SUPPORTING INFORMATION:

Size-Resolved Field Performance of Low-Cost Sensors for Particulate Matter Air Pollution

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Low-cost sensor descriptions and specifications

All three sensors utilize light-scattering to estimate aerosol concentrations, including a focused laser diode to illuminate particles that pass through a small sensing zone and a photodiode (placed near the sensing zone but orthogonal to the direction of laser light propagation) to detect the intensity scattered light across a truncated solid angle. Air flow is drawn through each device by a miniature induction fan.

The Plantower PMS5003 is described by the manufacturer as a "digital universal particle concentration sensor" [1]. This sensor has been used in multiple commercial low-cost air quality monitors, including the popular PurpleAir (older versions of the PurpleAir used the PMS1003 and newer versions use the PMS6003, but most units including the ones we evaluated use the PMS5003). The Sensirion SPS30 is described by the manufacturer as a particulate matter sensor for air quality monitoring [2]. Piera describes the IPS-7100 as a "photon counting intelligent particle sensor", and their technology as "intuitive direct-particle counting" [3]. The IPS-7100 firmware is user-upgradable, and we updated from v1.9.9 to v1.9.10 on Piera's request before the start of our first (fall/winter) data collection period.

Table S1. Low-cost sensors specifications.

	Plantower PMS5003	Sensirion SPS30	Piera IPS-7100
Stated Outputs			

Mass concentration	$PM_{1.0}$, $PM_{2.5}$, PM_{10}	$PM_{1.0}$, $PM_{2.5}$, PM_4, PM_{10}	$PM_{0.1}$, $PM_{0.3}$, $PM_{0.5}$, $PM_{1.0}$, $PM_{2.5}$, PM_5, PM_{10}
Number concentration	$PC_{0.3}$, $PC_{0.5}$, $PC_{1.0}$, $PC_{2.5}$, PC_5, PC_{10}	$PC_{0.5}$, $PC_{1.0}$, $PC_{2.5}$, PC_4, PC_{10}	$PC_{0.1}$, $PC_{0.3}$, $PC_{0.5}$, $PC_{1.0}$, $PC_{2.5}$, PC_5, PC_{10}
Cost at quantity of 1	\$15	\$50	\$80
Weight	42 grams	26 grams	26 grams
Size	50 x 38 x 21 mm	41 x 41 x 12 mm	46 x 42 x 12 mm

We chose these sensors for three reasons: (1) the technology featured in these devices, while similar across the three models, represents the state-of-the-art for commercial low-cost (<\$100 USD) aerosol sensing; (2) the selected sensors are from major suppliers that span three continents: Asia (Plantower), North America (Piera), and Europe (Sensirion); and (3) these sensors (especially the Plantower PMS5003) represent the majority of in-use technologies across the world. For example, the Plantower has been deployed widely and in large numbers in networks throughout countries in Asia, like China and Taiwan [4–6], where it has a large share of the PM sensor market. The SPS30 and IPS-7100 were selected because they provide geographic diversity (they are from companies in North America and Europe, respectively).

Reference monitor operating conditions

The EDM 180 is an approved federal equivalent method (FEM) monitor for $PM_{2.5}$ when operated continuously at a 1.2 L min-1 volumetric flow rate with a Nafion air dryer inside an isothermal inlet[7,8]. We complied with this configuration and added the fully temperature-controlled weather protection housing suggested by the manufacturer. This monitor is also UK-MCERTS certified for PM_{10} [9].

Datalogging

We used a PurpleAir PA-II to collect data from two PMS5003 sensors. Logs in CSV format were downloaded from PurpleAir's website. We developed a custom data logger and housing to collect data from two SPS30 sensors (Figure S3). The data logger used a Particle Boron LTE microcontroller to read the sensors' data and send it via a cellular network to a server hosted by the Center for Energy Development and Health (CEDH) at Colorado State University. We collected data from two IPS-7100 sensors and sent those data to the server using a Wi-Fi enabled Espressif ESP32 microcontroller. We made a custom housing for the Piera IPS-7100 sensors similar to what we developed for the SPS30 sensors.

For the Plantower PMS5003 sensor, the "CF=1, standard particle" output variables were used in all calculations involving $PM_{1.0}$, $PM_{2.5}$, and/or PM_{10} concentrations. The "CF=1" variables from the PMS5003 are uncorrected, according to the manufacturer, as opposed to the "ATM" variables which use a proprietary algorithm and calibration unspecified by the manufacturer to estimate atmospheric aerosol concentrations.

One-minute averages of all reported outputs were logged for the SPS30 and IPS-7100 sensors, whereas the PMS5003 (which was operated in a PurpleAir device) logged 2-minute averages. Unless otherwise stated, raw sensor mass and number readings were recorded directly, and only time-based averaging was applied.

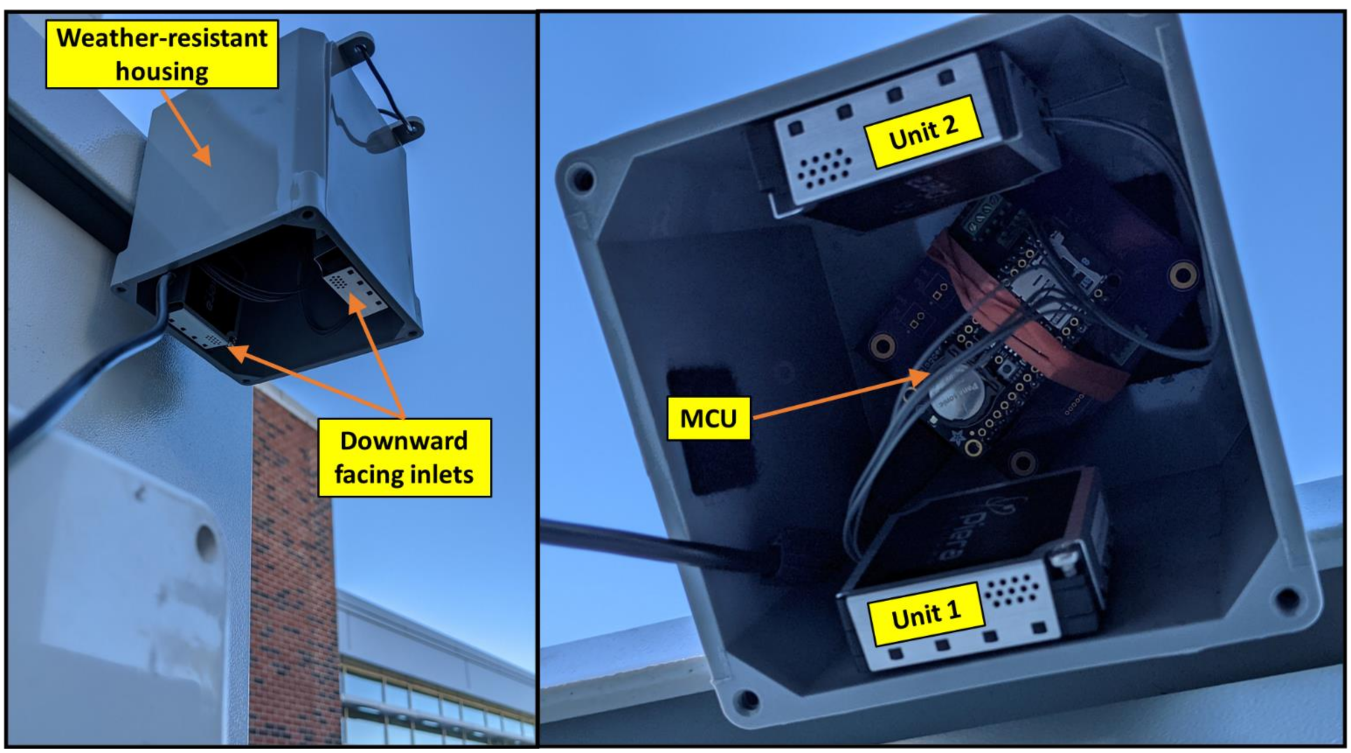

Figure S1. Data logger and housing used for the IPS-7100 (shown in picture) and SPS30 sensors.

Field evaluation location and setup

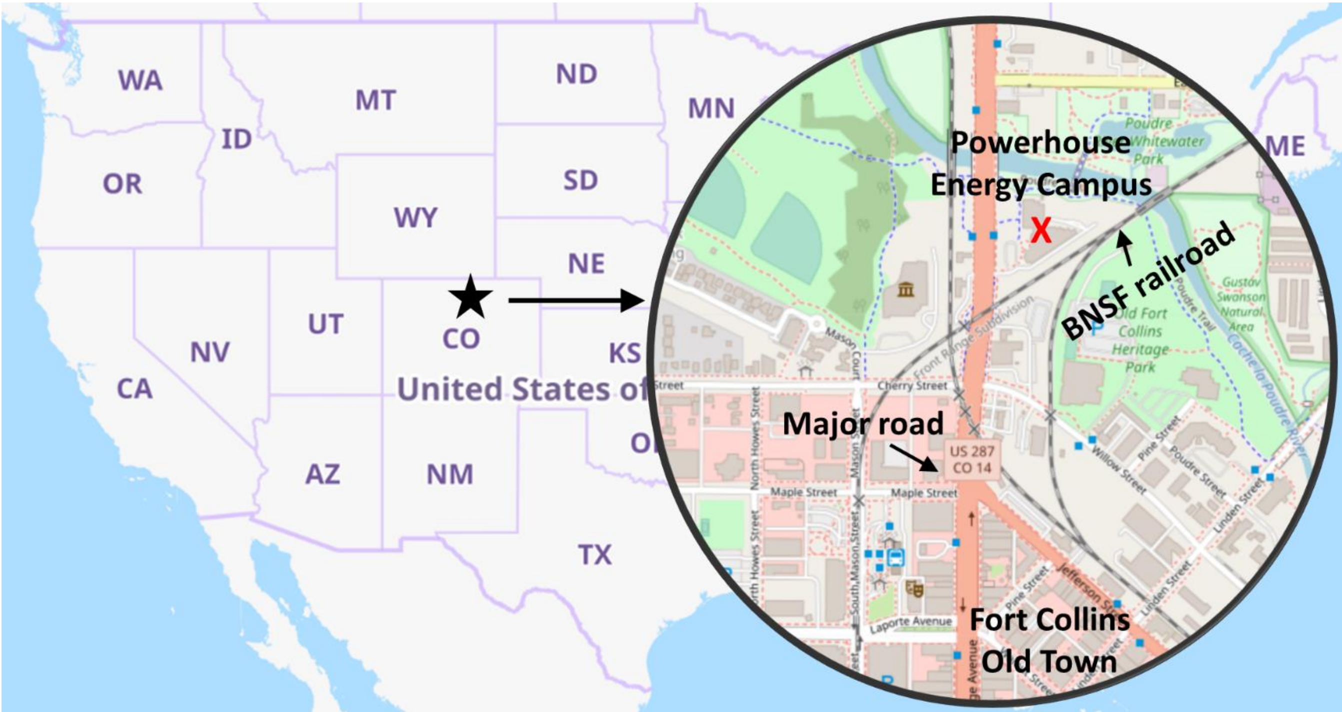

Figure S2a. Map of the Powerhouse Energy Campus building in Fort Collins, where the sensors were tested.

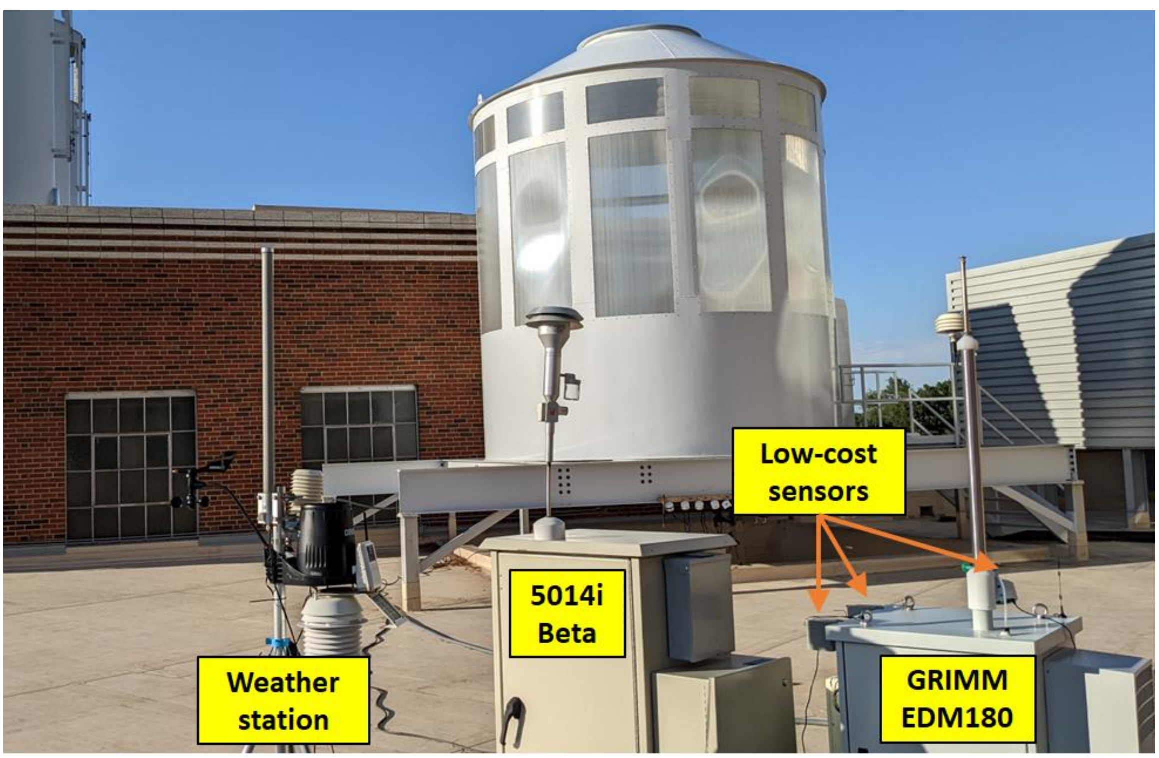

Figure S2b. Layout of the instruments used for the field evaluation.

Common variables

PM_x : Cumulative particulate matter concentration up to the particle size indicated by the subscript (in µm).

$PM_{a\text{-}b}$: Differential particulate matter concentration within the size range indicated by the subscript (in µm).

$PM_{a\text{-}b}$: Also defined as **$PM_b – PM_a$** .

Statistical analyses

Descriptive statistics were calculated for each sensor. We present the statistical metrics corresponding to a single unit (i.e., “unit a”) of each sensor model, except for the metrics that measure intra-model (unit-to-unit) variability. Standard statistical metrics were calculated to assess sensor precision (coefficient of variation among co-located devices of the same model), linearity (coefficient of determination vs. reference), and bias (e.g., RMSE, MAE, NMB vs. reference) as a function of particle size range. Where appropriate, we developed linear regression models between sensor and reference data using ordinary least squares to estimate slope, intercept, and as inputs to estimate relative expanded uncertainty (REU), which has been adopted by the European Commission air quality directive as a measure of low-cost sensor performance relative to reference monitors [10]. Visual diagnostics were used to assess model assumptions (i.e., linearity, normality, and homoscedasticity) (Figures S8 and S9). Time-series and scatter plots were developed to visualize sensor performance as a function of particle size range.

Performance metrics - Equations

Root mean square error (RMSE):

$$RMSE = \sqrt{\sum_{i=1}^{n} \frac{(y_i - x_i)^2}{n}}$$

Where n is the number of data pairs, y_i is the ith low-cost sensor measurement, and x_i is the ith reference monitor measurement.

Mean absolute error (MAE):

$$MAE = \frac{1}{n}\sum_{i=1}^{n}|y_i - x_i|$$

Where n is the number of data pairs, y_i is the ith low-cost sensor measurement, and x_i is the ith reference monitor measurement.

Mean bias error (MBE):

$$MBE = \frac{1}{n}\sum_{i=1}^{n}(y_i - x_i)$$

Where n is the number of data pairs, y_i is the ith low-cost sensor measurement, and x_i is the ith reference monitor measurement.

Normalized mean bias (NMB):

$$NMB = \frac{\sum_{i=1}^{n}(y_i - x_i)}{\sum_{i=1}^{n} x_i}$$

Where n is the number of data pairs, y_i is the ith low-cost sensor measurement, and x_i is the ith reference monitor measurement.

Coefficient of variation (CV):

$$CV = \frac{\sigma}{\mu} = \frac{\sqrt{\frac{\sum(x_j - \mu)^2}{N}}}{\mu}$$

Where σ is the standard deviation of the measurements of all units, μ is the mean of the measurements of all units, N is the number of sensor units, and x_j is the measurement of the jth sensor.

Relative expanded uncertainty (REU):

The European Commission guide to the demonstration of equivalence of ambient air monitoring methods recommends the following equation to estimate the REU of low-cost sensors [10]:

$$REU(y_i) = \frac{2\sqrt{\frac{RSS}{n-2} - u^2(bs, RM) + u^2(bs, s) + [b_0 + (b_1 - 1)x_i]^2}}{y_i}$$

Where n is the number of pairs of collocated data (i.e., reference monitor and LCS), y_i is the low-cost sensor measurement, and x_i is the reference monitor measurement. The slope and intercept of a linear regression of y_i as a function of x_i are given by b_1 and b_0 respectively. RSS is the sum of the squared residuals and is calculated as:

$$RSS = \sum_{i=1}^{n} [y_i - (b_0 + b_1 x_i)]^2$$

$u(bs, RM)$ is the between reference method standard uncertainty. Values of this uncertainty are tabulated for many reference monitors. If not available, it is recommended to use a value of 0.67 µg/m^3. This was the case for our reference monitor.

$u(bs, s)$ is the between LCS standard uncertainty. When multiple units of the same sensor model are tested, $u(bs, s)$ can be estimated as:

$$u(bs, s) = \sqrt{\left(\frac{\sum_{l=1}^{N} \sum_{j=1}^{p} (y_{l,j} - \bar{y}_l)^2}{N(p-1)}\right)}$$

Where $y_{l,j}$ is the measurement of sensor unit j for period l. $\bar{y}_l$ is the mean for period l of all sensor units. N is the number of measurements over time. p is the number of collocated sensor units.

Relative expanded uncertainty (REU) plot

The REU plot aids in the qualitative and quantitative analysis of errors. The position of the point on the y-axis is a measure of the bias. The scattering of the points along the y-axis is a measure of noise.

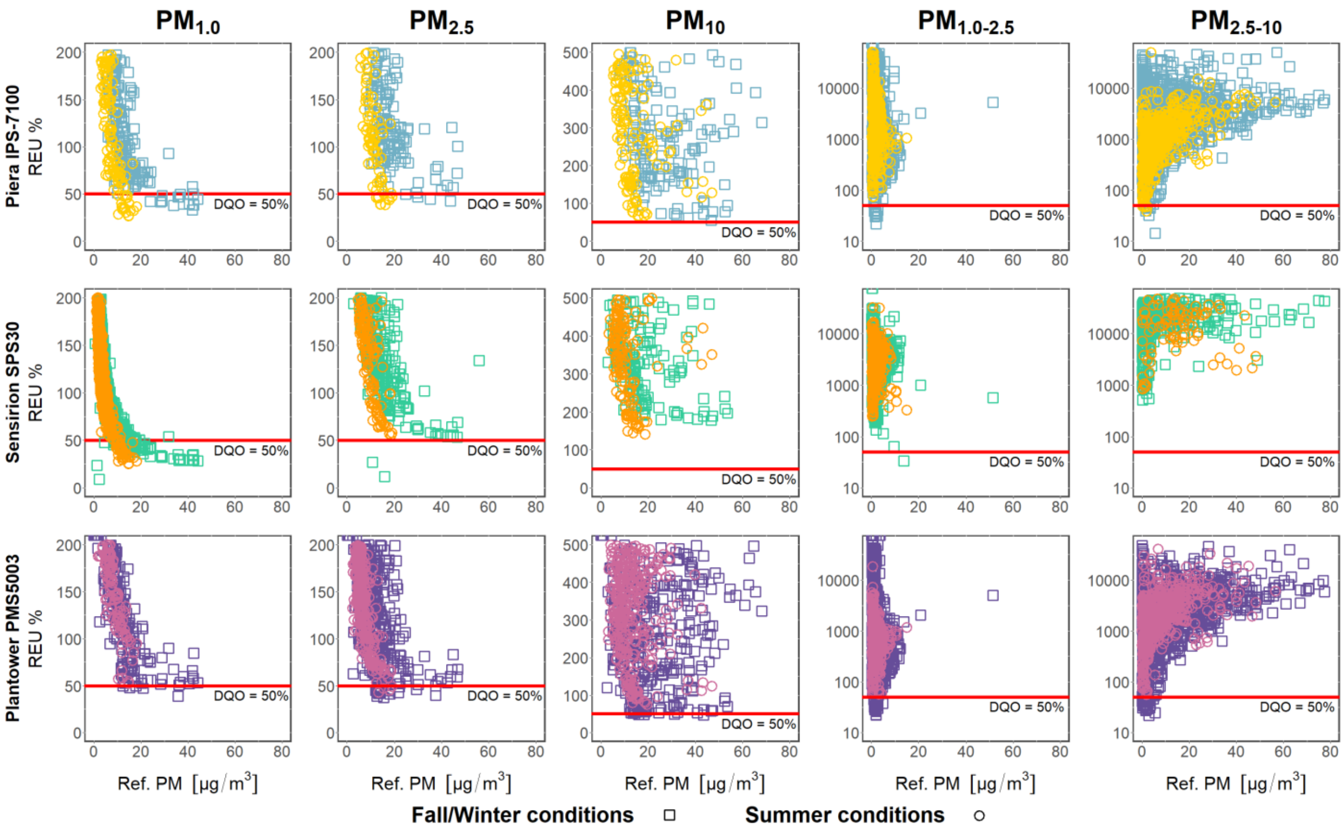

Figure S3. Relative expanded uncertainty (REU) plots for PM estimates from the low-cost sensors. Horizontal axes correspond to the GRIMM EDM180 measurements. The red line is the data quality objective established by the European Commission for low-cost PM sensors (points under the red line have adequate uncertainty). Some points are not shown in the plots due to the axes range.

Weather data during the evaluation

The first testing period (23-Nov-2021 to 09-Jan-2022) included late fall and early winter conditions with 13 inches of snowfall. Temperature ranged from -22°C to 23°C and relative humidity ranged from 0% to 77%.

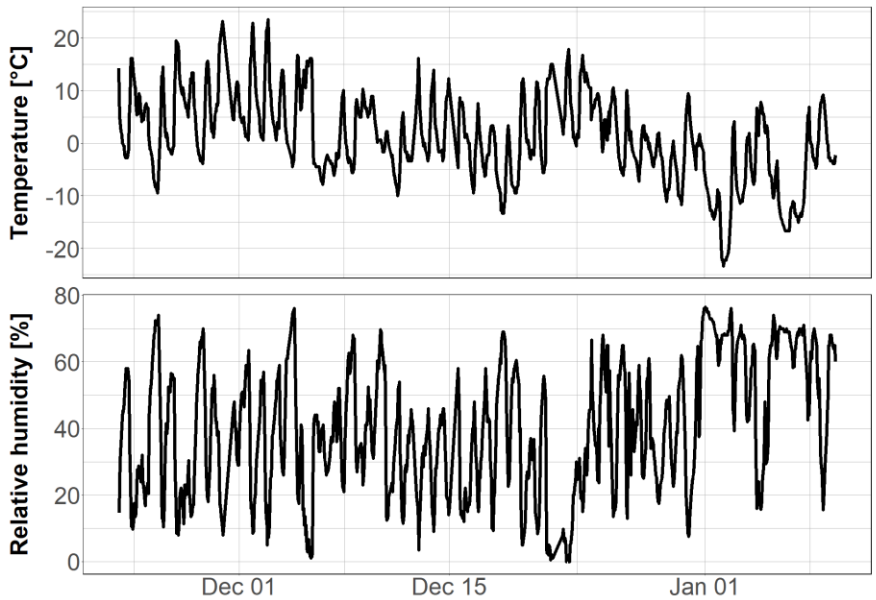

Figure S4. Ambient temperature and relative humidity at 1-hour resolution during the fall/winter campaign.

The second testing period (13-Jun-2021 to 30-Jul-2022) was comprised of summer conditions with temperature ranging from 11°C to 38°C and relative humidity ranging from 0% to 82%.

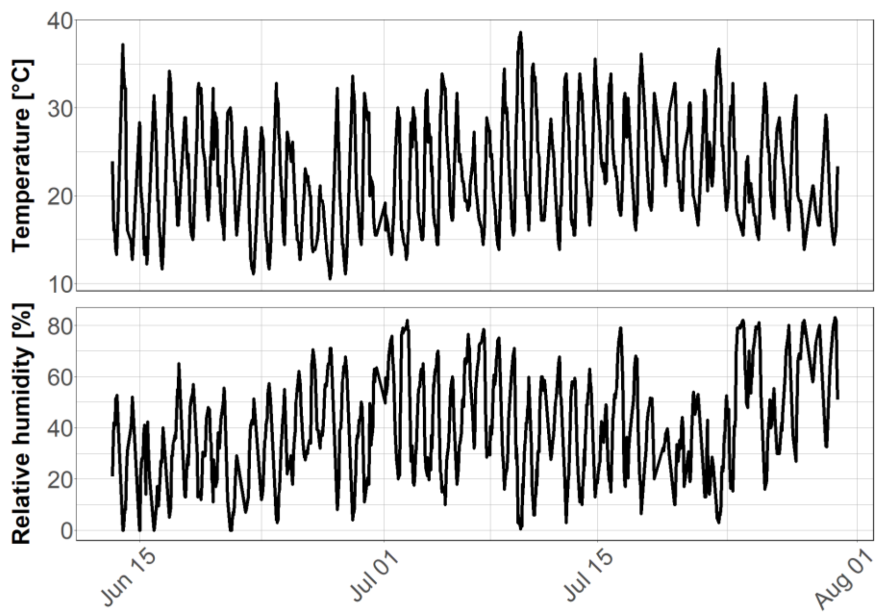

Figure S5. Ambient temperature and relative humidity at 1-hour resolution during the summer campaign.

GRIMM EDM180 vs. Thermo Scientific 5014i BAM $PM_{2.5}$ and PM_{10} data for quality assurance

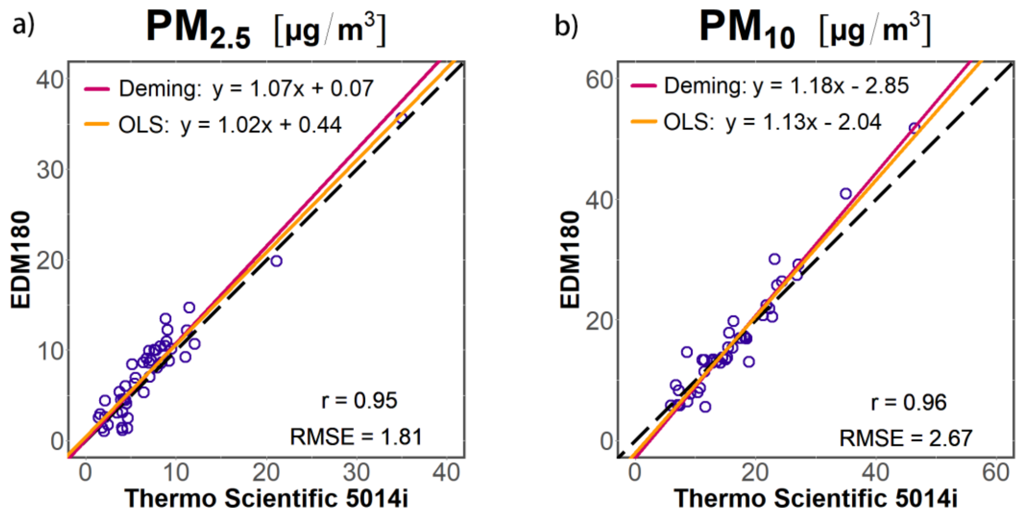

Figure S6. Scatterplots of $PM_{2.5}$ (left) and PM_{10} (right) daily concentrations for the GRIMM EDM180 (reference monitor) and the Thermo Scientific 5014i Beta-attenuation monitor (an FEM monitor). The dashed black line corresponds to the "1:1" relationship. Constant error was assumed for the Deming regression.

Time-series plot of the summer period

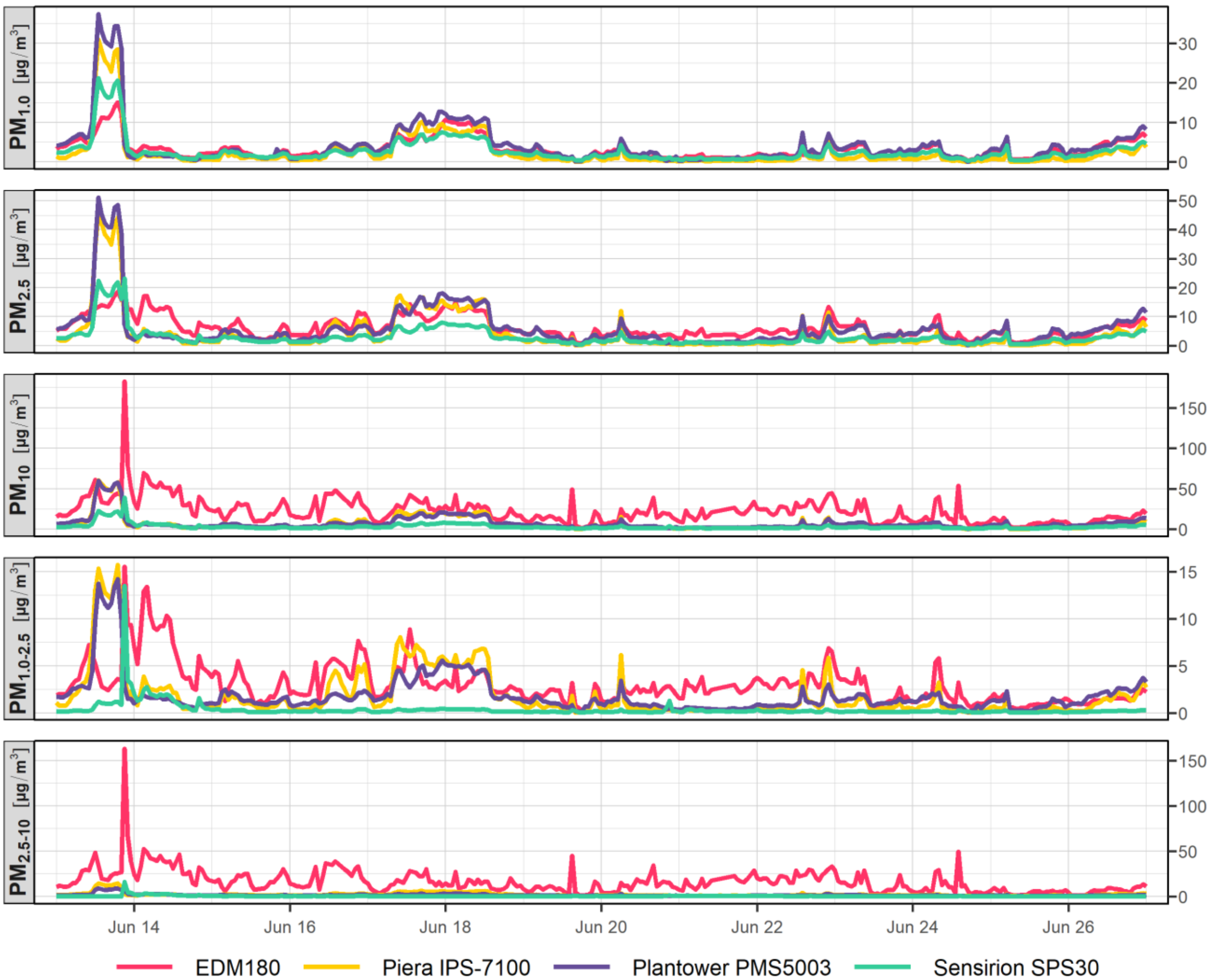

Figure S7. Time series graph of PM concentrations (cumulative and differential) during the first 14 days of the summer period.

Confidence intervals of regression model estimates

Table S2. Confidence intervals (2.5% to 97.5%) of the model parameters presented on Table 1. The models are linear regressions of the low-cost sensor vs. the reference monitor (EDM180).

	$PM_{1.0}$	$PM_{2.5}$	PM_{10}	$PM_{1.0-2.5}$	$PM_{2.5-10}$
Slope					
Piera IPS-7100	0.85 to 0.89	1.64 to 1.76	0.17 to 0.25	0.11 to 0.46	0 to 0.015
Sensirion SPS30	0.86 to 0.89	0.75 to 0.80	0.15 to 0.18	0.19 to 0.26	0.05 to 0.06
Plantower PMS5003	1.41 to 1.46	1.62 to 1.73	0.16 to 0.23	0.07 to 0.23	0 to 0.012
Intercept					
Piera IPS-7100	-1.67 to -1.41	-7.04 to -5.98	1.44 to 3.33	1.04 to 2.09	1.45 to 1.73
Sensirion SPS30	-0.62 to -0.45	-1.60 to -1.18	0.46 to 1.22	-0.26 to -0.05	-0.60 to -0.40
Plantower PMS5003	-1.17 to -0.84	-3.41 to -2.61	5.04 to 6.82	1.95 to 2.44	1.36 to 1.68

Residual plots of the linear models used in the study

Residual plots are mainly used to evaluate the assumptions of a linear model, such as homoscedasticity, independence, and normality. Qualitatively, a “good model” will have residuals that are uncorrelated (independent), normally distributed and centered around the zero line, and constant with respect to the magnitude of the predicted value (homoscedastic). Residuals that do not follow these patterns suggest one or more violations of the assumptions for a linear model (which is often the case for low-cost sensor data and increasingly evident in the larger size fractions).

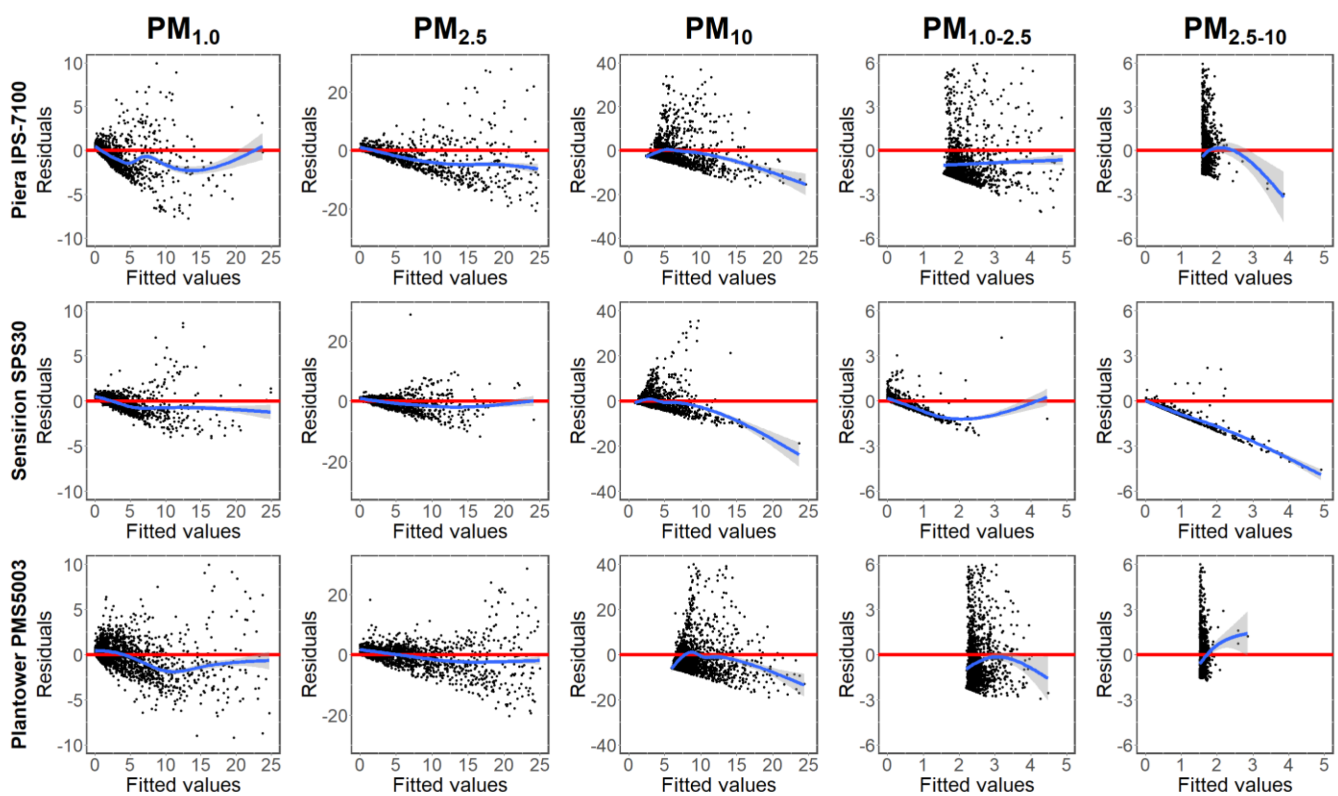

Figure S8. Residual plots corresponding to the low-cost sensor vs. reference monitor linear regression models presented in Figure 2 and mentioned throughout the manuscript. The horizontal red line represents perfect modeled-measured agreement across the range of fitted values; the blue lines represent a LOESS (locally estimated scatterplot smoothing) fit to the observed residuals.

Quantile-Quantile plots of the linear models used in the study

Quantile-Quantile plots are used to assess the normality assumption for a linear regression model. The distribution of the residuals (i.e., black dots) is compared against the expected distribution of residuals for an ideal model (i.e., red line). On a “good” Quantile-Quantile plot, the points sit close to the 1:1 line across the data range.

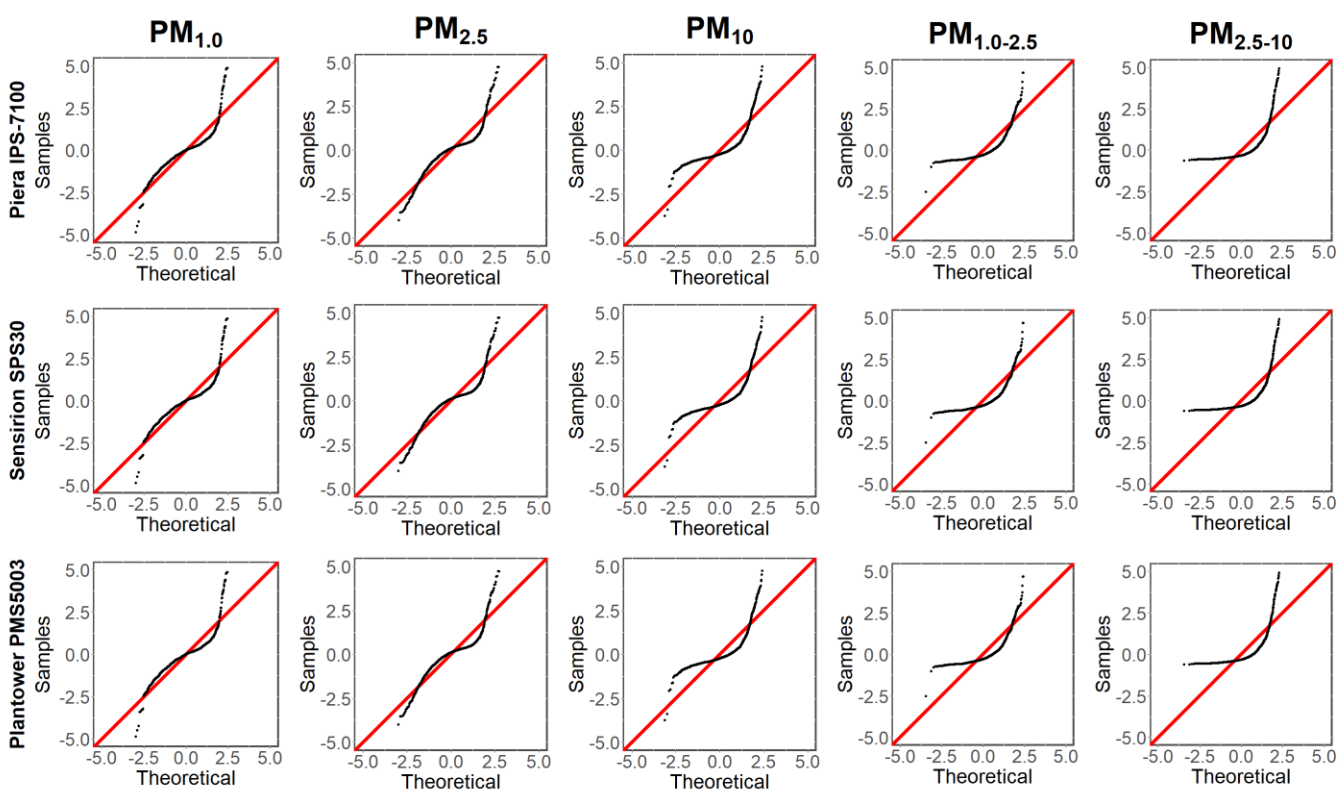

Figure S9. Quantile-Quantile plots corresponding to the low-cost sensor vs. reference monitor linear regression models presented in Figure 2 and mentioned throughout the manuscript.

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