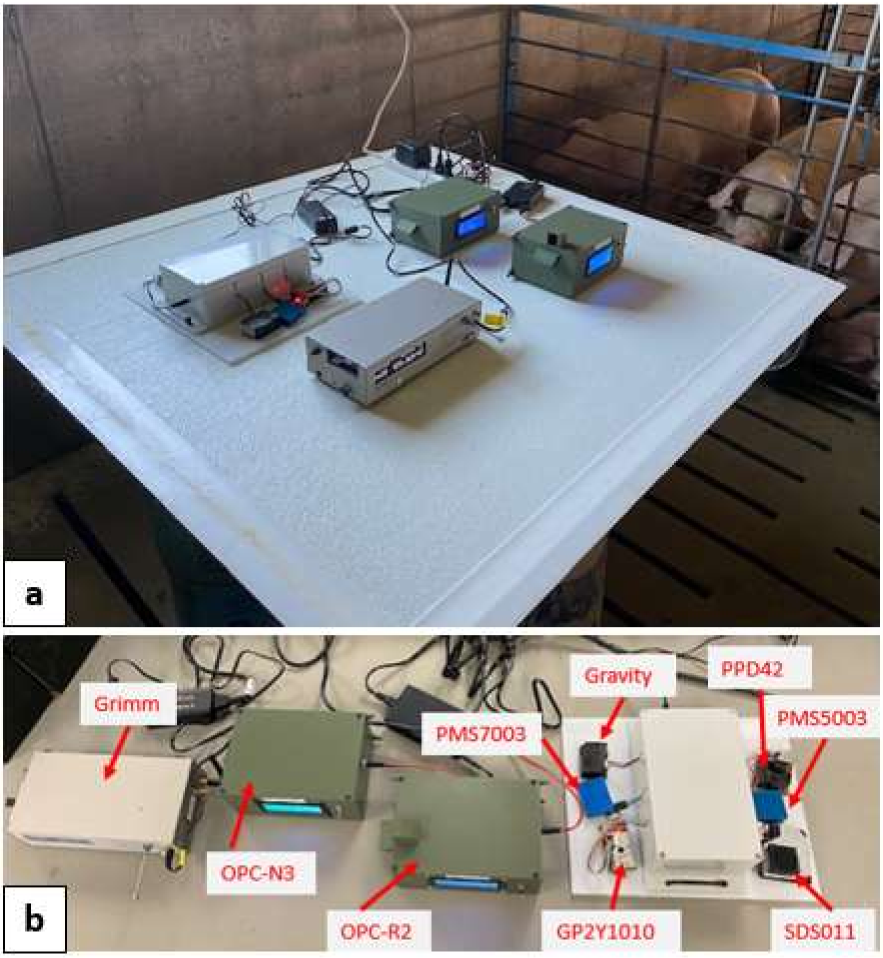

Figure 4. The experimental setup in the barn (a) and office (b) measurements

2.4. Data analysis

To analyze the data from the performance of LCSs against a reference instrument, several statistical metrics were employed, including coefficient of Variation (CV), Bias, R^2, and Root-Mean-Squared Error (RMSE). CV measures the dispersion of data points in a probability distribution relative to its mean. It is useful for comparing the degree of variation from one data series to another, even if the means are drastically different from each other. A higher CV indicates greater variability in sensor readings. Bias measures the average difference between the measurements recorded by the LCS and those recorded by the reference instrument. A positive bias indicates that the LCS typically overestimates the true value, while a negative bias indicates an underestimation.

$$Bias_t = \left(\frac{LCS_t}{GRIMM_t} - 1\right) \times 100 \qquad \text{(Eq. 1)}$$

Where; LCSt is the low-cost sensor readings at time t and GRIMM is the reference concentration at time t for each of the hourly measurement points (Sayahi et al., 2019). R-squared (R^2) is a statistical measure representing the proportion of the variance for a dependent variable that can be explained by an independent variable or variables in a regression model. In this context, it indicates how well the LCS measurements correlate with those from the reference instrument. A higher R^2 value closer to 1 indicates that the LCS closely matches the reference instrument's readings. Root-Mean-Squared Error (RMSE) measures the average magnitude of the error by squaring the differences between predicted values and actual values. The RMSE will give a sense of how much error there is between the LCS measurements and those of the reference instrument. Each of these metrics provides insight into different aspects of the LCS performance, CV and RMSE provide a measure of reliability and precision. Bias gives an indication of accuracy. R^2 offers a measure of the degree to which the LCS can reproduce the reference instrument's results.

3. Results and Discussion

3.1. Preliminary test in the field

Low-cost PM sensors are becoming increasingly popular for air quality assessments, but they are not designed for highly dusty environments. The performance of these sensors inside animal barns has not been well studied, with limited reports in the literature. This study developed eight different low-cost PM sensors specifically for use in barn environments and conducted preliminary tests in both an office and a production room. Initially, all sensors were tested in an office room for 48 hours to prepare them for the dusty conditions. Subsequently, they were tested in the production room for seven days. The two nephelometers including Sharp GP2Y1010 and Shinyei PPD42 were used to measure the total suspended particle (TSP) concentrations in the office and production room environments. *Figure 5* shows the comparison of total particle concentrations measured by the LCSs and the GRIMM. R^2 values for the comparison of GP2Y1010 and PPD42 sensors with the reference monitor were 0.059 and 0.001, respectively. The results show that the two nephelometers (Sharp GP2Y1010 and Shinyei PPD42) did not measure the total particle concentration properly. In practice, enhancing the performance of low-cost sensors such as the Sharp GP2Y1010 and Shinyei PPD42 is highly challenging, if not impossible. As outlined in *Table 1*, both sensors operate as nephelometers, estimating particulate matter (PM) concentrations based on the intensity of light scattered by PM at a fixed angle. However, unlike research-grade nephelometers, these sensors lack integrated fans or pumps. Instead, PM of varying sizes passively enters their optical sensing chambers through environmental or convective airflows. This passive sampling mechanism results in highly unpredictable efficiency in PM transfer to and deposition in the chambers, limiting their measurement accuracy and reliability. Additionally, these two sensors are most commonly used for smoke detection in built environments and are typically calibrated with smoke particles. However, the optical properties of smoke (e.g., size and refractive index) differ significantly from the particulate matter (PM) found in animal production facilities. As a result, it is not surprising that these sensors performed relatively poorly when measuring PM inside animal barns.

The other low-cost PM sensors are active devices, incorporating a fan or pump to drive airflow and improve PM transfer efficiency to the sensing chamber. However, variations in flow channel design can still lead to differences in PM transfer and deposition efficiencies. Sensors priced below $50 per unit, in particular, tend to show poor PM transfer and greater deposition. Furthermore, these inexpensive sensors are typically designed for ambient PM measurements, where particle sizes are considerably smaller than those found in animal production facilities. A recent study (Quimette et al., 2024) highlighted that these sensors often misclassify large PM as smaller particles, due to limitations in their optical particle counter (OPC) design and PM size retrieval algorithms.

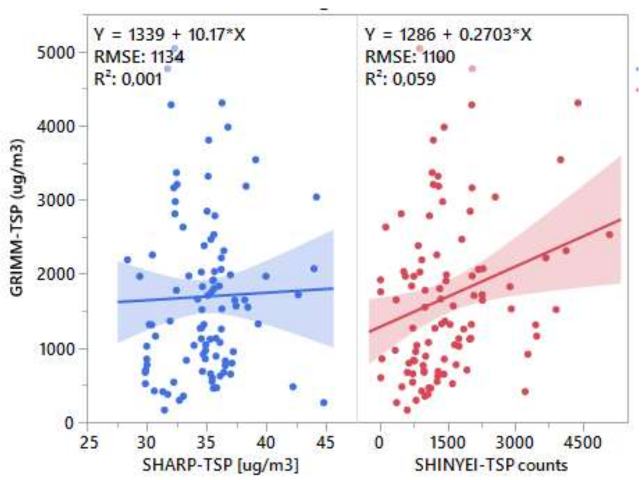

Figure 5. TSP concentrations of preliminary test in a barn environment

The PM_1, $PM_{2.5}$, and PM_{10} concentrations were measured with OPC-N3, OPC-R2, Gravity, PMS5003 and PMS7003 low-cost sensors, then compared the reference GRIMM monitor for the performance of the LCSs in the office and barn environment. *Figure 6* shows the comparison of LCSs for different PM concentrations. *Table 2* shows the bias estimates of hourly PM concentration for the LCSs for all concentrations. The GRIMM data provided the reference concentrations for the bias determination (Eq. 1). *Table 2* shows the bias estimates of the LCSs for the office and production room measurements in this study. The lowest bias in the barn measurements was 13.7% for PM_{10} concentrations with OPC-N3 while PMS7003 showed the lowest bias (19.1%) for PM_{10} measurements in the office measurements.

For the PM_1 measurements, the PMS7003 showed the highest R^2 of 0.90, while the second highest R^2 of 0.586 was with the OPC-N3 sensor. The OPC-N3 also demonstrated the best correlation for $PM_{2.5}$ and PM_{10} measurements, with R^2 values of 0.423 and 0.406, respectively (*Table 2*). The findings indicated that the OPC-N3 sensor demonstrated decent performance for PM_1 in both environments, as well as for $PM_{2.5}$ in both settings. Additionally, the OPC-N3 outperformed other sensors for PM_{10}. However, the PMS7003 and Gravity sensors performed well in the production room but not in the office. The NOVA SDS011 sensor showed relatively good performance in the production room. Dubey et al. (2022) compared two particulate matter sensors, OPC N2 and PM Nova, using the Grimm instrument as a reference. The OPC-N2 excelled in measuring finer particles, achieving R^2 values from 0.54 to 0.93 for PM_1 and 0.31 to 0.95 for $PM_{2.5}$, but it was less effective for PM_{10} (R^2 = 0.19–0.89). Conversely, the PM Nova sensor performed well for both $PM_{2.5}$ (R2 = 0.1–0.96) and PM_{10} (R^2 = 0.19–0.78), showing a similar performance pattern to the OPC-N2. It should be noted that Dubey et al. (2022) conducted their study in ambient air conditions. In our study, the OPC-N3 sensor showed a high correlation with the reference monitor, achieving 0.97-0.98 in the office room. However, this correlation dropped to 0.40-0.59 in the production room due to increased particle density, which adversely affects the sensor's sensitivity.

Table 2. Low-cost PM sensors selected in this study

Location	Particulate matter	Parameters	OPC-N3	OPC-R2	Gravity	PMS5003	PMS7003	SDS011
Barn	PM_1	Mean Bias (%)	-72.7	95.0	-46.7	49.1	49.1	
		Obs.	98	98	98	98	98	
		RMSE	2.77	4.30	1.54	4.18	1.35	
		R^2	0.586	<0.001	0.872	0.060	0.901	
	$PM_{2.5}$	Mean Bias (%)	-44.9	-32.2	-65.2	-65.2	-65.2	-90.4
		Obs.	98	98	98	98	98	98
		RMSE	7.62	9.98	9.86	10.00	9.96	9.91
		R^2	0.423	0.009	0.034	0.005	0.014	0.023
	PM_{10}	Mean Bias (%)	13.7	-89.3	-91.8	-91.8	-86.2	-59.4
		Obs.	98	98	98	98	98	98
		RMSE	115.00	147.80	142.10	144.80	143.90	121.50
		R^2	0.406	0.020	0.093	0.059	0.07	0.337
Office	PM_1	Mean Bias (%)	-80.4	992.3	-62.3	1434.0	-68.2	
		Obs.	98	98	98	98	98	
		RMSE	0.35	3.29	3.30	3.30	3.30	
		R^2	0.989	0.009	0.003	0.002	0.001	
	$PM_{2.5}$	Mean Bias (%)	-70.3	779.1	-45.7	1011.7	-30.4	-113.3
		Obs.	98	98	98	98	98	98
		RMSE	1.30	13.04	13.03	12.99	13.04	13.05
		R^2	<0.001	0.002	0.003	0.010	0.001	<0.001
	PM_{10}	Mean Bias (%)	-31.4	635.6	-27.7	728.0	19.1	-287.8
		Obs.	98	98	98	98	98	98
		RMSE	10.20	62.20	62.10	61.40	62.10	62.00
		R^2	0.973	<0.001	0.003	0.026	0.002	0.007

The study highlighted that the performance of low-cost nephelometers in animal barns is often suboptimal due to several design limitations. Firstly, the passive and inadequately designed flow channels result in inconsistent particle transfer efficiency from the sensor's inlet to its optical chamber. This variability affects the nephelometer's ability to accurately measure particle concentrations. Secondly, these devices typically use red photodiodes or laser diodes as light sources, operating at a wavelength of approximately 650 nm. This choice of wavelength leads to a poor response to the coarse particles that are commonly present inside barns, further compromising the sensor's effectiveness in these environments (Crilley et al., 2018).

The Grimm OPC differentiates itself from most low-cost OPC sensors through its sophisticated flow design. This design allows for the sequential release of particles through a nozzle, where they are immediately measured by light. This precise handling of particles mitigates issues commonly faced by lower-cost OPCs, which measure particles only once at the laser focal point. Such an approach often leads to inaccurate particle size estimations. For instance, a small particle positioned directly at the focal point and a larger particle situated nearby may emit similar optical signals under less precise conditions, leading algorithms in less advanced models to incorrectly classify both as small. This capability of the Grimm OPC to deliver more accurate measurements makes it superior in environments where such distinctions are critical.

The OPC-N3 sensor is distinguished from other low-cost optical particle counters due to its advanced features. One significant advantage of the OPC-N3 is its sophisticated optical design, which improves its response to coarse particles while reducing the chances of particle misclassification. This enhanced optical design enhances the sensor's capability to precisely detect and differentiate larger particles, thereby boosting its overall performance in particle measurement. Moreover, the OPC-N3's straight flow channel design significantly enhances particle transfer efficiency, especially for larger particles. The streamlined flow channel design facilitates better particle movement through the sensor, resulting in more precise and efficient particle concentration measurements. These design elements collectively establish the OPC-N3 as a dependable and efficient choice for measuring particulate matter concentrations in various settings.

Preliminary tests of low-cost PM sensors for animal houses are crucial for ensuring accurate and reliable monitoring of particulate matter levels in these environments. Low-cost sensors have the potential to provide valuable insights into indoor air quality (IAQ) in animal houses, aiding in the identification and mitigation of potential health risks associated with poor air quality. These sensors offer a cost-effective solution for continuous monitoring, allowing for real-time data collection and analysis to support decision-making processes aimed at improving the living conditions for animals and workers in these facilities. Laboratory evaluations, as highlighted in studies such as Bulot et al. (2023), play a vital role in assessing the performance of low-cost PM sensors under controlled conditions. These tests help determine key parameters such as lower limit of detection, response time, and the sensors' ability to detect transient pollution events. Additionally, field evaluations, as discussed in Huang et al. (2022), are essential for validating sensor performance in real-world scenarios, ensuring their accuracy and reliability in practical applications. Furthermore, Lowther et al. (2019) emphasize the importance of using low-cost sensors to provide personalized IAQ information, which can be particularly beneficial in animal houses where air quality can directly impact the health and well-being of both animals and workers. By leveraging the data collected from these sensors, stakeholders can implement targeted interventions to improve IAQ and create healthier environments for all occupants.

The study highlighted the need for extensive field testing of sensors across different concentrations and environmental conditions to fully evaluate the effectiveness of low-cost PM sensors (Mei et al., 2020). It also pointed out that the correlation between low-cost sensors and reference devices depends on operational conditions, aerosol characteristics, and the selection of reference instruments, which influences the calibration of the sensors (Zheng et al., 2018). Our research found that while some low-cost PM sensors performed reasonably well in animal production facilities, most failed to provide accurate PM concentration measurements. Setting aside technical details, a fundamental reason is that these sensors are typically designed for environments with significantly lower PM concentrations or smaller particle sizes than those found in animal production facilities. As a result, a thorough field assessment against reference monitors or methods is essential before deploying any low-cost PM sensors—or low-cost environmental sensors in general—in such settings. It is also important to note that environmental conditions, such as temperature and humidity, can impact sensor performance. We recommend concurrently measuring these variables to better interpret measurement results and potentially implement machine learning-based calibration methods to enhance sensor accuracy. Regarding the applicability of the OPC-N3 sensor in other livestock environments, based on our experience with poultry and cattle farms, the sensor is expected to perform reasonably well. However, a thorough field assessment remains necessary to calibrate the sensor and understand its limitations.

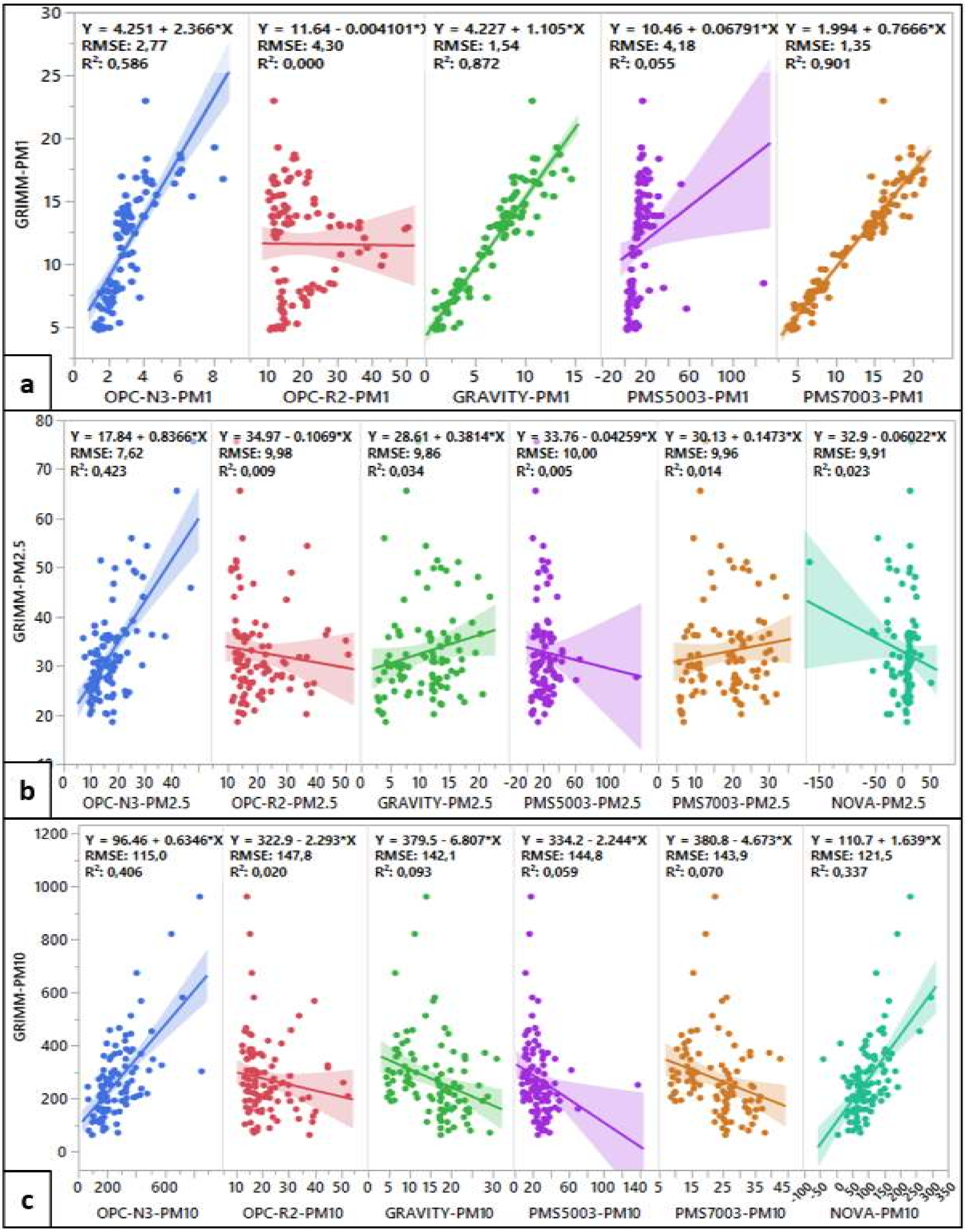

Figure 6. Comparison of low-cost sensors for measuring different PM size fractions in the barn environment

3.2. PM concentrations in the swine house

PM concentrations showed substantial variations in both the office and production room. In both environments, coarse particles (diameter > 2.5 µm) are dominant. *Figure 7* shows the hourly PM concentrations of office (a) and production room (b). The average PM concentrations in the swine house were as follows: TSP 1491.3 µg m^{-3}, PM_1 14.99 µg m^{-3}, $PM_{2.5}$ 34.4 µg m^{-3}, PM_{10} 240.8 µg m^{-3}. Analyzing the data relative to the particle size for the production room revealed that PM_{10} accounted for 16.1% of the total PM concentration, while $PM_{2.5}$ accounted for 2.3%. This shows a higher proportion of particles around 10 µm in size. The PM concentrations for the office room were significantly lower than in the production room. The average TSP, PM_1, $PM_{2.5}$, and PM_{10} concentrations were 61.7, 1.44, 3.57, and 15.9 µg m^{-3}, respectively.

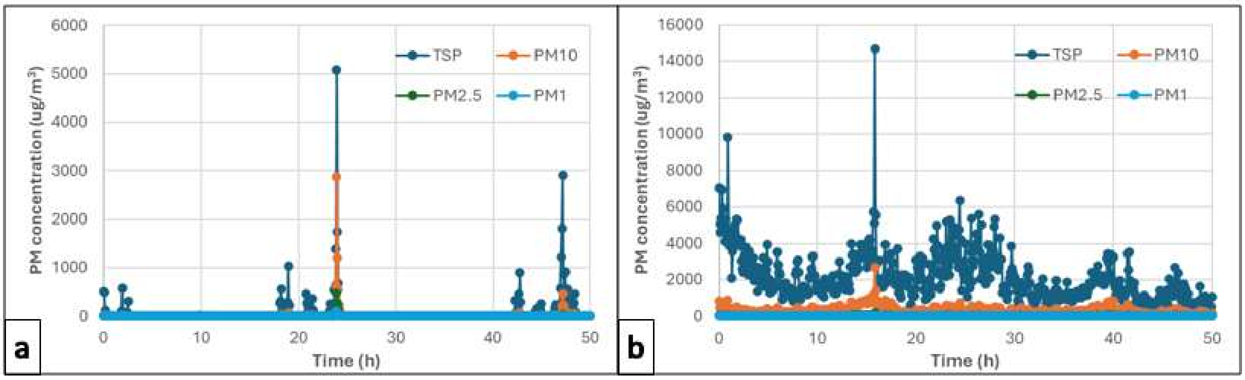

Figure 7. Hourly PM concentrations of office (a) and production room (b)

3.3. Environmental parameters in the swine house

The investigation of meteorological factors concerning the efficacy of the LCSs has been a subject of thorough examination, primarily due to the issues of overestimation or underestimation of particulate matter (PM) concentrations and the influence of temperature (T) and relative humidity (RH) on the response of the LCS (Macías-Hernández et al., 2023). The temperature and relative humidity in the barn environment were also monitored by using HOBO (MX1101, ONSET) sensor during the LCS experiment. *Figure 8* shows the hourly variation of temperature and relative humidity in the barn environment.

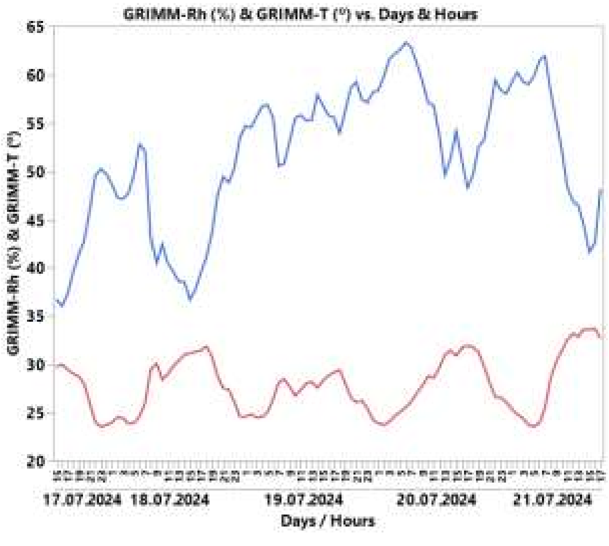

Figure 8. Hourly variation of temperature and relative humidity in the barn environment

Throughout the experiment, the temperature inside the barn ranged from 23.5ºC to 33.7ºC, with an average temperature of 28.04ºC. Relative humidity ranged from 36% to 63.3%, averaging 52.9%. Temperature impacts LCSs less than relative humidity, with minimal error values (–5 to 5 µg m^{-3}) even at low temperatures (–5 to 5°C). In calibration models for temperature, the error term is typically larger than the coefficient, indicating that temperature effects are negligible under normal conditions but not in extreme environments like deserts (Magi et al., 2020).

4. Conclusions

To conclude, LCSs have emerged as a cost-effective solution for personalized monitoring of PM levels in animal houses. The preliminary tests in the field for low-cost PM sensors underscore their potential in animal houses despite challenges in dusty environments. Testing in both office and production settings revealed that while some sensors like the OPC-N3 performed well, others showed limitations due to design flaws affecting particle transfer efficiency. These findings highlight the need for ongoing evaluation and calibration to enhance sensor accuracy and reliability in real-world conditions. Continuous monitoring using these sensors could significantly improve air quality management in animal housing, contributing positively to both animal welfare and operational efficiencies. The integration of low-cost sensors for indoor air quality monitoring in animal houses presents a promising approach to address PM pollution. These sensors offer a cost-effective solution for continuous monitoring, enabling stakeholders to make informed decisions to improve air quality and create healthier environments for animals and workers. Ongoing research and field testing are essential to validate sensor performance and ensure their effectiveness in diverse environmental conditions.

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Ethical Statement

There is no need to obtain permission from the ethics committee for this study.

Conflicts of Interest

We declare that there is no conflict of interest between us as the article authors.

Authorship Contribution Statement

Concept: Uguz, S., Yang, X.; Design: Uguz, S., Yang, X.; Data Collection or Processing: Uguz, S., Kumar, P., Tiwari, S.; Analyses: Uguz, S., Kumar, P., Tiwari, S; Literature Search: Uguz, S., Kumar, P.; Writing, Review and Editing: Uguz, S., Kumar, P., Tiwari, S., Chang, Y., Yang, X.

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