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Guidance for Evaluating the Performance and Use of Air Quality Sensors for Construction Dust (PM_{10}) Monitoring

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Dr Emil Varghese

Dr R Subramanian

Center for Study of Science, Technology and Policy (CSTEP)
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Editor: Veena P
Designer: Devashish Shukla

Bengaluru

No. 18, 10th Cross, Mayura Street

Papanna Layout, Nagashettyhalli

RMV Stage 2, Bengaluru 560094

Karnataka (India)

Noida

1st Floor, Tower-A

Smartworks Corporate Park

Sector 125, Noida 201303

Uttar Pradesh (India)

Tel.: +91 (80) 6690 2500

Email: cpe@cstep.in

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Executive Summary

Executive Summary

This guidance document for the use of air quality sensors at construction sites has been developed based on the evaluation of low-cost sensors conducted at the India Sensor Evaluation and Training (Indi-SET) facility. A first-of-its-kind facility in India, Indi-SET is established at the Bengaluru campus of the Centre for Study of Science, Technology and Policy (CSTEP). During the evaluation period, six particulate matter (PM) sensor models from five Indian manufacturers were evaluated for one year, covering all seasons and varying pollution loads.

Recommendations for sensor node installation and calibration at construction sites

Particular	Recommendation
Sensor node installation	• Use sensor nodes with Ingress Protection 65 (IP65) or higher rating. • Ensure battery backup for more than three days of sensor operation or integrate with solar charging capabilities. • Install away from a direct pollution source. • Periodically clean sensor inlets and solar panels. • Integrate sensors to measure $PM_{2.5}$, PM_{10}, temperature, and relative humidity.
PM sensor model to be integrated in each sensor node	• $PM_{2.5}$: Plantower PMS5003, Plantower PMS7003, Tera Sensor NextPM, and Sensirion SPS30. • PM_{10}: Alphasense OPC-R2.
Data transmission and storage	• Transmit sensor data through Internet-of-Things (IoT) SIM cards. • Collect real-time data at 1-minute resolution from sensor nodes installed with a real-time clock. • Data access based on an application programming interface to be provided by the integrator every 15 minutes. • Store and manage data using a data management system (DMS) for quality assurance.
Data standardisation	• Ensure data availability in the local time zone and uniformity in names and units for parameters. • Compare hourly averaged data of PM sensors with that of reference-grade instruments.
Requirements for sensor evaluation (collocation study)	• Evaluate all sensor nodes for 15 days for inter-unit precision (all sensor nodes collocated with each other). • Evaluate three to five high-precision sensor nodes collocated with a reference monitor (e.g., beta attenuation monitor [BAM] or Continuous Ambient Air Quality Monitoring Stations [CAAQMSs]) for accuracy. • Test in dusty conditions and varying relative humidity for a minimum of 15 days. • Collocate sensor nodes with reference instruments every six months to ensure data reliability.

Particular	Recommendation
Development of calibration models	• Collocate sensors with reference instruments for 2–4 weeks. • Best algorithm to be used: Multiple linear regression and quadratic regression. • Best model applied for $PM_{2.5}$: Use a calibration model with input variables including the $PM_{2.5}$ value reported by the Plantower (or a similar) sensor and the relative humidity value measured by the sensor node. • Best model applied for PM_{10}: Use a calibration model with input variables including PM_1, $PM_{2.5}$, and PM_{10} values reported by the Alphasense OPC sensor; the PM_1 value from the Plantower (or a similar) sensor; and the relative humidity value measured by the sensor node.

Recommended performance metrics for sensor use at construction sites (adapted from the United States Environmental Protection Agency [US EPA] recommendations)

Particular	Performance Metric (Hourly Averaged Data)		Target Value	
			$PM_{2.5}$	PM_{10}
Inter-node precision within each manufacturer	**Precision**	Pearson correlation coefficient (r)	≥ 0.9	≥ 0.9
		Coefficient of determination (R^2)	≥ 0.8	≥ 0.8
		Standard deviation (SD)	≤ 5 μg/m³	≤ 5 μg/m³
		Coefficient of variation (CV)	≤ 30%	≤ 30%
Accuracy of each sensor node with reference-grade instruments	**Bias**	Slope (a)	1 ± 0.35	1 ± 0.35
		Intercept (b)	−5 ≤ b ≤ 5 μg/m³	−10 ≤ b ≤ 10 μg/m³
	Linearity	Pearson correlation coefficient (r)	≥ 0.8	≥ 0.8
		Coefficient of determination (R^2)	≥ 0.7	≥ 0.7
	Error	Root mean square error (RMSE)	≤ 7 μg/m³	≤ 14 μg/m³
		Normalised root mean square error (NRMSE)	≤ 30%	≤ 30%
		Bias-corrected coefficient of variation in mean absolute error (CvMAE)	≤ 30%	≤ 30%

Table of Contents

List of Figures

List of Tables

Introduction

1. Introduction

Construction activities such as earth excavation and backfilling, loading and unloading of materials, concrete placement and curing, drilling, welding, chiselling, demolition, and material transportation emit dust into the atmosphere. These sources contribute to particulate matter 2.5 ($PM_{2.5}$; ambient particles smaller than the 2.5-micron aerodynamic diameter [PM ≤ 2.5 µm]) and PM_{10} (PM ≤ 10 µm, which includes $PM_{2.5}$). Low-cost sensors (LCSs) can be used to qualitatively assess the dust control measures at construction sites. In India, many manufacturers (or integrators) sell sensor nodes (or sensor boxes) for measuring PM. These manufacturers integrate different sensor models that operate on the principle of light scattering (including optical particle counting [OPC]) into their sensor nodes, along with sensors for measuring temperature and relative humidity.

A year-long evaluation of six PM sensor models used by five different sensor manufacturers (Table 1) was conducted at the India Sensor Evaluation and Training (Indi-SET) facility in the Center for Study of Science, Technology and Policy (CSTEP) campus in Bengaluru. This document outlines guidelines for evaluating the performance and use of air quality sensors for monitoring construction dust (PM_{10}).

***Table 1**: Description of the PM sensors evaluated in the Indi-SET facility during 2024–25*

Sensor Manufacturer	PM Sensor Model Integrated	Number of Sensor Nodes Evaluated
Aeron Systems Pvt Ltd	Alphasense OPC-N3	5
	Tera Sensor NextPM	
Airveda	Plantower PMS7003	5
Aurassure Pvt Ltd	Sensirion SPS 30	25
Respirer Living Sciences Pvt Ltd	Alphasense OPC-R2	5
	Plantower PMS7003	
Sensit Technologies	Alphasense OPC-R2	5
	Plantower PMS5003	

Guidelines Part 1: Sensor Specifications and Installation

2. Guidelines Part 1: Sensor Specifications and Installation

2.1. Use sensor nodes that are operational in the outdoor environment (weatherproof) and have Ingress Protection 65 (IP65) or higher ratings

Sensor deployment in construction sites poses environmental challenges, such as exposure to extreme temperatures, rainfall, moisture, dust, debris, vibration, and mechanical stress. To ensure reliable operation under such conditions, it is recommended to use sensor nodes rated IP65 or higher. An IP65-rated device signifies that the device is 'dust-tight' and 'protected against water jets'.

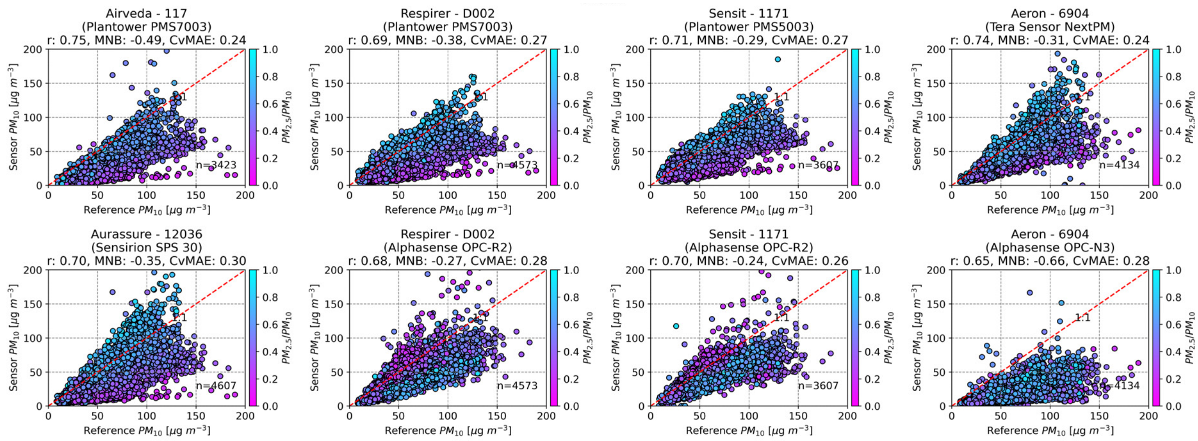
2.2. Use sensor nodes that incorporate a combination of Plantower (or similar sensors such as Tera Sensor or Sensirion) and Alphasense OPC-R2

At construction sites, the $PM_{2.5}/PM_{10}$ ratio ranges from 0.06 to 0.4, depending on the construction activity. Sensor nodes incorporating sensors from Plantower / Tera Sensor / Sensirion or similar models are best for particles smaller than 1 micron (e.g., diesel exhaust from trucks and excavators at construction sites); they significantly under-report larger particles (diameter 2–10 micron; Ouimette et al., 2023). Sensor nodes incorporating Alphasense OPC-R2[1] better track PM concentrations in dust-prone conditions where larger particles (diameter 2–10 microns) dominate PM_{10} (Figure 1). Hence, sensor nodes integrated with both types of sensors are the best to deploy at a construction site.

We recommend visualising the comparison between the sensor output and the reference monitor as a function of the $PM_{2.5}/PM_{10}$ ratio (as in Figures 1 and 5). If the sensors are evaluated under non-dusty conditions (e.g., $PM_{2.5}/PM_{10} > 0.5$), they may perform well in testing for PM_{10} but perform poorly when deployed at construction sites (where $PM_{2.5}/PM_{10}$ can range from 0.06 to 0.4).

[1] We have not found other suitable alternatives; we tested sensors with Alphasense OPC-N3, but they did not perform as well as sensors with OPC-R2. A new sensor from Cubic is now available that has not yet been officially evaluated at Indi-SET. A field evaluation at the Air Quality Sensor Performance Evaluation Center (AQ-SPEC), CA, USA, shows poor performance (R^2 of 0.1 to 0.14) for Cubic PM_{10} (https://www.aqmd.gov/aq-spec/evaluations/summary-table).

Figure 1: Comparison of as-reported 1-hr average PM_{10} data from (a) Airveda Plantower PMS7003; (b) Respirer Plantower PMS7003; (c) Sensit (RAMP model) Plantower PMS5003; (d) Aeron Tera Sensor NextPM; (e) Aurassure Sensirion SPS30; (f) Respirer Alphasense OPC-R2; (g) Sensit (RAMP model) Alphasense OPC-R2; and (h) Aeron Alphasense OPC-N3 with the reference beta attenuation monitor (BAM) PM_{10} during the one-year collocation at Indi-SET, Bengaluru, for PM_{10}. The magenta colour of the markers represents a greater influence of coarse dust particles (dusty conditions), and the blue colour represents clean air. The sensor node ID is marked alongside the integrator name.



2.3. Maintain data transmission from sensor nodes through SIM cards, real-time data collection at 1-minute resolution, and application programming interface (API)–based data access every 15 minutes

The sensor nodes should be equipped with a real-time clock (RTC) to keep track of time even when the main power source is off. This provides accurate time and date information, which is crucial for data logging. The data logged by the sensor nodes should be stored on a secure digital (SD) card and should be transmitted in near real-time through Internet-of-Things (IoT) SIM cards. The data received should be reported at a 1-minute resolution. The integrator should provide API-based data access every 15 minutes to enable near real-time monitoring of air quality.

2.4. Store and manage data through a data management system (DMS)

Two or three levels of data are available from the sensor nodes: (i) raw data that is directly reported by the sensor, (ii) manufacturer-corrected (factory-calibrated) data reported by the manufacturer, and (iii) locally calibrated data that is corrected by collocating with reference instruments at similar locations (here, from a construction site). These levels of data fetched through API from various sensors and/or integrators can be stored, processed, and analysed through a DMS. The DMS can be used to standardise and store data, apply correction models and analyse and display data in near real-time, track sensor health, and alert officials to take quick action if pollution levels are too high.

2.5. Use sensor nodes equipped with long-duration batteries or integrated with solar charging capabilities

Construction sites are prone to electrical challenges that include wet conditions, raising the risk of shock, voltage fluctuations, ungrounded cords, and circuit overload. Under these circumstances, to ensure the safe and continuous operation of sensor nodes, it is suggested to use sensor nodes equipped with high-capacity batteries (providing battery backup for more than three days of sensor operation) or integrated with solar charging capabilities.

2.6. Install sensor nodes away from pollution sources in an area with free air movement

Figure 2: *Examples of sensor node installations for ambient air quality monitoring following the United States Environmental Protection Agency (US EPA) guidelines, ensuring free airflow (no large walls or trees nearby).*

For ambient monitoring, the sensor nodes should be installed in an area with free airflow, at human breathing height (2–5 m above ground level), and away from pollution sources (Figure 2). However, panel 3 in Figure 2 will be influenced by traffic-related air pollution (vehicular exhaust and resuspended road dust), so it is considered a roadside or kerbside location. Similarly, in Figure 3, the sensor node is placed directly above a dust pile. The readings can be high when wind resuspends dust due to the node's proximity to the pile, but the dust may be redeposited a short distance away. Thus, the sensor's readings may overestimate the dust pile's contribution to ambient air pollution. More research is needed on the optimal placement of sensor nodes at construction sites to ensure that the contribution of construction-related emissions (fugitive dust and excavator and truck exhaust) to ambient air quality is properly captured.

Figure 3: *A bad example of sensor node installation. As the sensor node is installed on top of the pile of construction material, it will report high PM values, especially in dry and windy conditions.*

2.7. Clean sensor inlets and solar panels periodically to maintain sensor performance

Due to dust accumulation or cobweb formation, PM sensors and solar panels experience performance degradation over time. Sensors can underreport PM if their inlets get blocked, while solar panels lose efficiency as dust covers them and reduces sunlight absorption, necessitating regular inspection and cleaning for both.

Guidelines Part 2: Sensor Evaluation and Calibration

3. Guidelines Part 2: Sensor Evaluation and Calibration

3.1. Standardise the data in near real-time before data analysis

If using sensor nodes from multiple integrators, standardise the data in near real-time before analysis. General standardisation includes converting timestamps to Indian Standard Time (IST; local time zone), assigning uniform names and units to the parameters ($PM_{2.5}$ and PM_{10} reported in µg/m³), and averaging measurements to uniform time intervals (1-minute average, 15-minute average, 1-hour average, etc.). The standard data format for the various parameters under testing is provided in Table 2. Reference-grade PM monitors such as BAMs generally report data as 1-hour averages. Hence, aggregating the sensor data on an hourly basis can assist in comparing it with the reference monitors. However, this should be done only if 75% of the data points are available for that particular hour. For routine monitoring and data visualisation, reporting at 1-minute or 15-minute intervals is recommended.

***Table 2**: Standard data format for various parameters*

Parameter	Notation	Unit
PM_1	pm1 (if non-OPC sensor), pm1_opc (if OPC sensor)	µg/m³
$PM_{2.5}$	pm2_5 (if non-OPC sensor), pm2_5_opc (if OPC sensor)	µg/m³
PM_{10}	pm10 (if non-OPC sensor), pm10_opc (if OPC sensor)	µg/m³
Temperature	temperature	°C
Relative humidity	relative humidity	%

3.2. Collocate the sensors to evaluate the inter-unit precision

All sensor nodes need to be collocated for a minimum of 2 weeks (15 days) in dusty conditions and tested under varying relative humidity conditions. This will check for inter-unit precision of the sensors. Inter-unit precision among nodes from the same integrator can be assessed by comparing all nodes within the integrator using various metrics: Pearson correlation coefficient (r), coefficient of determination (R^2), standard deviation (SD), and coefficient of variation (CV).

The formulas to calculate these precision metrics are given below.

1. To determine (R^2), the simple linear regression fitting of sensor measurements (y-axis) is used to reference instrument measurements (x-axis).

2.

$$SD = \sqrt{\frac{1}{(N \times M) - 1} \sum_{j=1}^{M} \left[\sum_{h=1}^{N} (x_{hj} - \bar{x}_h)^2 \right]}$$

where SD = SD of 1-hour averaged sensor PM concentration measurements (μgm^{-3}),

N = number of 1-hour periods during which all identical instruments are operating and returning valid averages over the duration of the field test,

M = number of identical sensors operated simultaneously during a field test,

x_{hj} = 1-hour averaged sensor PM concentration for hour h and sensor j (μgm^{-3}), and

$\bar{x}_h$ = 1-hour averaged sensor PM concentration for hour h from the three sensors (μgm^{-3}).

3.

$$CV = \frac{SD}{\bar{x}} \times 100$$

where CV is in %, and

SD = SD of 1-hour averaged sensor PM concentration measurements (μgm^{-3}).

3.3. Collocate sensor nodes with reference monitors before deploying at construction sites to evaluate sensor accuracy

The high-precision sensor nodes (3 to 5 devices) from each integrator need to be collocated with reference monitors (BAMs, tapered element oscillating microbalance (TEOM), or aerosol spectrometers) for a minimum of 2 weeks (15 days) in dusty conditions and tested over varying relative humidity conditions. Figure 4 shows the collocation of a few sensor nodes with the reference instruments at Indi-SET to check the accuracy of the sensors against reference monitors. The bias, linearity, and error in the data reported by the sensors through the reference monitor can be assessed using the metrics: slope (m), intercept (c), mean normalised bias (MNB), Pearson correlation coefficient (r), coefficient of determination (R^2), root mean square error (RMSE), normalised root mean square error (NRMSE), and bias-corrected coefficient of variation in mean absolute error (CvMAE).

The formulas to calculate these accuracy metrics are given below.

1.

$$MNB = \frac{\sum_{i=1}^{N}(x_h - R_h)}{\sum_{i=1}^{N} R_h}$$

where MNB is in μgm^{-3}, and

x_h= 1-hour averaged sensor PM concentration for hour h (μgm^{-3}).

2.

$$RMSE = \sqrt{\frac{1}{N}\sum_{h=1}^{N}(x_h - R_h)^2}$$

where RMSE = is in μgm^{-3},

N = number of 1-hour periods during which all identical instruments are operating and returning valid averages over the duration of the field test,

x_h = 1-hour averaged sensor PM concentration for hour h (μgm^{-3}), and

R_h = 1-hour averaged reference monitor PM concentration for hour h (μgm^{-3}).

3.

$$NRMSE = \frac{RMSE}{\overline{R_d}} \times 100$$

where RMSE is in μgm^{-3}, and

$\overline{R_d}$ = valid 1-hour averaged reference PM concentration over the entire testing period (μgm^{-3}).

4.

$$CvMAE = \frac{\sum_{i=1}^{N}|x_h - n_{bias} - R_h|}{\sum_{i=1}^{N} R_h}$$

where

$$n_{bias} = \frac{1}{N}\sum_{i=1}^{N}(x_h - R_h),$$

N = number of 1-hour periods during which all identical instruments are operating and returning valid averages over the duration of the field test,

x_h = 1-hour averaged sensor PM concentration for hour h (μgm^{-3}), and

R_h = 1-hour averaged reference monitor PM concentration for hour h (μgm^{-3}).

Figure 4: *The Indi-SET facility established at the CSTEP campus in Bengaluru. The PM monitors for $PM_{2.5}$ and PM_{10} are placed outdoors in weatherproof enclosures next to the sensor test bed that accommodates up to 60 sensor nodes.*

3.4. Development of localised calibration models improves the sensor performance

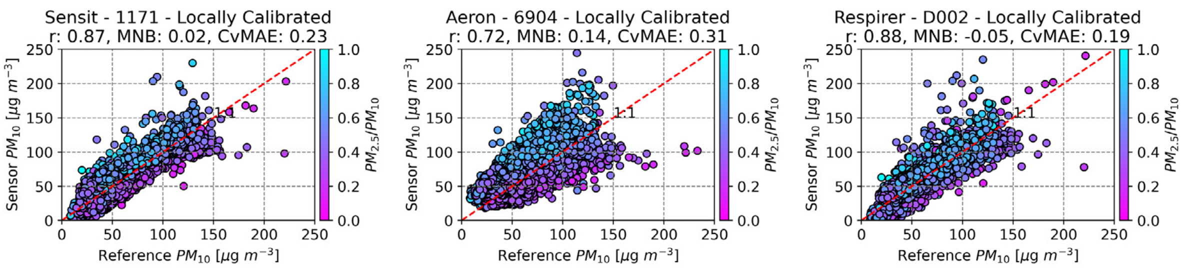
To improve data reliability and accuracy, sensor data collected during the collocation period can be used to develop localised corrections using calibration models. The collocation period can be varied from 2 to 4 weeks for developing calibration models. The performance of the sensors varies with relative humidity. Therefore, the calibration models have to be trained using sensor data, reference monitor data, and the relative humidity reported by the sensors during the collocation period. In sensor nodes with an OPC sensor, a hybrid model can be developed by training it with data from both Plantower and similar sensors, as well as the OPC sensor. Two types of calibration models can be considered, either sensor-specific or generalised. The former is built for each individual sensor node, whereas the latter is built for each integrator by considering the median values measured across all sensor nodes of that integrator, if the sensors show high inter-unit precision. The model inputs for each device are given in Table 3. Either parametric methods (multiple linear regression and quadratic regression) or non-parametric methods (using machine learning algorithms such as random forest regression, support vector regression, and XG Boost regression) are used to develop the calibration models. The simplest and best model that can be used is generalised multiple linear regression or the sensor-wise quadratic regression algorithm, using model inputs from both Plantower (or similar sensors such as Tera Sensor or Sensirion) and Alphasense OPCs. The most preferred models based on long-term performance assessment of the various models are the 'PM2.5 model' and the 'PM10_hybrid model'. Figure 5 shows the performance of the PM_{10} sensors after applying the 'PM10_hybrid calibration model'. It shows that even with corrections using models, the PM_{10} sensors are usually indicative (e.g., indicates whether pollution is high or low) and not regulatory (highly accurate).

Table 3: Model inputs used to build various calibration models

Model Name	Model Input	Remark
PM2.5	PM2.5_plantower, RH_sensor	Preferred
PM2.5_hybrid	PM1_plantower, (PM2.5–PM1)_OPC, RH_sensor	NA
PM2.5_OPC	PM2.5_OPC, RH_sensor	NA
PM10	PM10_plantower, RH_sensor	NA
PM10_hybrid	PM1_plantower, (PM2.5–PM1)_OPC, (PM10–PM2.5)_OPC, RH_sensor	Preferred
PM10_OPC	PM10_OPC, RH_sensor	NA

RH_sensor: Relative humidity reported by the sensor
PM1_plantower: PM_1 value reported by Plantower or similar type sensors, such as Tera Sensor or Sensirion
PM2.5_plantower: $PM_{2.5}$ value reported by Plantower or similar type sensors, such as Tera Sensor or Sensirion
PM10_plantower: PM_{10} value reported by Plantower or similar type sensors, such as Tera Sensor or Sensirion
PM2.5_OPC: $PM_{2.5}$ value reported by Alphasense OPC
PM10_OPC: PM_{10} value reported by Alphasense OPC
(PM2.5−PM1)_OPC: The difference between $PM_{2.5}$ and PM_1 value reported by Alphsense OPC sensors
(PM10−PM2.5)_OPC: The difference between PM_{10} and $PM_{2.5}$ value reported by Alphsense OPC sensors

***Figure 5:** Comparison of locally calibrated 1-hr average PM_{10} data reported from (a) Aurassure, (b) Airveda, (c) Sensit (RAMP model), (d) Aeron, and (e) Respirer to the BAM measurement during the one-year collocation period at Indi-SET, Bengaluru. The magenta colour of the markers represents a greater influence of coarse dust particles (dusty conditions), and the blue colour represents clean air. The IDs of the sensor nodes are marked along with the integrator name. The model used for this calibration is a generalised PM10_hybrid model (see Table 3) built by the median data of all the sensor nodes from each manufacturer.*



3.5. Periodic collocation with reference monitors to track the ageing of sensors

Over a period of time (usually after several months), PM sensors can lose their accuracy due to sensor ageing (e.g., dust accumulation on the sensor optics and laser degradation after prolonged use at high temperatures). Indicators include reporting the same concentration for days or reporting zeroes or reporting very high/unrealistic values. Hence, periodic collocation (e.g., every six months) with a reference PM monitor is recommended to ensure data reliability.

Recommended Performance Metrics for Sensor Use at Construction Sites

4. Recommended Performance Metrics for Sensor Use at Construction Sites

Adapted from the US EPA recommendations, the target values for the performance evaluation metrics for sensor use at construction sites are listed in Table 4 (EPA/600/R-20/280; US EPA, 2021; EPA/600/R-23/145, US EPA, 2021). Ideally, air quality sensor performance for construction dust monitoring should be evaluated in dusty conditions, defined as $PM_{2.5}/PM_{10}$ ratio (from the reference monitors) less than 0.4.

Table 4: *Recommended performance metrics and target values for $PM_{2.5}$ and PM_{10}*

Performance Metric (Hourly Averaged Data)		Target Value	
		$PM_{2.5}$	PM_{10}
Precision	r	≥ 0.9	≥ 0.9
	R^2	≥ 0.8	≥ 0.8
	SD	≤ 5 μg/m³	≤ 5 μg/m³
	CV	≤ 30%	≤ 30%
Bias	Slope (a)	1 ± 0.35	1 ± 0.35
	Intercept (b)	−5 ≤ b ≤ 5 μg/m³	−10 ≤ b ≤ 10 μg/m³
Linearity	r	≥ 0.8	≥ 0.8
	R^2	≥ 0.7	≥ 0.7
Error	RMSE	≤ 7 μg/m³	≤ 14 μg/m³
	NRMSE	≤ 30%	≤ 30%
	CvMAE	≤ 30%	≤ 30%

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CENTER FOR STUDY OF SCIENCE, TECHNOLOGY AND POLICY

+91 8066902500

cpe@cstep.in

www.cstep.in

@cstep_india

Bengaluru

No. 18, 10th Cross, Mayura Street, Papanna Layout, Nagashettyhalli (RMV II Stage), Bengaluru-560094 Karnataka, India

Noida

1st Floor, Tower-A, Smartworks Corporate Park, Sector-125, Noida-201303, Uttar Pradesh, India