The Field Evaluation of Innovative $PM_{2.5}$ Monitoring Using Air Sensor Co-location with Regulatory Equipment

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Abstract

This research aims to study the performance of $PM_{2.5}$ air sensors using the light scattering technique in comparison to the Federal Equivalent Method (FEM), during June 2020 - December 2021. The study found consistency in the measurements among the 3 sensors, and excellent data completeness above 90% indicating the reliability and the precision of the sensors. Pearson's correlation reveals good agreement among the sensor units (0.70 – 0.98). However, a notable issue arises with the tendency to report extremely high concentrations (445 – 564 $\mu g/m^3$) compared to FEM (235 $\mu g/m^3$). Regression analysis shows substantial biases in the sensor measurements with the slope values ranging 0.8 - 1.3, and low to moderate fit (R^2 0.18 - 0.58) for the hourly concentration. The regression performs significantly better with the rolling 24-hour average values (R^2 0.47 - 0.91). The trend lines of the offset values showed general agreement among the sensor units for most of the study period, except for the dry season where the deviation increased from each other and from the FEM, suggesting possible influence from the weather. This paper shows that the sensors are suitable for moderate accuracy requirements. However, for public warning purposes, there are potential areas of improvement, the first priority being the report of extreme values, which may trigger false alarms and cause unnecessary panic among the public.

Keyword: $PM_{2.5}$, air sensor, FEM, light scattering, innovative

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1. Introduction

Air pollution is a pressing global issue with significant impacts on human health and socio-economic well-being. The State of Global Air Report, produced by the Health Effects Institute (HEI), estimated that air pollution contributed to around 6.7 million premature deaths worldwide in 2019, about half can be accounted for $PM_{2.5}$, the fine particulate matter with a diameter of 2.5 microns or smaller. $PM_{2.5}$ is of particular concern because of its ability to penetrate deep into the respiratory system and enter the bloodstream. Chronic exposure to elevated levels of $PM_{2.5}$ has been linked to a range of adverse health effects, including respiratory issues, cardiovascular problems, reduced lung function, exacerbation of asthma, and increased risk of heart attacks and strokes (U.S.EPA 2020 and WHO 2022).

Consequently, monitoring $PM_{2.5}$ levels becomes crucial for quantifying the extent of the pollution and its impact. The United States Environmental Protection Agency (U.S.EPA) recommends the use of the Federal Reference Method (FRM) and the Federal Equivalent Method (FEM) for routine monitoring by the authorities, to monitor compliance with environmental regulations and emission standards, to evaluate pollution control measures. The public utilize $PM_{2.5}$ sensors instead of regulatory equipment for its affordability as a proactive measure to monitor personal exposure to air pollution, particularly in indoor environments. To support individuals seeking to make informed decisions on buying and understanding the monitoring process and the measurements, the U.S.EPA has published the Air Sensor Guidebook (U.S.EPA 2022), which provides preliminary criteria for reliable sensors.

2. Literature Reviews

In Thailand, the Pollution Control Department (PCD), Ministry of Natural Resources and Environment, is responsible for the official record on the ambient air quality. For $PM_{2.5}$ routine monitoring, PCD utilizes Federal Equivalent Method (FEM), comprised of four types; 1) beta ray attenuation, 2) tapered element oscillating microbalance (TEOM), 3) light scattering and 4) dichotomous air sampler method (Announcement of the National Environment Board; Royal Gazette, 2022), in which the equipment have to pass the U.S.EPA standards and approval. PCD's $PM_{2.5}$ monitoring network comprises of 87 air quality monitoring stations, located in 56 provinces.

PCD have been monitored PM_{10} since 1996, and $PM_{2.5}$ since 2011. Both PM_{10} and $PM_{2.5}$ concentrations have consistently exceeded the national ambient air quality standards (NAAQS) every year during the dry season since the beginning of measurement (NAAQS for 24-hour average PM_{10} set to 120 µg/m^3, and $PM_{2.5}$ was at 50 µg/m^3 in 2010, and lowered to 37.5 µg/m^3 in 2023). The problem is not limited to Bangkok but extends to other large cities and urban areas across all regions.

In the Action Plan for driving National Agenda on "Pollution Problem Management; Particulate Matter" (Pollution Control Department, 2020), PCD plans to expand its monitoring network to cover all 77 provinces and increase monitoring areas for a better understanding of air pollution within year 2024, which proves to be difficult as the current regulatory monitoring equipment is costly in terms of installation and maintenance. Recent innovation in air quality sensors offers advantages such as affordability, ease of operation, and real-time data readings. If these sensors are proved to be accurate and reliable, they have the potential to supplement the existing regulatory network or provide support to various sectors in measuring $PM_{2.5}$ for their own use.

3. Research Objective

This study aims to evaluate the performance of the $PM_{2.5}$ air sensors in an outdoor environment to test for their reliability, accuracy and precision in comparison to the regulatory equipment.

4. Study Desigh snd Methods

4.1 Site description and reference data

The study was carried out from June 2020 to December 2021. The study site is located at the Pollution Control Department's (PCD) air quality monitoring station in Din Daeng district, Bangkok, Thailand. The station is classified as a roadside monitor at 13.762523 latitude and 100.550197 longitudes. Din Daeng is a predominantly


Figure 1. Co-location site at Din Daeng air quality monitoring station, Bangkok, Thailand is in the center of Bangkok (left). The placement of 3 air sensor nodes on the roof of the station (right).

residential area with a mix of commercial and industrial zones, known for its iconic Victory Monument roundabout, serving as the transportation hubs and open-air markets. The district is located inland, approximately 20 kilometers north of the Gulf of Thailand, and about 6 kilometers west of the main river of Bangkok, the Chao Phraya (see Figure 1).

Air sensors used in this study were designed and developed by researchers in the Northern part of Thailand, based on light scattering technology. The PCD operates the regulatory air quality monitoring stations in Thailand, which include meteorological variables provided for this study. The continuous $PM_{2.5}$ measurements at the site were conducted using beta-ray attenuation, providing hourly averages calibrated every month or twice a month in a critical duration. Additionally, 10-minute interval data were recorded from this equipment.

4.2 Methodology

4.2.1 Data pre-processing

All data used in the study is automatically recorded and then accessed by online. Basic data filtration was conducted. Extreme values of $PM_{2.5}$ concentrations exceeding 999 and non-numeric entries were treated as missing values. For the rolling average calculation in 24-hour windows, any windows with fewer than 18 hours of valid data were also considered as missing values. Hours with missing $PM_{2.5}$ concentrations from either the PCD or the sensors were eliminated from the dataset before regression analysis (U.S.EPA.2020). To address the mismatched timestamps between the 7-minute interval data from the sensors and the 10-minute interval data from the PCD's equipment (FEM), data interpolation was performed. The FEM's 10-minute data showed less variability due to its continuous measurement, allowing for interpolation into 20-second intervals, and then used the nearest timestamps within a 30-second window as the matching criteria. Shorter time intervals were tested during interpolation and found that the 20-second intervals achieved the necessary accuracy.

4.2.2 Analysis methods

1) The study employed a combination of data preprocessing, exploratory data analysis, correlation analysis, and simple linear regression to analyze the collected data. Descriptive statistics, including mean, standard deviation, minimum, maximum, and quartiles, were calculated to provide an overview of the relevant variables.

2) Pearson's correlation analysis was conducted to explore the relationships between variables, including meteorological parameters. However, due to the absence of significant relationships, these variables were excluded from further analysis.

3) Simple linear regression models were constructed using ordinary least squares (OLS), with the intercept constrained at zero. The significance level was

set to α = 0.05 to evaluate the statistical significance of the regression coefficients. Statistical measures, such as the coefficient of determination (R-squared) and the root mean square error (RMSE), were used to assess the goodness-of-fit and predictive performance of the regression models.

4) Offsets analysis was used to indicate over-measurements and under-measurements by the sensors in comparison to the regulatory equipment.

4.2.3 Software

The data pre-processing and analysis was conducted using Python version 3.10.4 on Jupyter Notebook, with standard libraries including Pandas (1.5.2), Numpy (1.24.1), Matplotlib (3.5.3), Seaborn (0.12.2).

5. RESULTS

5.1 Descriptive Statistic Overview

The descriptive statistics summary of the hourly concentrations is shown in table 1. The maximum $PM_{2.5}$ concentrations reported by Sensor 1, 2 and 3 were 445, 564 and 453 μg/m^3 respectively, significantly higher than maximum reported by FEM (PCD), 160 μg/m^3. In 2020, The mean concentrations by the sensors were 33, 25 and 33 μg/m^3 respectively, which exhibited small bias compared to 28 μg/m^3 reported by FEM (PCD). In 2021, the maxima reported by the sensors were 253, 151 and 315 μg/m^3, not as extreme as the previous year, close to 235 μg/m^3 reported by FEM (PCD). The mean concentrations by the sensors were 37, 27 and 41 μg/m^3, also exhibited small bias compared to 33 μg/m^3 reported by FEM (PCD). Figure 2 shows the time series of the hourly $PM_{2.5}$ concentrations (μg/m^3) measurements by the sensors and FEM (PCD) during June 2020 – December 2021, which was relatively high value reported by sensors. On average, Sensor 1 and Sensor 3 reported slightly higher concentrations, while Sensor 2 reported slightly lower concentrations when compared to FEM (PCD). All three sensors in one model exhibited almost twice the standard deviations as FEM (PCD). The completeness of the data were excellent in the study periods, all above 90%. However, Sensor 1 and Sensor 2 started to malfunction more often after this periods.

The descriptive statistics summary of the 7-minute interval data is shown in Table 2. Two weeks data during 1 - 15 November 2021 were selected and shown as examples, the maximum $PM_{2.5}$ concentrations reported by sensor 1, 2 and 3 were 579, 325 and 826 μg/m^3 respectively, significantly higher than maximum reported by FEM (PCD), 67 μg/m^3. The mean concentrations by the sensors were 32, 22 and 34 μg/m^3 respectively, exhibited small bias comparing to 31 μg/m^3 reported by FEM (PCD). The completeness of the 7-minute data was excellent. All sensors reported more than 99% of valid data. The concentrations of $PM_{2.5}$ (μg/m^3) at 7 minutes-interval measurements by the sensor devices and FEM (PCD) during November 1 – 15, 2021 is shown in figure 3.

Table 1. Descriptive statistic summary, $PM_{2.5}$ measurement at 1-hour interval.

Year	Device	Data Count	% Complete	$PM_{2.5}$ μg/m^3			
				Max	Min	Mean	SD.
2020* (1 June – 31 December)	FEM (PCD)	5104	99.4	160	5	28	16
	Sensor 1	4696	91.5	445	1	33	28
	Sensor 2	4660	90.7	564	1	25	23
	Sensor 3	4695	91.4	453	1	33	29
2021	FEM (PCD)	8699	99.3	235	1	33	18
	Sensor 1	8682	99.1	253	1	37	28
	Sensor 2	8353	95.4	151	1	27	20
	Sensor 3	8687	99.2	315	1	41	32

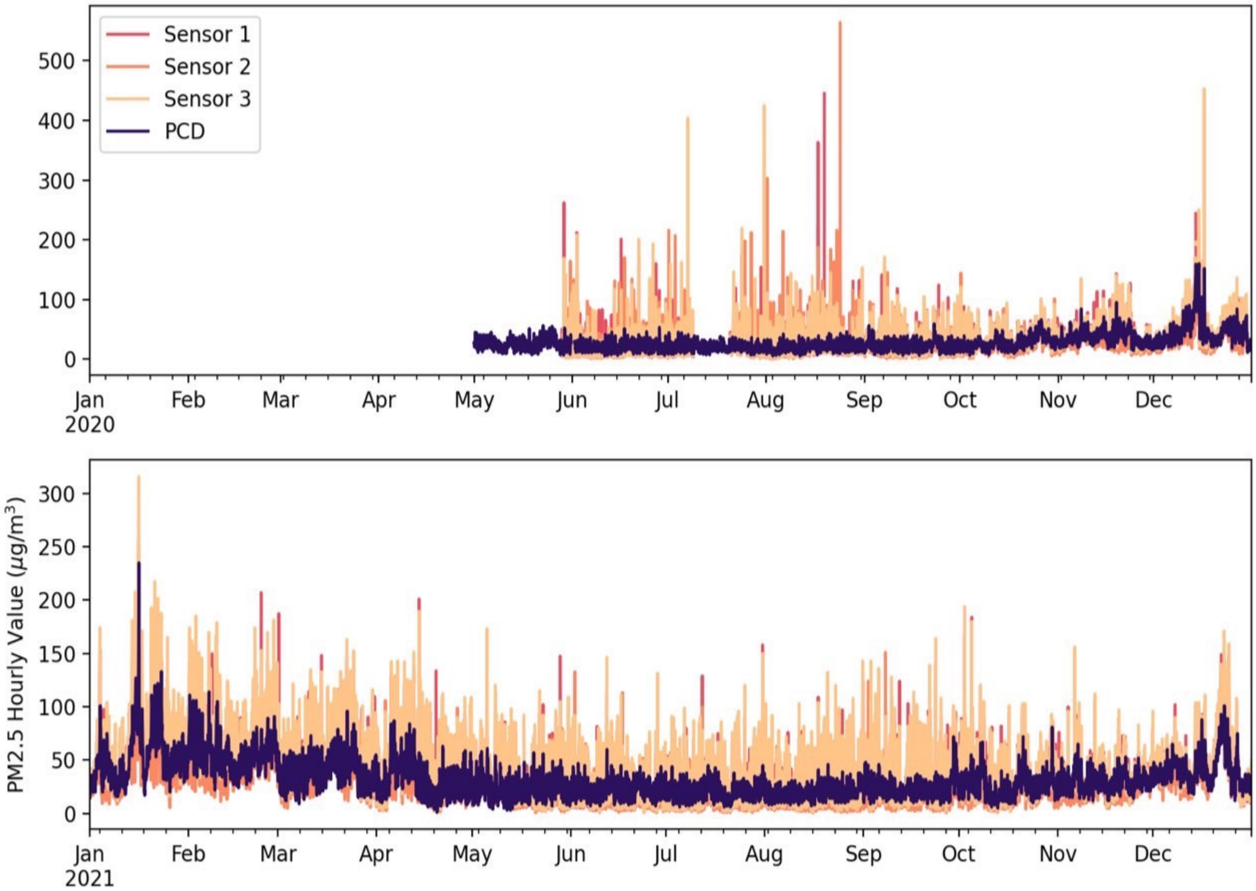

Figure 2. Time series of the hourly $PM_{2.5}$ concentrations (µg/m^3) measurements by the sensor devices and FEM (PCD) during 2020 – 2021.

Table 2. Descriptive statistic summary, $PM_{2.5}$ concentrations at 7-minute intervals

Period/	Device	Data Count	% Complete	$PM_{2.5}$ (µg/m^3)			
				Max	Min	Mean	SD.
November 1 -15, 2021	FEM (PCD)	2980	100	67	2	31	10
	Sensor 1	2956	99.2	579	4	32	24
	Sensor 2	2974	99.8	325	3	22	14
	Sensor 3	2957	99.2	826	4	34	27

Comparing the measurements at one-hour intervals with those at seven-minute intervals, a notable difference is observed in the maximum values reported, where the maximum concentrations can be 10 times more than reported by the regulatory equipment. In contrary, the annual mean concentrations show better agreement with the FEM (PCD), and the standard deviations were comparable between the two dataset, suggesting that extreme measurements occurred infrequently enough that they have a limited impact on the overall trend and the average variability of the measurements.

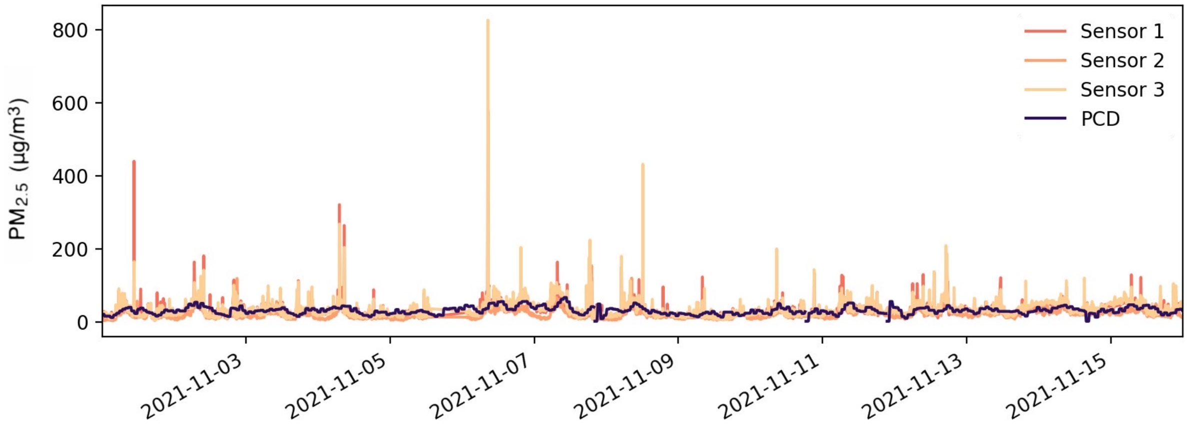

Figure 3. $PM_{2.5}$ concentrations (μg/m^3) at 7 minutes-interval measurements by the sensor devices and FEM (PCD) during 1–15 November 2021.

Table 3. Pearson's correlation of hourly concentrations, 2020 – 2021

Device	Correlation partner	Pearson's Correlation	
		2020	2021
FEM(PCD)	Sensor 1	0.63	0.74
	Sensor 2	0.43	0.68
	Sensor 3	0.67	0.76
Sensor 1	Sensor 2	0.77	0.89
	Sensor 3	0.86	0.98
Sensor 2	Sensor 3	0.70	0.88

5.2 Relationship Analysis

5.2.1 Correlation

The Pearson's correlation analysis was performed to examine the agreement between the measurements from the three sensors over the study period, June 2020 – December 2021, using the hourly concentrations. Other methods of correlation were also tested and found to be lesser values, and therefore not published here. The results in table 3 show that correlations between the sensors were consistently strong throughout the study period. Between Sensor 1 and Sensor 2, the correlation values ranged from 0.77 – 0.89 across the one and a half years, and ranged from 0.70 – 0.88 for Sensor 2 and Sensor 3. The correlations between Sensor 1 and Sensor 3 ranged from 0.86 – 0.98, showing the strongest level of agreement among the pairs. In contrast, when comparing the sensor measurements with the regulatory equipment FEM(PCD), the correlations were found to be moderately high. The correlation values for Sensor 1 ranged from 0.63 – 0.74, while Sensor 2 showed correlations ranging from 0.43 – 0.68. Sensor 3 exhibited best correlations among the three in the range of 0.67 – 0.76.

These results indicate that the sensor measurements are strongly correlated with each other, demonstrating the consistency of the measurement method and reproducibility of the data. However, when compared to the federal equivalent method (FEM) operated by PCD, the correlations suggest a moderate level of agreement, indicating some extent of problems in the accuracy and precision of the monitoring.

5.2.2 Regression

The regression analysis was conducted using a simple linear regression with the intercept constrained at zero. This constraint acknowledges the fact that both the sensors and the FEM(PCD) have undergone a zero-span calibration, ensuring accurate zero readings for clean air. Table 4 displays the results, slopes of the regres-

Table 4. Regression results between sensors and FEM (PCD), 2020 – 2021.

Year	Device	Hourly Concentrations			Rolling 24 - hr Averages		
		Slope	R^2	RMSE	Slope	R^2	RMSE
2020	Sensor 1	1.1	0.40	21	1.2	0.86	5.8
	Sensor 2	0.8	0.18	20	0.8	0.47	6.7
	Sensor 3	1.2	0.45	20	1.2	0.89	5.8
2021	Sensor 1	1.1	0.56	19	1.2	0.91	6.5
	Sensor 2	0.8	0.46	14	0.8	0.84	5.5
	Sensor 3	1.3	0.58	21	1.3	0.91	7.5

sion lines for the three sensors were found to be different among the sensors, but self-consistent throughout the study period, indicating persistence of the biases. The slopes ranged from 0.8 to 1.3, moderately deviating from the ideal slope of 1.0. These deviations were close to an acceptable range according to the JRC of the EU Commission (2019)[1] specified at the range of 0.75 – 1.2.

In the case of hourly concentrations, the R^2 values were in the range of 0.18 – 0.58 for all sensors, suggesting that the FEM measurements accounted for some portions of the variability of the sensors. Furthermore, it was observed that the regression analysis of the rolling 24-hour averages yielded much higher R^2 compared to that of hourly concentrations, in the range of 0.47 – 0.91 (see figure 4). The RMSE were in the range of 14 – 21 μg/m³ for hourly concentrations and ranged from 5.5 – 7.5 μg/m³ for rolling 24-hour averages. The reverse was observed when examining the regression results of the 7-minute measurements, which fits poorer than the hourly data (results not shown).

5.2.3 Offsets analysis

Offsets provide clarity in viewing data comparison by offering simultaneous access to both the magnitude and direction of the discrepancies. Table 5 shows the result in this analysis, positive offsets indicate over-measurements, and the negative value indicates the under-measurements by the sensors in comparison to the FEM (PCD). The maximum offsets observed were in the range of 122 – 533 μg/m^3, indicating the presence of significant over-measurements reported by the sensors, and its tendency to capture extreme concentrations of particulate matter. However, the means of the offsets were found to be in the range of -5.4 to 8.7 μg/m^3, relatively close to zero, in agreement with the bias range observed in the previous analysis. This suggests that on average the sensors performed reasonably well in measuring $PM_{2.5}$ concentrations compared to the FEM despite the extreme spikes in the data.

Another indicator often used to describe discrepancies is the percentage difference, which is the absolute values of the offsets taken percentage in relation to the FEM (PCD) readings. The means of the percentage differences were in the range of 45 – 56%, and the maximum differences in the range of 1007 – 1835%. The elevated maxima indicate that the data spikes might not always coincides with the elevated $PM_{2.5}$ concentrations detected by the regulatory equipment. It ranges from 0 up to over a thousand percent makes the interpretation quite difficult, unsuitable for being an indicator of sensor performance.

The offsets plotted over time allows for a visual representation to help identify patterns, trends, or any irregularities (see Figure 5). Sensor 1 and Sensor 3 generally agree with each other with slight positive biases. Sensor 2 consistently exhibits a more negative bias compared to the other sensors, indicating a potential systematic bias or external issues, for example, the calibration or sensor placement. However, during the one and a half years of measurement, seasonal data drifting and some equipment failures have been observed. Some sensors exhibited extreme over-measurements after maintenance, but the subsequent data were corrected.

[1] https://publications.jrc.ec.europa.eu/repository/handle/JRC116534

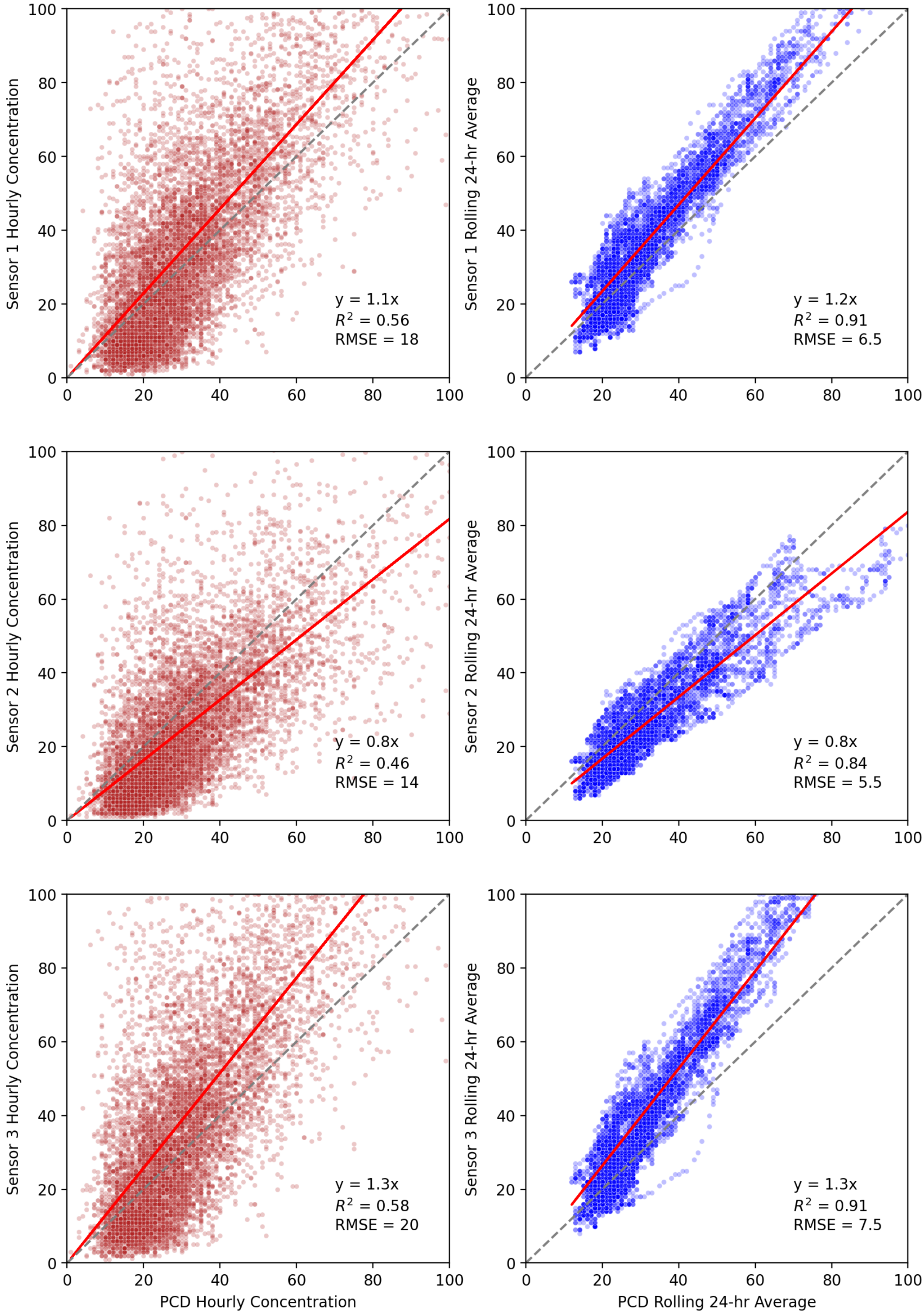

Figure 4. Scatter plot and linear regression line (interception constrained at 0) between the $PM_{2.5}$ measurements by the sensor devices and FEM (PCD) in 2021. Left column: Hourly $PM_{2.5}$ concentrations (μg/m^3). Right column: Rolling averaged concentrations at 24-hour window (μg/m^3).

Table 5. Statistic summary of the offsets and percentage differences in relation to FEM (PCD).

Year	Sensor Unit	Data Count	Offset			% Difference		
			Max	Min	Mean	Max	Min	Mean
2020	Sensor 1	4666	422	-94	4.4	1835	0	55
	Sensor 2	4630	533	-103	-3.7	1719	0	53
	Sensor 3	4665	398	-91	5.1	1525	0	54
2021	Sensor 1	8621	154	-67	4.5	1117	0	51
	Sensor 2	8292	122	-138	-5.4	1007	0	45
	Sensor 3	8626	164	-45	8.7	1338	0	56

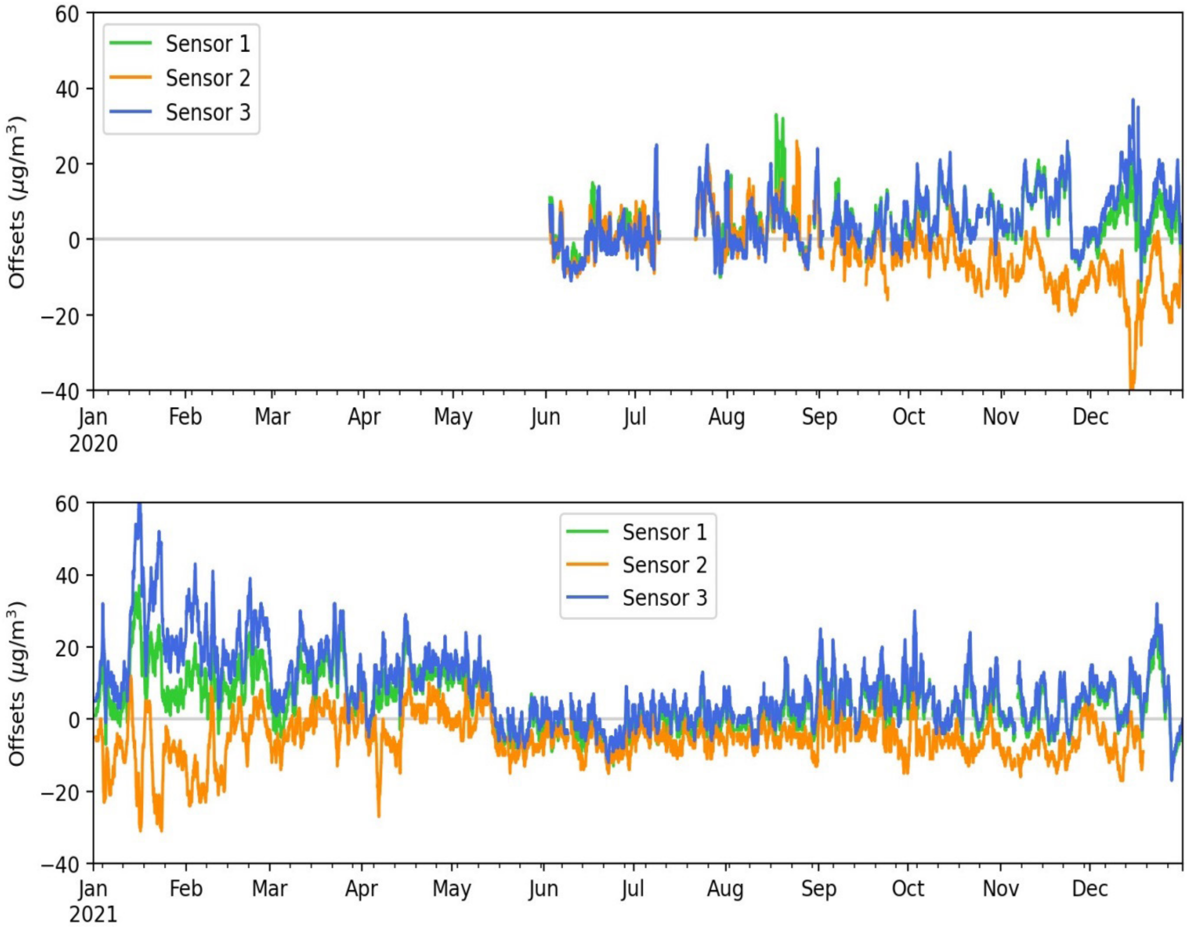

Figure 5. Time series of 'offsets', $PM_{2.5}$ hourly measurements (μg/m^3) by the sensors subtracted with the FEM (PCD), showing the trend lines of the 24-hour averaging window during June – December 2020 (Upper) and in 2021 (Lower).

6. Result Summary

1) The correlation analysis using Pearson's score showed strong correlations between the sensor nodes (0.70 – 0.98), indicating excellent reproducibility and reliability of the data. The correlations with the FEM (PCD) are also significant, although slightly lower (0.43 – 0.76).

2) The completeness of the sensor data is generally high, with over 90% valid data in the first two years. However, maintenance issues led to a drop in data completeness for 2 of the 3 sensors after one and a half years of operation.

3) Regression analysis shows that the sensors were in good agreement with the FEM (PCD), with R^2

values ranging from 0.47 – 0.91, when the data was averaged over 24-hour periods. However, the regression fit was moderate at 1-hour intervals, with R^2 values ranging from 0.18 – 0.58, and poorer at 7-minute intervals.

4) The regression slopes (0.8 – 1.3) slightly higher than the acceptable range suggested by the JRC of EU Commission (0.75 – 1.2) indicate the moderate accuracy that is acceptable for non-regulatory usage. It is notable that all sensor units consistently exhibit their unique bias throughout the study period, except Sensor 1 whose bias was altered after the two year of operation.

5) The analysis of offset trends reveals general agreement among the sensor units. However, some seasonal data drifting and some equipment failures were observed during the one and a half years of operation.

6) The study highlights that percentage differences may not be a reliable measure of sensor performance, as it can produce extreme values above 1800%.

Therefore, the air sensors using light scattering technique in this study can perform to monitor $PM_{2.5}$ and suitable for moderate accuracy requirements. However, these air sensors can potentially produce more accurate and reliable measurement if precaution measures such as calibration or/and sensors inter-comparison were taken.

7. Discussion and Sugguestion

Based on the findings of the study, a valid observation was confirmed from the sensors that gave consistent performance and data completeness.

They also exhibited small bias and tend to report extreme values at hourly intervals. Performing 24-hour averages was shown to lessen the extreme value and improve the accuracy.

However, we do not recommend the sensors for public warning as due to their tendency to report extremely high values and exhibit substantial bias at hourly intervals. In order to assist in the regulatory monitoring network and for public warning it is crucial to address the accuracy issue:

1) The tendency of sensors to report extremely high values: This paper shows that the extreme events were consistent across the sensor units, indicating that it was not a design or monitoring technique issue but rather reflected the actual true measurements. The frequency of the measurement maybe the cause, when consider that the FEM (PCD) using continuous measurement, taking in the air volume continuously during the measurement duration, and thus the extreme events would be smoothen out. To bring the sensor data closer to that of the FEM (PCD), a higher frequency of sampling, as close to continuous measurement as possible would be ideal.

2) The biases: The trend lines of offsets reveal that the sensors initially demonstrated satisfactory performance following calibration, but subsequently exhibited consistent and unique biases throughout the one and a half years period. Notably, the bias of one sensor underwent alteration after maintenance, indicating that short-term calibration efforts alone may not effectively mitigate biases in the long run. Moreover, the observed differences in biases among the sensors suggest a random drift in bias over time. To ensure accurate and reliable measurements, it is recommended that users have access to multiple sensors at a single location and able to identify biases among sensors, allowing for the remediation of the problem. Future research and development efforts should focus on improving calibration procedures and minimizing bias drift in sensor measurements.

3) Sensitivity to weather conditions: The sensors have no heated facility to remove the liquid portions of the particles. The measurement offsets were larger and more frequent during certain seasons, suggesting the influence of weather conditions. This point is suggested by Jayaratne et al. (2018) and Dejchanchaiwong et al. (2023). The sensor maker should provide methods to control the temperature and humidity of the air intake and provide better protection around the sensor unit to mitigate the influence of the weather. Nevertheless, this is an important aspect to aware when using air sensor to measure air pollutants in the atmosphere.

Air sensor manufacturers should adopt the aforementioned suggestions to enhance the accuracy and reliability of their sensors. Key recommendations include implementing finer measurement intervals, improving calibration methods, transparently publishing precision and accuracy data, and ensuring convenient replacement options for units that may be susceptible to failure.

Sensor users should be aware that the performance of the sensors could drift over time and the possibility of failure within a couple of years after use. It is advisable to regularly review the data obtained from the sensors and compare it with readings from other sensors. To facilitate this, manufacturers should consider establishing an online platform dedicated to such comparisons and data analysis.

Researchers conducting field tests are encouraged to publish these statistics for comparability across studies; regression slope, R-squared, and RMSE, which effectively assess sensor performance and can represent other statistics such as standard deviations and correlation scores. Additionally, publishing the time series of offsets throughout the year can provide valuable insights into bias tendency, and the influence of weather conditions on sensor measurements.

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