EVALUATING THE PERFORMANCE OF LOW-COST SENSORS AGAINST REGULATORY-GRADE EQUIPMENT FOR PARTICULATE MATTER

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Abstract

Accurate quantification and management of airborne particulate matter (PM), specifically $PM_{2.5}$ and PM_{10}, is key to the safe operation of a wide variety of industries across Australia and globally. Typically, regulatory-grade instruments such as Tapered Element Oscillating Microbalances (TEOMs) and Beta Attenuation Monitors (BAMs), or gravimetric air samplers provide reliable data. These systems, however, are costly and geographically static. In recent years, there has been an increase in the availability of portable, non-regulatory grade, low-cost sensors (LCS);however, there is limited understanding of how these sensors perform in comparison to regulatory-grade equipment.

This paper presents the results of a four-week co-location study of three AirGradient Open Air monitors and three AirBeam3 monitors against a TEOM regulatory grade monitor located at the Department of Climate Change, Energy, the Environment and Water (DCCEEW) Lidcombe Super-Site in western Sydney.

For $PM_{2.5}$, both sensors demonstrated consistent correlation with the reference monitor. The AirBeam units produced Pearson Correlation Coefficient (r) of 0.861 - 0.865 and the AirGradient units produced an r of 0.790-0.795. For PM_{10}, the performance was substantially weaker with correlations ranging from 0.596 to 0.629, with large systematic underreporting of concentrations below 25 $\mu g/m^3$. In an attempt to increase accuracy of sensor, a hygroscopic look-up table (LUT) correction methodology was adopted. Results binned by temperature and relative humidity, partially reduced AirBeam PM_{10} bias (NMB: -21% to -35% post-correction) but had negligible effect on AirGradient units.

The results indicate that both low-cost sensors can provide indicative $PM_{2.5}$ data suitable for trend monitoring and event detection in Sydney's ambient environment, but neither is appropriate for PM_{10} quantification or regulatory compliance without substantial site-specific correction. Extending the co-location period to include smoke-affected conditions and higher-humidity episodes would potentially improve correction robustness.

Keywords: Low-cost sensors, Monitoring, Dust

1. Introduction

1.1. Importance of PM Monitoring and Regulatory Challenges

Management of airborne Particulate Matter (PM), specifically $PM_{2.5}$ and PM_{10}, is vital to the safe operation of many industries across Australia and globally. Quantification of PM is undertaken using monitoring equipment which varies widely in cost and accuracy. In key locations, where there is a risk of human exposure to PM, measurements are typically undertaken with regulatory-grade equipment, such as Beta Attenuation Monitors (BAM), Tapered Element Oscillating Microbalances (TEOM), or Gravimetric Air Samplers. While these monitors provide high-quality and consistent PM data, they are limited by their high cost, maintenance requirements, deployment logistics, and siting constraints (Castell, et al., 2017). Consequently, while they provide highly accurate hourly measurements, their cost results in sparse deployment across networks, which cannot capture small scale local variations (Karagulian, et al., 2019).

1.2. Emergence and limitations of Low-Cost Sensors

In recent years, there has been an increase in the availability of portable, low-cost, non-regulatory grade PM sensors. These low-cost sensors (LCS) offer the promise of high spatiotemporal resolution, allowing for dense monitoring networks due to their compact size and low power consumption (Narayana, et al., 2022).

However, there is limited understanding of how these sensors perform in varied real-world environments when compared directly to regulatory-grade equipment.

1.2.1. AirGradient Open Air

The AirGradient Open Air air quality sensor ,hereafter known as the 'Air Gradient', was developed in Northern Thailand as a volunteer project to monitor air pollution in classrooms during "burn season" (AirGradient, 2023).

This development context is important to note, as it contextualises the AirGradient as a solution initially intended for use in developing countries, which are expected to have higher particulate matter concentrations than developed countries (Mannucci & Franchini, 2017).

The AirGradient measures the following:

- $PM_{2.5}$, PM_{10} and CO_2 using optical sensors
- TVOCs and NOx using a metal oxide-based sensor.

The Open Air also measures relative humidity and temperature.

1.2.2. AirBeam

The AirBeam was designed by Habitat Map, an American nonprofit organisation, with the goal of providing a tool for marginalised communities to advocate for environmental health through affordable access to monitoring. The AirBeam3 sensor exclusively measures $PM_{2.5}$ and PM_{10} using optical sensors, as well as relative humidity and temperature (Habitat Map, 2026).

1.2.3. Limitations in low-cost sensors

Because many LCS rely on optical particle counting rather than direct mass measurement, they are susceptible to environmental interferences. For example, the accuracy of optical sensors like the AirBeam is significantly influenced by relative humidity, precipitation, and local ambient aerosol profiles, such as the presence of highly hygroscopic sea salts (Huang, et al., 2022). Furthermore, while the AirBeam can perform well under specific meteorological conditions with sea salt or dust sources, its correlation with regulatory reference monitors degrades under other ambient conditions (DeWitt, et al., 2020).

Similarly, monitors utilizing the popular Plantower PMS5003 sensor module, such as the AirGradient (AirGradient, N.D.), face well-documented physical limitations. Because the sensor does not force individual particles through a single focal point in the laser beam, large particles that miss the focal point can still scatter light, causing the device's photodiode to misclassify particle sizes (Caseiro, et al., 2024)

This results in discrepancies when attempting to quantify exact PM mass concentrations without robust calibration. This study focuses on two LCS, the AirGradient and the AirBeam, both passive air samplers which utilise optical sensors to quantify PM.

1.3. Study objectives

Given the variable performance of LCS under different ambient conditions and the widespread recognition that their data quality can drop significantly when moved from laboratory settings to the field (Narayana, et al., 2022), localized field evaluation is necessary. This paper presents the methodology and results from a colocation study, comparing PM from two low-cost sensors (the AirBeam and AirGradient air quality monitors), against regulatory-grade equipment installed at a Department of Climate Change, Energy, the Environment and Water (DCCEEW) Super-Site in Lidcombe, NSW. Continuous $PM_{2.5}$ and PM_{10} measurements were recorded with the aim to quantify the accuracy and inter-unit reproducibility of each platform under ambient Sydney conditions.

2. Methodology

Three AirGradient and three AirBeam3 monitors were affixed to a railing within three metres of the inlet to the TEOM particulate monitor at the Lidcombe Super Site (33°52'53.01"S, 151° 2'48.09"E) on 12 May 2025. Monitors were placed underneath a solar panel, to provide basic shelter from the elements. A photograph of the experimental setup is presented in Figure 1. Monitors were decommissioned four weeks later, on 9 June 2026.

For both sensors, data was limited to download as post-processed time averaged normalised data. The resulting data, unlike the DCCEEW data was adjusted to remove negative values. This is considered as a limitation of the sensor implementation.

It is noted that these monitors are not reference grade monitors, nor are they compatible with siting requirements set out in AS/NZS 3580.1.1, as the low volume inlet is not weatherproof, and requires shelter. As such the inlet cannot and will not have a 120° clear-sky angle view. This is considered as a limitation of the monitoring technology. Furthermore, the site was selected so as to have proximity to the reference grade monitor, without impacting operations on site. This is noted as a limitation of this study.



Figure 1. AirGradient monitors (left) and AirBeam monitors (right)

3. Results

3.1. $PM_{2.5}$ performance

$PM_{2.5}$ data from both the AirGradient and AirBeam monitors showed correlation with data from the Lidcombe DCCEEW TEOM unit. Linear regression plots are shown below in Figure 2.

Quantile-Quantile (Q-Q) plots also show a close relationship between the two monitors: however, the AirBeam monitors appear to under report $PM_{2.5}$ concentrations below 10 µg/m^3 and the AirGradient monitors appear to over-report $PM_{2.5}$ concentrations above ~7.5 µg/m^3.

For $PM_{2.5}$, the AirBeam3 units achieved stronger Pearson correlations (r = 0.861 - 0.865) and higher Lin's concordance correlation coefficients (CCC = 0.805 - 0.818) than the AirGradient units (r = 0.790 - 0.795; CCC = 0.687 - 0.772), indicating better agreement in both precision and accuracy. The between-unit consistency of the AirBeam3 fleet was exceptional, with an intraclass correlation coefficient (ICC) of 0.99, compared to 0.89 for the AirGradient units, confirming that AirBeam3 sensors are highly reproducible across co-located devices.

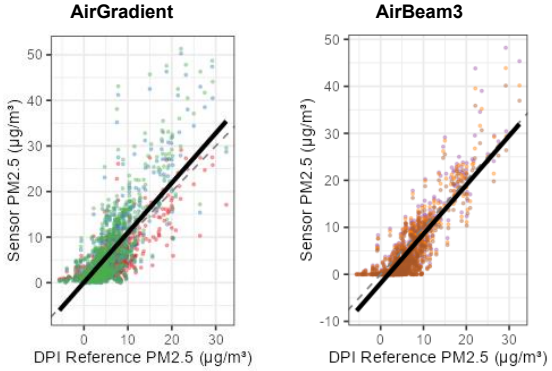


Figure 2. $PM_{2.5}$Linear Regression Analysis

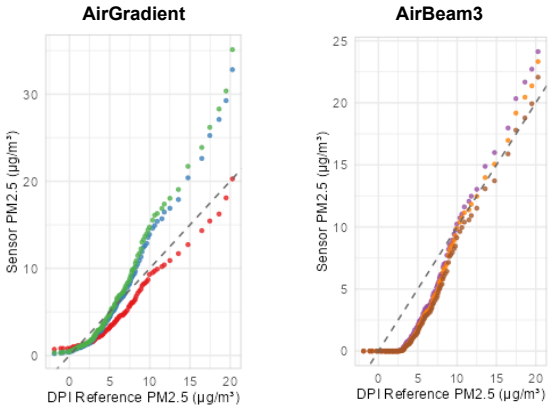


Figure 3. $PM_{2.5}$ Quantile to Quantile distribution

Table 1. $PM_{2.5}$ Statistical summary

Sensor	n	Slope	r	CCC	ICCa	MB (ug/m3)	RMSE (ug/m3)	FAC2	NMB (%)
AirGradient-1	709	0.739	0.790	0.772	0.890	-1.07	3.46	0.652	-17.8
AirGradient-2	709	1.233	0.795	0.714	0.890	1.19	5.20	0.628	20.0
AirGradient-3	709	1.302	0.795	0.687	0.890	1.70	5.70	0.621	28.5

AirBeam3-1	709	1.117	0.865	0.818	0.992	-1.30	3.69	0.446	-21.6
AirBeam3-2	709	1.050	0.861	0.813	0.992	-1.62	3.64	0.417	-27.1
AirBeam3-3	709	0.969	0.861	0.805	0.992	-1.96	3.58	0.394	-32.7

a ICC = intraclass correlation coefficient (computed across all three co-located units of the same type). CCC = Lin's concordance correlation coefficient. r = Pearson correlation. MB = mean bias (positive = sensor over-reads). RMSE = root mean square error. FAC2 = fraction of estimates within a factor of 2 of reference. NMB = normalised mean bias (%).

3.2. PM_{10} performance

Relative to $PM_{2.5}$, PM_{10} measurements showed substantially weaker correlation to measurements from the DCCEEW Lidcombe TEOM monitor (Figure 4 and Figure 5).

Both the AirBeam3 and AirGradient under-reported PM_{10} concentrations up to a concentration of 20 µg/m^3. Once reported concentrations exceeded ~20 µg/m^3, both monitors began to frequently exceed concentrations measured at the DCCEEW Lidcombe monitor.

PM_{10} performance was substantially weaker for both platforms. Correlations ranged from r = 0.596 to 0.629, with large and consistent negative biases (MB: -5.5 to -7.3 µg/m³; NMB: -47% to -62%). FAC2 values of 0.23–0.27 indicate that the majority of hourly PM_{10} measurements fell outside a factor of two of the reference. CCC values (0.40–0.45) confirm poor overall agreement (Table 2).

Despite this, inter-unit consistency remained high (ICC: 0.986 for AirBeam, 0.999 for AirGradient), indicating that all sensors were measuring a common signal that simply does not correspond well to the reference PM_{10} fraction. This is likely attributable to the intrinsic limitations of optical particle counters (Caseiro, et al., 2024), as well as potential hygroscopic loading of particulate matter during high humidity events (Huang, et al., 2022).

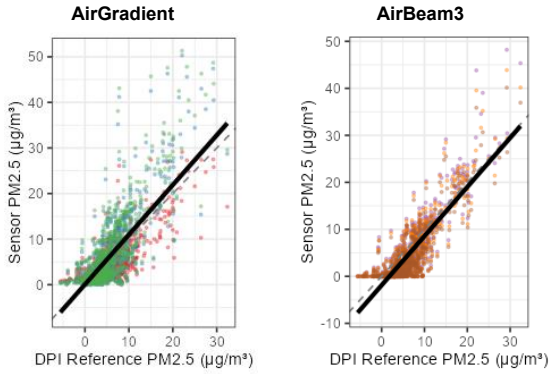


Figure 4. PM_{10} Linear Regression Analysis

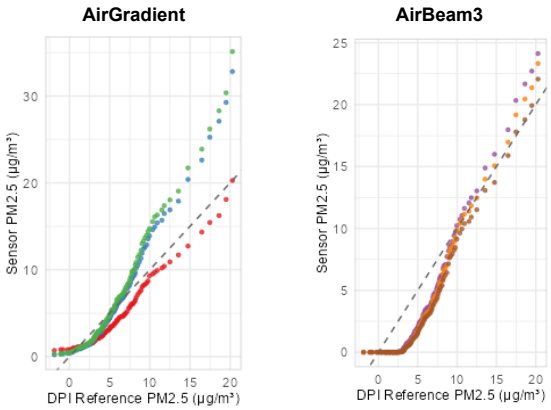


Figure 5. PM_{10} Quantile to Quantile distribution

Table 2. PM_{10} Statistical summary

Sensor	n	Slope	r	CCC	ICCa	MB (ug/m3)	RMSE (ug/m3)	FAC2	NMB (%)
AirGradient-1	710	0.996	0.601	0.447	0.999	-5.48	10.19	0.235	-46.8
AirGradient-2	710	0.966	0.598	0.445	0.999	-5.57	10.07	0.244	-47.6
AirGradient-3	710	0.949	0.596	0.440	0.999	-5.75	10.08	0.238	-49.1
AirBeam3-1	710	0.830	0.625	0.442	0.986	-6.46	9.39	0.273	-55.2
AirBeam3-2	710	0.766	0.628	0.424	0.986	-6.88	9.35	0.246	-58.8
AirBeam3-3	710	0.685	0.629	0.397	0.986	-7.30	9.36	0.225	-62.4

a ICC = intraclass correlation coefficient (computed across all three co-located units of the same type). CCC = Lin's concordance correlation coefficient. r = Pearson correlation. MB = mean bias (positive = sensor over-reads). RMSE = root mean square error. FAC2 = fraction of estimates within a factor of 2 of reference. NMB = normalised mean bias (%).

3.3. Influence of local meteorology on measurements

To investigate whether hygroscopic effects could be corrected in post-processing, a hygroscopic correction was developed using look-up tables (LUTs) binned by ambient temperature (2°C resolution) and relative humidity (5% resolution), with correction factors derived as the median ratio of reference to raw sensor PM over the co-location period. The LUT contained a median of 12 observations per bin (min. three required). Results of this analysis are presented in Figure 6 and Figure 6 below).

For AirGradient units, which apply a manufacturer Plantower correction to $PM_{2.5}$, the LUT had negligible additional effect: $PM_{2.5}$ RMSE remained ~6.4 µg/m³ and NMB at -11% to -12% before and after correction. PM_{10} performance was similarly unchanged (RMSE ~10.2 µg/m³; NMB -46% to -49%), indicating that the dominant source of error for AirGradient is not hygroscopic loading (Huang, et al., 2022) but likely optical sizing limitations of the Plantower sensor itself (Caseiro, et al., 2024).

For AirBeam3 units, the LUT correction had a more meaningful impact on systematic bias. $PM_{2.5}$ NMB improved from a range of -24% to -34% (uncorrected) to -12% to -25% after correction, with FAC2 increasing from 0.42 - 0.47 to 0.47 - 0.52. RMSE was broadly unchanged (~3.6–3.9 µg/m³), suggesting the correction addressed systematic bias but not the random variability component. For PM_{10}, the correction substantially reduced bias: AirBeam NMB improved from -56% to -63% (uncorrected) to -21% to -35% post-correction, with FAC2 rising from 0.23 - 0.28 to 0.40 - 0.41. RMSE increased modestly (from ~9.4 to ~10.5 µg/m³), reflecting that the correction redistributes remaining error from systematic to random. These results suggest environment-specific LUT corrections can meaningfully reduce systematic bias in AirBeam measurements, particularly for PM_{10}, though correlation-based performance remained limited by random variability. It is expected that longer co-location datasets would improve LUT bin coverage and stability.

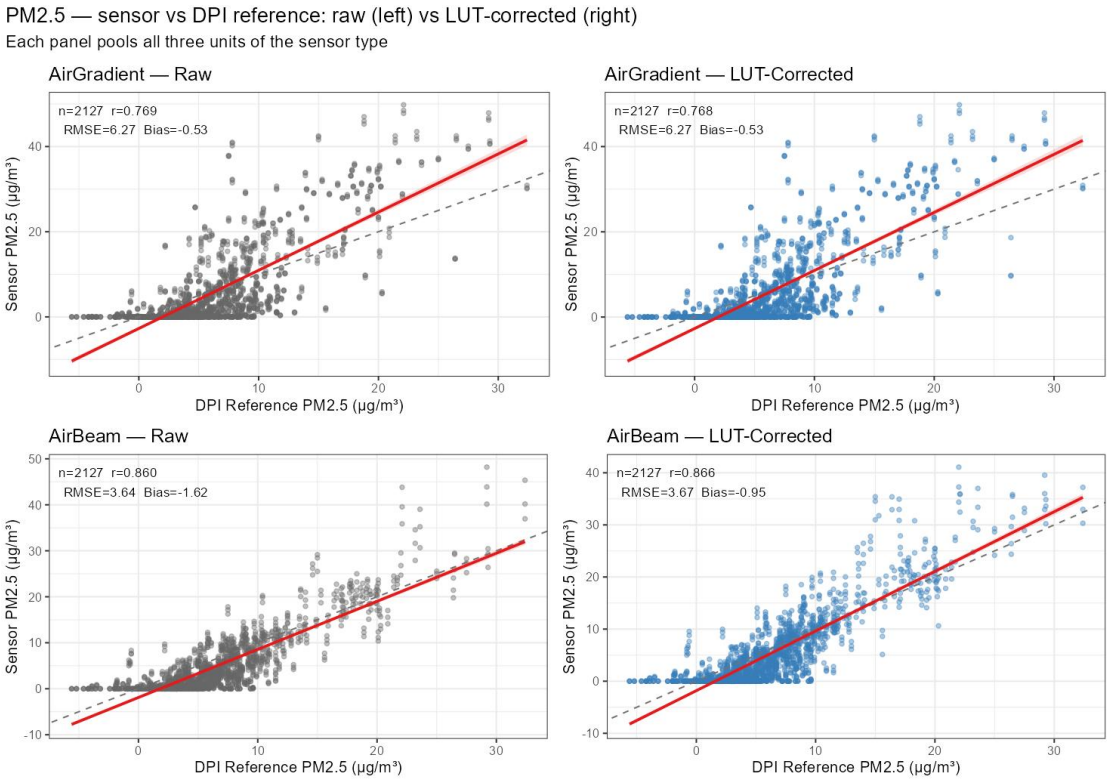


Figure 6 *$PM_{2.5}$ scatter plots before (left) and after (right) LUT hygroscopic correction, for AirGradient (top row) and AirBeam3 (bottom row) units.*

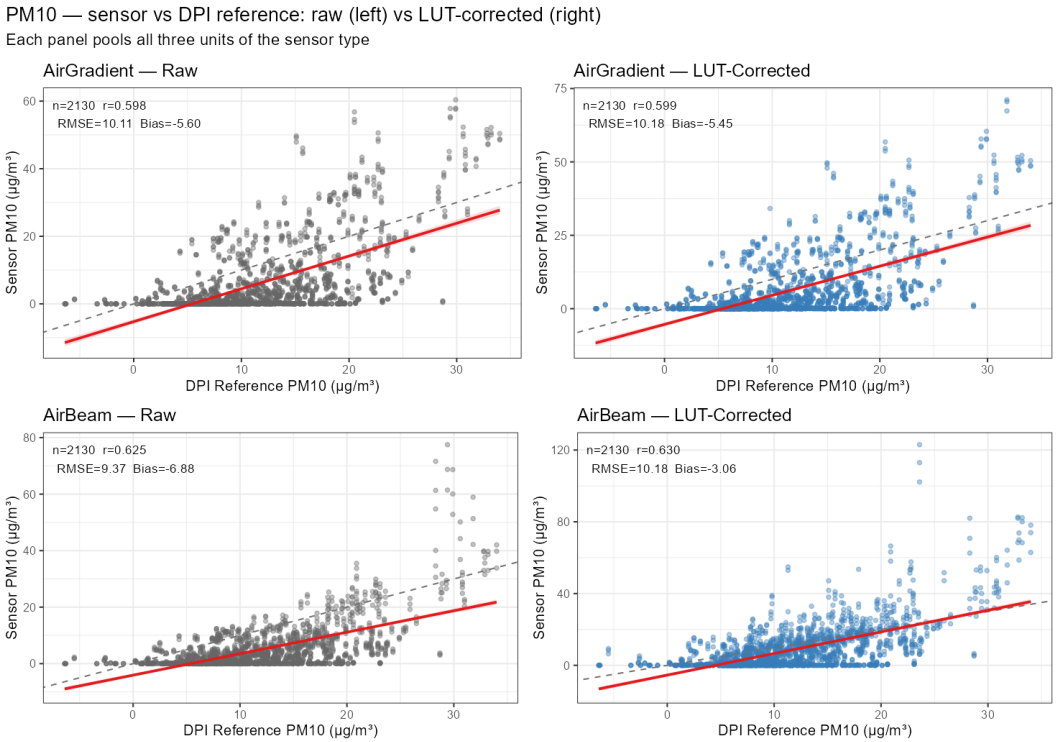


Figure 7 *PM_{10} scatter plots before (left) and after (right) LUT hygroscopic correction, for AirGradient (top row) and AirBeam (bottom row) units.*

4. Discussion

The results indicate that both sensor platforms can provide useful indicative $PM_{2.5}$ data for community air quality monitoring in Sydney, particularly for identifying elevated events and supporting spatial coverage where reference-grade monitoring is absent. AirBeam3 units offer marginally stronger absolute $PM_{2.5}$ agreement and consistent inter-unit reproducibility. AirGradient units show comparable correlation but higher inter-unit bias variability. Crucially, neither platform should be considered suitable for compliance monitoring or reliable PM_{10} characterisation without substantial site-specific correction. The hygroscopic LUT correction demonstrates that a portion of AirBeam PM_{10} bias is attributable to humidity effects, with NMB improving from -56% to -63% uncorrected to -21% to -35% post-correction; however, substantial residual bias remains.

While these results demonstrate potential use cases for LCSs in $PM_{2.5}$ monitoring, there is still uncertainty in applications for PM_{10} monitoring. It should be noted that this study only had four weeks of data, and given more data, the hygroscopic LUTs could potentially increase robustness of PM_{10} data. While these results demonstrate potential use cases for LCS in $PM_{2.5}$ monitoring, the study has important limitations. The four-week deployment period limits the range of meteorological and pollution conditions sampled, and the LUT correction bins are accordingly sparse at higher temperatures and humidity extremes. The co-location was conducted under conditions typical of a temperate coastal city; results may not transfer directly to sites with different aerosol composition such as smoke-dominated or dust-dominated environments. Future work should extend the co-location period to encompass smoke-affected episodes, evaluate correction transferability across sites, and assess whether the AirGradient manufacturer correction can be supplemented with site-specific adjustments. As such it is recommended that the LUT-correction approach be evaluated over a minimum of a six-to-12-month period encompassing seasonal variation, and that correction factors be validated against an independent dataset before operational deployment.

5. Conclusions

This study evaluated the performance of three AirGradient's and three AirBeam3 monitors against a DCCEEW TEOM reference instrument over a four-week monitoring period at the Lidcombe Super-Site in western Sydney. Both platforms demonstrated useful $PM_{2.5}$ correlation (r = 0.790 - 0.865) and are suitable for indicative trend monitoring and elevated-event detection in ambient urban conditions. AirBeam3 units exhibited stronger absolute agreement (CCC: 0.805 - 0.818) and exceptional inter-unit reproducibility (ICC: 0.99), indicating that they may be a more reliable platform for indicative $PM_{2.5}$ monitoring. AirGradient units showed comparable correlation but greater inter-unit bias variability (NMB: -18% to +29%), suggesting potential manufacturing variance in Plantower sensors.

PM_{10} performance was substantially weaker for both platforms (r = 0.596 - 0.629; CCC: 0.40–0.45; NMB: -47% to -62%), with negative coefficients of efficiency confirming that raw PM_{10} readings from these devices are not suitable for direct quantitative use. A hygroscopic look-up table (LUT) correction, stratified by temperature and relative humidity, partially reduced AirBeam3 PM_{10} bias (NMB improving to -21% to -35% post-correction) but had negligible effect on AirGradient units, suggesting the dominant source of error for the latter may be optical particle-sizing rather than hygroscopic loading.

Neither platform is suitable for PM_{10} quantification or regulatory compliance monitoring without substantial site-specific correction. It is recommended that the LUT correction approach be evaluated over a minimum six to 12-month period encompassing seasonal variation, smoke-affected episodes, and high-humidity extremes, and that correction factors be validated against an independent holdout dataset before operational deployment. Future co-location studies should also explore whether supplementary site-specific adjustments to the AirGradient manufacturer correction can reduce inter-unit bias variability and improve fitness-for-purpose across a broader range of Australian ambient conditions.

Acknowledgments

The authors thank the NSW Department of Climate Change, Energy, the Environment and Water (DCCEEW) for access to the Lidcombe Air Quality Monitoring Super-Site and the associated reference-grade PM data used in this study.

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