Hindawi
Journal of Sensors
Volume 2018, Article ID 5096540, 16 pages
https://doi.org/10.1155/2018/5096540

Research Article

Evaluation of Low-Cost Sensors for Ambient $PM_{2.5}$ Monitoring

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Received 28 February 2018; Revised 3 June 2018; Accepted 30 July 2018; Published 31 October 2018

Academic Editor: Michele Penza

Low-cost sensors are an opportunity to improve the spatial and temporal resolution of particulate matter data. However, such sensors should be calibrated under conditions close to the final ones before any monitoring actions. The paper presents the results of a collocated comparison of four models of low-cost optical sensors with a TEOM 1400a analyser. SDS011 (Nova Fitness), ZH03A (Winsen), PMS7003 (Plantower), and OPC-N2 (Alphasense) sensors were used in this research. Three copies of each sensor model were placed in a common box to compare the sensor performance under the same measurement conditions. Monitoring of the $PM_{2.5}$ fraction was conducted for almost half a year from 21 August 2017 to 19 February 2018 in Wrocław (Poland). Reproducibility between sensor units was assessed on the basis of coefficient of variation (CV). CV values were lower than 7% in the case of SDS011 and PMS7003 sensors and equal to 20% for OPC-N2 units. CV was higher than 50% for ZH03A, mainly due to malfunctions. During the measurements, the trends of outputs from sensors were generally similar to TEOM data, but significant overestimation of $PM_{2.5}$ concentrations was observed for the sensor raw data. A high linear relationship between TEOM and sensors was noticed for 1 min, 15 min, and 1-hour averaged data for PMS7003 sensors ($R^2 \approx 0.83$–0.89), for SDS011 units ($R^2 \approx 0.79$–0.86), and for one unit of ZH03A ($R^2 \approx 0.74$–0.81). R^2 values for daily averages were at the level 0.91–0.93 for PMS7003, 0.87–0.90 for SDS011, and 0.89 for ZH03A. OPC-N2 had only a moderate linear relationship with TEOM ($R^2 \approx 0.53$–0.69 for daily data and 0.43–0.61 for shorter time averages). Quite large dispersion of data and high relative errors of $PM_{2.5}$ estimation were observed for concentration ranges below 20–30 $\mu g/m^3$. The impact of high relative humidity level was observed for SDS011 and OPC-N2 devices—clear overestimation of outputs was observed above 80% RH.

1. Introduction

Particulate matter (PM) is presently considered as one of the most serious air pollutants. PM could originate from natural sources (e.g., volcanic dust or desert dust particles and sea spray aerosols), but anthropogenic activities are also responsible for its emission. Transport, agriculture, industrial processes, and household fuel combustion can be considered the main sources of that contaminant [1].

The adverse health effects of particulates are nowadays well documented. Exposure to PM is linked mainly to respiratory and cardiovascular health effects [2–5]. Moreover, the International Agency for Research on Cancer (IARC) classified particulates as carcinogenic to humans [6].

Despite the fact that particulates may vary in origin, chemical composition, shape, or surface area, the harmful effects of PM are usually related to the size of particles. The particles with smaller aerodynamic diameters (d_a) have greater ability to penetrate into the lower parts of the respiratory tract. Coarse PM (particles with d_a in the range 2.5–10 μm) deposit mainly in the upper respiratory tract, and fine PM (particles with d_a below 2.5 μm) deposit throughout the respiratory tract and can penetrate to the lower parts and alveoli, whereas ultrafine particles (particles with d_a below

Table 1: Characteristic of PM sensors used in the research.

Sensor model	SDS011	ZH03A	PMS7003	OPC-N2
Manufacturer	Nova Fitness	Winsen	Plantower	Alphasense
Approximate price ($)	20	20	20	500
Dimensions (mm)	71 × 70 × 23	50 × 32.4 × 21	48 × 37 × 12	75 × 63.5 × 60
Approximate weight (g)	50	30	30	105
Power supply voltage (V)	5	4.5–5.5	4.5–5.5	4.8–5.2
Working current (mA)	220	70–140	≤100	175
Detectable size range (μm)	0.3–10	0.3–10	0.3–10	0.38–17
Size bins	Not available	Not available	6 size bins	16 size bins
Estimated PM_x concentration	$PM_{2.5}$, PM_{10}	PM_1, $PM_{2.5}$, and PM_{10}	PM_1, $PM_{2.5}$, and PM_{10}	PM_1, $PM_{2.5}$, and PM_{10}
Concentration range (μg/m^3)	0–999.9	0–1000 (for $PM_{2.5}$)	Effective range: 0–500 Maximum range: above 1000 (for $PM_{2.5}$)	0.01–1500·10^3 (for PM_{10})

0.1 μm) may cross the endothelial barrier and enter the blood [2–5]. The mass concentrations of PM_{10} (d_a below 10 μm) and $PM_{2.5}$ (d_a below 2.5 μm) are broadly used for air quality standard establishment and for assessing the air pollution levels.

Today, information about the current air quality is available to the public through websites or mobile apps (for example, [7]). High-quality data for such portals comes from the monitoring stations of governmental agencies, where automated measuring systems (AMS) are used. The most commonly used instruments are β-ray attenuation monitors (BAMs) and tapered element oscillating microbalances (TEOMs). These instruments are capable of measuring daily and hourly PM variation. However, the spatial coverage of monitoring stations is not very dense and nowadays new techniques are sought to improve the spatial and temporal resolution of PM data. Technological progress leads, among other things, to the development of miniaturized low-cost sensor devices and makes them promising tools for air quality monitoring application [8].

Currently, low-cost pollution monitoring is possible via different commercial sensors and a growth in the popularity of the use of such devices is observed worldwide [8–10]. Sensors for particulate matter measurements are also available in many types. The common feature of all commercial PM sensors is the principle of operation—they measure light scattered by particles carried in an air stream through a light beam. Prices of such optical sensors range from tens to hundreds of US dollars, because they are generally cheap to manufacture. In addition, PM sensors are easy to use and in many cases ready to connect to microcomputers. Because of this, they are often adopted for use by citizen scientists [9, 11, 12].

Another advantage of optical PM sensors is the low energy consumption—they require power supply voltage at the level of 5 V, and the working current is usually lower than 250 mA (see Table 1 for examples). They are also relatively small and light, and the output data could be collected with high frequency. For these reasons, they are good candidates for creating widely dispersed sensor networks [12–15]. That kind of monitoring may supplement the existing AMS infrastructure [9, 12].

Optical sensors have, however, a major drawback—the amount of scattered light is dependent on particle parameters: size, shape, density, and refractive index [16]. In other words, calibration factors obtained for one type of particulate matter (in most cases in laboratory conditions) may not be appropriate in the measurement environment. Therefore, PM sensors should be calibrated or recalibrated under conditions close to the final ones [17]. In the case of ambient air monitoring, the practical way to calibrate low-cost sensors is using collocated data from more recognized, higher-class, instruments [18]. Devices that meet regulatory requirements might be used for that purpose—for example, those that fulfil the criteria of European Standards EN 12341 [19] or EN 16450 [20]. Other types of control instruments, commonly used in low-cost sensor testing, are research-grade devices that were previously strictly tested, and their performance was reported in peer-review journals [21].

The article presents the results of a collocated comparison of four models of low-cost optical particulate matter sensors and a TEOM 1400a analyser. A great advantage of the TEOM device is the possibility of near real-time monitoring (at the level of minutes) [22]. This type of equipment is widely used in regulatory monitoring stations and for scientific research, especially for PM_{10} monitoring [23, 24]. Furthermore, TEOM 1400a proved to be also useful in $PM_{2.5}$ measurements [25] and in low-cost sensor testing campaigns [26, 27].

PM sensors were evaluated in several respects. Firstly, the operational stability of sensors was checked. This property is especially important for measurement systems dedicated to long-term monitoring. In case of low-cost PM sensors, accumulation of particles inside the measuring chamber could be the main cause of sensor aging. Moreover, severe meteorological conditions (e.g., high humidity or extreme temperatures) can affect the functioning of electronics. In fact, many sensor models are dedicated strictly to indoor environments and special attention should be paid when they are used outdoors [28].

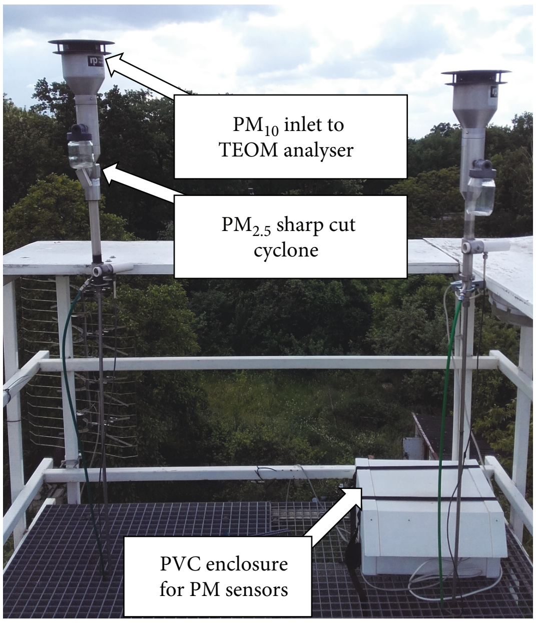


Figure 1: The placement of the PM sensor measurement box and TEOM inlet.

Secondly, the precision of sensors was tested in terms of reproducibility between units of the same sensor model (so-called intramodel variability). Calibration efforts of devices with high reproducibility are considered smaller, because they do not have to be calibrated individually.

Thirdly, the relationship to TEOM instrument and linearity of sensor responses were assessed. Linear responses are favourable in case of many measurement devices, because they simplify calibration procedures.

Additionally, the performance of sensor operation in air with high relative humidity (RH) was examined. The impact of humidity is particularly important for monitoring of ambient air, where large variations of that parameter occur. Some sensors seem affected by humidity, and their performance may deteriorate in very humid air [21].

All these features were considered as crucial for the end-users and for the creators of sensor systems and distributed sensor nets.

2. Materials and Methods

2.1. Measurement Site Description. Measurements were carried out at the Meteorological Observatory of Department of Climatology and Atmosphere Protection of University of Wrocław (the location is presented in Figure S1 in the Supplementary Material). The observatory is located in an area of detached houses and allotments, close to the large city park (about 100 ha of land). Emission sources of particulate matter are related mainly to individual heating systems in households and, to a lesser extent, city road transport. There are no large point sources of particulate emission nearby.

The Observatory is equipped with PM_{10} and $PM_{2.5}$ measuring instruments (TEOMs); however, PM_{10} instruments were out of service during this campaign.

2.2. Measurements of $PM_{2.5}$ Fraction. $PM_{2.5}$ was measured by means of a TEOM 1400a analyser (Rupprecht & Patashnick Co., USA) and low-cost PM sensors, placed in a measurement box. TEOM was equipped with a PM_{10} inlet with $PM_{2.5}$ sharp cut cyclone. The instrument also used a heated flow tube (40°C) to lower the RH and remove moisture droplets from the sampled air. In this type of device, sampled air is drawn through a filter, attached to the end of a hollow tapered glass tube. The tube is maintained in oscillation by an electronic feedback system. Particulates deposited on the filter decrease the frequency of oscillation of the tube, and this change is used to determine the PM mass increase. The device calculates PM mass concentration by dividing the obtained mass by the air flow rate [23]. TEOM provided 1-minute averaged data, stored in the database. To maintain the accuracy of the device, the service and calibration were performed annually by authorised service personnel.

PM sensors were enclosed in a PVC box (56 × 50 × 26 cm) with a rainproof lid. The airflow through the box was possible by means of two air inlets (13 × 10 cm), located at one wall of the housing, and a fan, mounted at the opposite wall. Air inlets were fitted out with mesh filters to provide protection against insects. The box was fastened to the measurement platform, below TEOM intake (see Figure 1). The distance between the inlet of the measurement box and the inlet of TEOM was approximately 1.5–1.8 m.

Four commercially available PM sensors were chosen for this research: SDS011 (Nova Fitness Co. Ltd., China), ZH03A (Zhengzhou Winsen Electronics Technology Co. Ltd., China), PMS7003 (Beijing Plantower Co. Ltd., China), and OPC-N2 (Alphasense, UK). A short characteristic of those devices is shown in Table 1.

SDS011, ZH03A, and PMS7003 sensors were chosen mainly because of their low price (≤20$) and small size. The earlier versions of Plantower sensors (i.e., PMS1003, PMS3003, and PMS5003) were evaluated as promising tools for $PM_{2.5}$ monitoring [29–31]; however, high air humidity influenced the sensor outputs [32, 33]. The SDS011 sensor from Nova Fitness also demonstrated its usefulness for particulates measurements, but in a portable version [34]. Based on the knowledge of the authors, the performance of ZH03A sensors (Winsen) has not been tested in scientific literature so far.

SDS011, ZH03A, and PMS7003 sensors compose of a small measurement chamber with light source (light emitting diode), light receptor (photodiode detector), and a set of focusing lenses. The airflow through every sensor is possible by means of a microfan. The output signals are digital and have a form of mass concentration, mainly for $PM_{2.5}$ and PM_{10} fractions. All output values are determined on the basis of light scattering intensity by algorithms implemented in sensors, but the details of the calculations are not provided by the manufacturers. PM mass concentration for Plantower PMS7003 is also available with so-called atmospheric environment correction factor ("AE"). Moreover, this sensor provides the number of particles per unit volume for 6 size bins. In case of all the tested low-cost sensors, the factory calibration procedures were not specified in the data sheets.

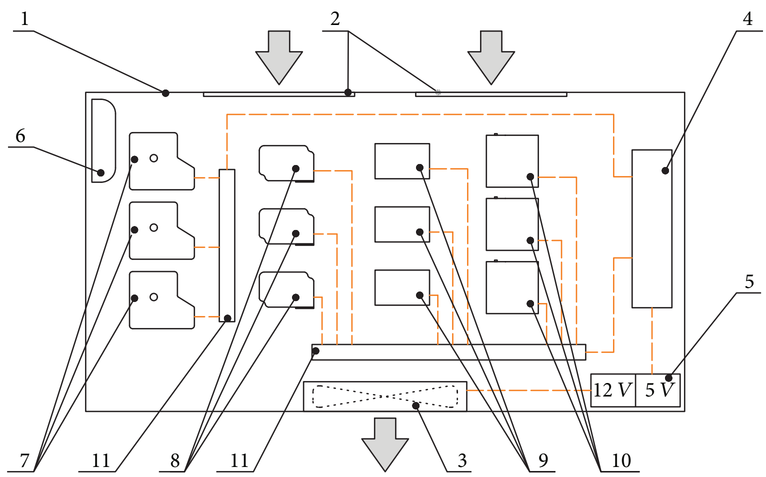


Figure 2: Schematic of PM sensor measurement setup: 1—PVC enclosure, 2—air inlets with mesh filters, 3—air outlet with fan, 4—Raspberry Pi microcomputer, 5—power suppliers, 6—temperature and humidity datalogger, 7—OPC-N2 sensors (Alphasense), 8—ZH03A sensors (Winsen), 9—PMS7003 sensors (Plantower), 10—SDS011 sensors (Nova Fitness), and 11—USB hubs. Figure 2 is reproduced from Badura et al. [38] (under the Creative Commons Attribution License/public domain).

OPC-N2 devices were selected as representatives of the higher-price segment (~500$). Their performance was evaluated both in the laboratory [35] and in the field conditions [36, 37]. The results presented in the literature were promising, although high ambient RH affected sensor performance [36].

OPC-N2 enclosure is a little bigger compared to previously described sensors, and they use an embedded diode laser light source that operates at a wavelength of 658 nm. Every OPC-N2 uses an elliptical mirror and dual-element photodetector, and the airflow is produced also by a small fan. Those devices are referred to as optical particle counters, and they classify particles to one of 16 size bins. The resulting particle size histograms are used to determine the mass concentration for PM_1, $PM_{2.5}$, and PM_{10} fractions. The calculations are made with assumptions of particle density (1.65 g/cm^3 by default) and refractive index (1.5 by default). OPC-N2 sensors are laboratory-calibrated using Polystyrene Spherical Latex Particles of a known diameter and known refractive index. Correction factors can be applied by the user when properties of particulates are known. In this study, the default values from the manufacturer were adopted.

The measurement setup consisted of three copies of each sensor model. Sensor units were mounted to a PVC board at a distance of a few centimetres from each other. Multiport USB hubs were used to connect the sensors with a Raspberry Pi microcomputer. All electronic connectors were coated with an anticorrosion agent. Sensor signals were read with a 1- or 2-second resolution and averaged in 1-minute intervals. Averaged data was stored in the database for further analysis. Two power supplies were utilized in this setup: 5 V for the microcomputer and 12 V to power the fan in the box. Temperature and relative humidity were measured inside the box by means of AR235 datalogger (APAR, Poland). A schematic of the described arrangement is shown in Figure 2 [38]. The applied setup allowed the comparison of the sensor performance under the same measurement conditions.

3. Data Analysis

3.1. Data Preparation. For the purpose of this research, data registered from 21 August 2017 to 19 February 2018 was used. To examine the relationship between TEOM and sensors, only sensor outputs related to the $PM_{2.5}$ mass concentration were taken into account. It was assumed that factory $PM_{2.5}$ outputs, determined by the sensor manufacturers, should reflect the $PM_{2.5}$ concentration in the best way.

TEOM and sensor signals were analysed in different time scales: (1) 1 minute, (2) 15 minutes, (3) 1 hour, and (4) 24 hours. The first two data types represent the short-time measurements, especially useful for indication of elevated PM concentration events or "hot-spots." The latter two are the most popular in informing the public about air quality. In every case, the averaging was made only for data sets with at least 75% completeness. Data analysis was performed in a MATLAB environment.

3.2. Reproducibility between Units. Precision of sensors could be assessed in terms of repeatability of measurements of a particular sensor unit and reproducibility of units of the same sensor model. Estimating the repeatability of PM sensors is very difficult in nonlaboratory conditions due to problems in maintaining constant particle type and concentration [17]. For this reason, only the variability of output signals from copies of the same sensor model (intramodel variability) was evaluated in this study.

Firstly, to visualize the dispersion of the data, scatterplots of sensor unit outputs versus the mean value of the 1-minute averaged data were presented. Secondly, the percentage coefficient of variation (CV) was calculated. For every sensor model, the temporary coefficient of variation was calculated as

$$CV_{(t)} = 100 \cdot \frac{\sigma}{\mu}, \%, \quad (1)$$

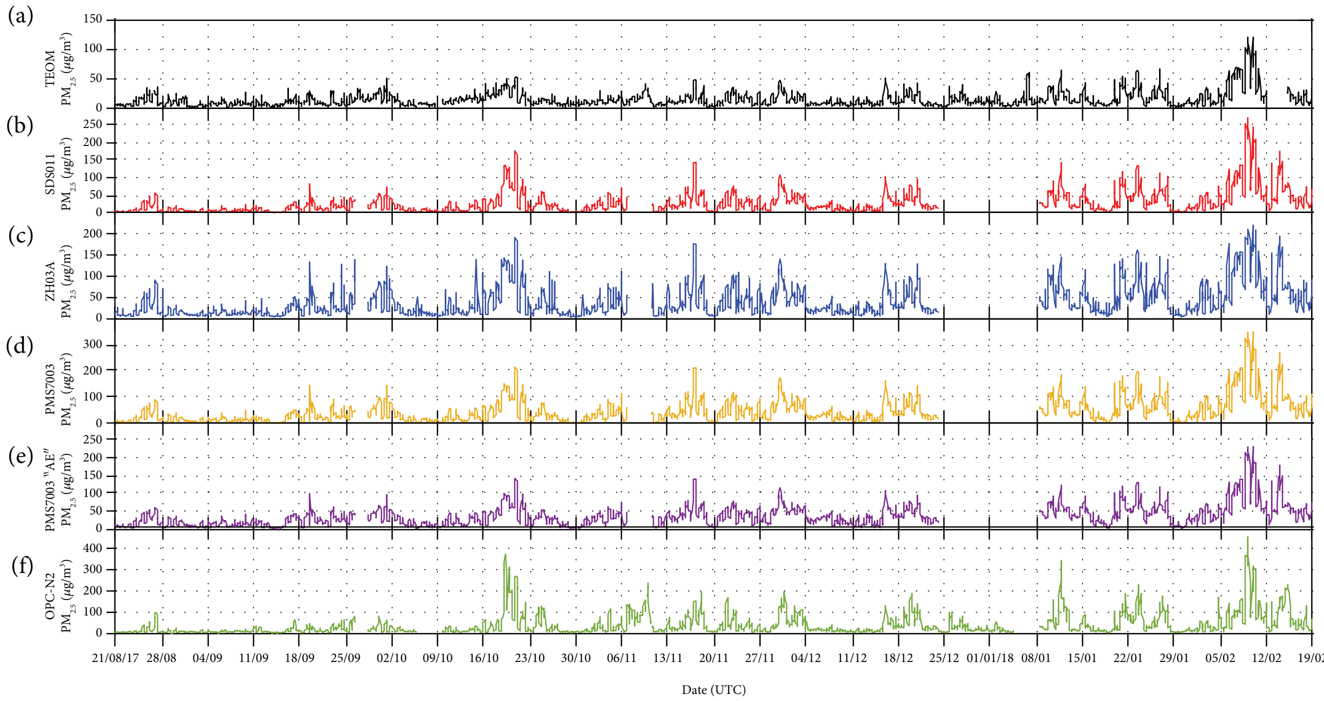


Figure 3: Results of $PM_{2.5}$ measuring campaign: (a) TEOM 1400a analyser, (b) SDS011 (Nova Fitness), (c) ZH03A (Winsen), (d) PMS7003 (Plantower), (e) PMS7003 "AE" (Plantower), and (f) OPC-N2 (Alphasense). 1-hour averaged data for selected sensors was plotted for clarity. Please note the different scales on the y-axes.

where σ is the standard deviation and μ is the mean of the 1-minute averaged data from units of the same sensor model. The final CV value for each model was determined as the average of all temporary $CV_{(t)}$ values. Sensors with low CV values are characterized with high reproducibility. The CV value below 10% is considered acceptable in the low-cost sensor testing studies [35, 39, 40].

3.3. Relationship between Sensors and TEOM Control Measurements. The relationship to TEOM control measurements was assessed on the basis of coefficient of determination (R^2) from ordinary least-squares regression fittings. Linear regression models were assumed with TEOM readouts as dependent variable and PM sensor data as predictor variables. The R^2 value near 1 reflects very good agreement with control measurements and linearity of responses. Small R^2 values indicate poor relationship.

Calculations between sensors and TEOM were made for all considered time scales. Pairwise matched data was used in every case.

3.4. Influence of $PM_{2.5}$ Concentration Range on Sensor Performance. Parameters of linear functions (slopes and intercepts) from regression fittings were used to calibrate the low-cost sensors. Afterwards, the distribution of relative error of $PM_{2.5}$ estimation over the measured mass concentrations was examined. On the basis of obtained results, the relationship between TEOM and PM sensors was considered for different $PM_{2.5}$ concentration ranges: low ($\leq 20\,\mu g/m^3$), medium (20–60 $\mu g/m^3$), and high ($>60\,\mu g/m^3$). Combined ranges were taken into account too. Calculations for 15 min and 1-hour time scales were made as an example.

3.5. Influence of Air Humidity Level on Sensor Performance. Conditions of a high air humidity can affect the performance of optical PM sensors in several ways. The first group of problems is related to a failure of the electronic circuits in a very moist environment. This can lead to biased measurement results or damage of sensors [41]. The second group of problems is associated with particle properties and the principle of operation of light-scattering devices. The hygroscopic growth of some particles (e.g., hygroscopic salts) is the most discussed cause of overestimated outputs and large positive artefacts in sensor signals [36, 42]. Moreover, in conditions close to the 100% RH, the formation of fog or mist may occur and the water droplets may be detected as particles [33]. The absorption of infrared radiation by water was described as responsible for deterioration of sensor performance too [41].

The purpose of this research was the evaluation of sensor performance in ambient air with variable humidity. The mechanisms that affect the operation of PM sensors in humid air were beyond the scope of this study. The RH level, above which the overestimation of particles concentration appears, was previously reported as 70%–75% [33, 42], in some cases even 60% [43], but the level of 85%–95% was also very often documented [28, 36].

In this study, sensor performance was tested in three ranges of relative humidity: (1) below 80%, (2) between 80% and 90%, and (3) above 90%. The comparison of

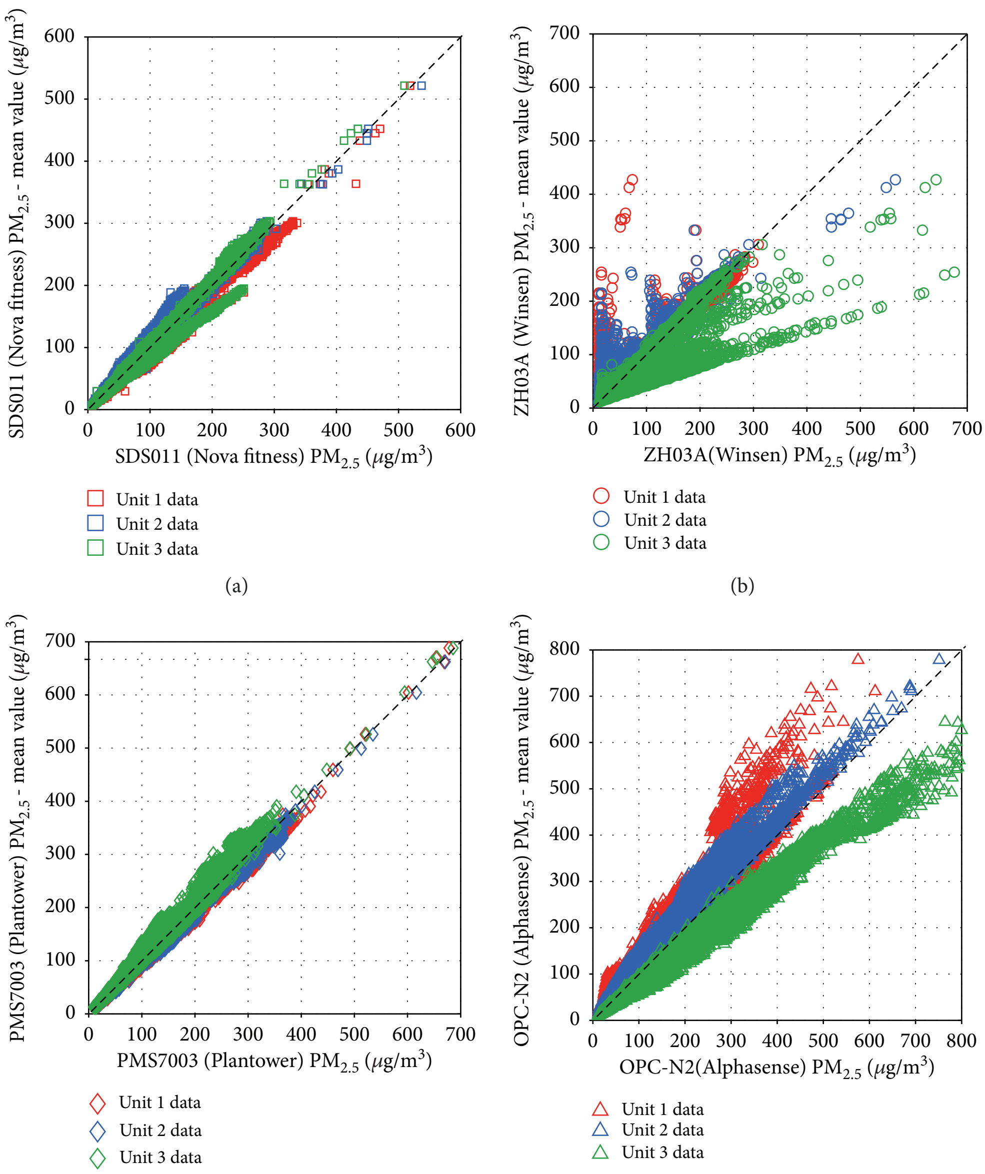


FIGURE 4: Scatterplots of sensor unit outputs versus the mean values of the 1-minute averaged data: (a) SDS011 (Nova Fitness), (b) ZH03A (Winsen), (c) PMS7003 (Plantower), and (d) OPC-N2 (Alphasense). Dashed lines denote the ideal relationship.

parameters of linear functions (slope and intercept) was made to assess the impact of RH level. Calculations for 15 min and 1-hour averages were made as an example.

4. Results and Discussion

4.1. Evaluation of PM Sensor Operation Stability. Figure 3 presents the results of $PM_{2.5}$ measurements for the period of 26 weeks (from 21 August 2017 to 19 February 2018). For the sake of clarity, 1-hour averaged data was presented. In case of PM sensors, outputs from only one selected copy of each model were plotted. Data gaps for TEOM device (Figure 3(a)) were related to power outages or maintenance activities. Power failures were also partly responsible for data losses from PM sensors (Figures 3(b)–3(f)). In addition to this, problems with USB hubs and data transfer to the database were observed.

TABLE 2: Coefficients of variation (CV, %) for tested PM sensors.

Sensor model	SDS011	ZH03A	PMS7003	PMS7003 "AE"	OPC-N2
CV, %	6.53	54.1* /10.8**	6.74	5.94	20.0

*CV calculated only for two units for the period 21 August 2017–24 December 2017; **CV calculated for three units after replacement of unit no. 1 and no. 2 on 08 January 2018.

All measurements were conducted under varying meteorological conditions. Sensors were exposed to temperatures in the range from −8°C to +36°C and relative humidity in

Table 3: Coefficients of determination (R^2) for tested PM sensors at different time scales.

Sensor model	SDS011			ZH03A			PMS7003			PMS7003 "AE"			OPC-N2		
Unit	1	2	3	1*	2**	3	1	2	3	1	2	3	1	2	3
1 min	0.79	0.83	0.80	—	0.70	0.74	0.85	0.85	0.83	0.83	0.83	0.80	0.59	0.43	0.46
15 min	0.80	0.85	0.81	—	0.71	0.77	0.87	0.87	0.85	0.85	0.85	0.81	0.60	0.44	0.47
1 hour	0.82	0.86	0.83	—	0.73	0.81	0.88	0.89	0.86	0.87	0.86	0.83	0.61	0.44	0.48
24 hours	0.88	0.90	0.87	—	0.78	0.89	0.93	0.93	0.91	0.91	0.91	0.88	0.69	0.53	0.59

*Unit no. 1 was excluded from calculations due to malfunction; **R^2 calculated for the period 21 August 2017–24 December 2017, before sensor replacement.

the range of about 27%–94% (parameters measured inside the measurement box). These conditions have not affected the data availability or electronic parts of sensors.

The maximum value of 1 min averaged outputs from TEOM was 145 μg/m^3, and for 1-hour data it was at the level of 120 μg/m^3. No saturation effect was observed for the tested PM sensors in the range of registered data. In general, the operation of tested PM sensors was stable throughout this 6-month study. Problems were observed only for Winsen ZH03A sensors. Unit no. 1 of that device was stable only for about three weeks, and after that time, the outputs did not correlate with other units. Failure of unit no. 2 was also noticed—this copy was stable for about eleven weeks. Units 1 and 2 were replaced by new specimens on 08 January 2018.

4.2. Reproducibility between Units. Figure 4 presents the relationships between signals of sensors units and the mean values of their 1-minute data. The smallest scatter between units was observed for the PMS7003 sensor from Plantower (Figure 4(c)). Slightly smaller results were recorded only for unit no. 3.

Units of SDS011 (Nova Fitness) were also characterized with high reproducibility (Figure 4(a)), but some part of the data was distant from the ideal relationship. The reason for this may be the high humidity of air (see Figure S2 in the Supplementary Material and further discussion).

OPC-N2 units were also characterized with high variability (see Figure 4(d)). Outputs from unit no. 3 were especially distant from other unit signals. The impact of humidity level was not so clearly observable in this case, due to the overall large data scatter.

In case of Winsen ZH03A units, high dispersion of data (Figure 4(b)) resulted from malfunctions of two units. Presumably, the accumulation of particles could be responsible for that situation.

These observations were confirmed by the values of coefficients of variation (see Table 2). The best reproducibility in the full measurement period was observed for Nova Fitness SDS011 and Plantower PMS7003 units. In both cases, the mean CV values were below 7%, so they met the acceptable level of sensor variations (10% [35, 39, 40]). In case of Plantower PMS7003, slightly better results were obtained for the signals with "AE" correction factor (CV below 6%). Good repeatability between Plantower sensors was also previously reported for air quality monitors with earlier versions of that sensor (PMS1003 [29], PMS3003 [30], and PMS5003 [31]).

Very high CV value was calculated for Winsen units—54.1%. This value represents only the reproducibility for two copies of that sensor (unit no. 2 and no. 3), before the replacement action on 08 January 2018. Unit no. 1 was excluded from the first calculations, because of its malfunction. CV at the level of 11% was computed for unit no. 3 and new units (no. 1 and no. 2) after the replacement. This result can be considered decent, but it represents only the 6-week measurement period.

In this campaign, Alphasense OPC-N2 counters were characterized with only moderate precision (CV value equal 20%). A previously reported laboratory evaluation of OPC-N2 sensors [35] revealed quite good reproducibility between units (CV between 4.2% and 16%). On the other hand, field evaluations of OPC-N2 [36, 37] demonstrated modest intramodel variability, with CV values higher than 20% [36]. Taking into account the cost of OPC-N2 (several times higher than other sensors), its usefulness in widely dispersed sensor networks for $PM_{2.5}$ monitoring may be considered as limited.

4.3. Relationship between Sensors and TEOM Control Measurements. Taking into account the whole measurement period, the trends of outputs from PM sensors were generally similar to TEOM data. What is important, the occurrence of episodes of elevated $PM_{2.5}$ concentrations could be readily observed from signals of each tested sensor (e.g., episode from 05 February 2018 to 12 February 2018 in Figure 3). Nevertheless, raw outputs from sensors overestimated TEOM data by a factor of about 2.5 in case of Nova Fitness devices, 3 for Winsen units, 3.5 for Plantower, and 4.5–5 for OPC-N2 sensors.

On this occasion, it should be mentioned that TEOM can underestimate PM concentrations, because of the use of the heated inlet [41]. This situation could lead to the loss of the semivolatile constituents of ambient particles [42, 43]. Generally, TEOM 1400a tracked well the variations of $PM_{2.5}$ mass concentration observed by means of a BAM analyser from the nearest governmental air quality station (Figure S3 in the Supplementary Material). The correlation between data sets was very high for nonheating periods (Figure S3a), but in heating periods, the outputs from TEOM were around 30%–40% lower than results from BAM (Figure S3b). However, it has to be taken into account that the governmental urban background station was located within 5 km from the TEOM measuring point (see Figure S1) and some different sources of $PM_{2.5}$ emission occurred in its

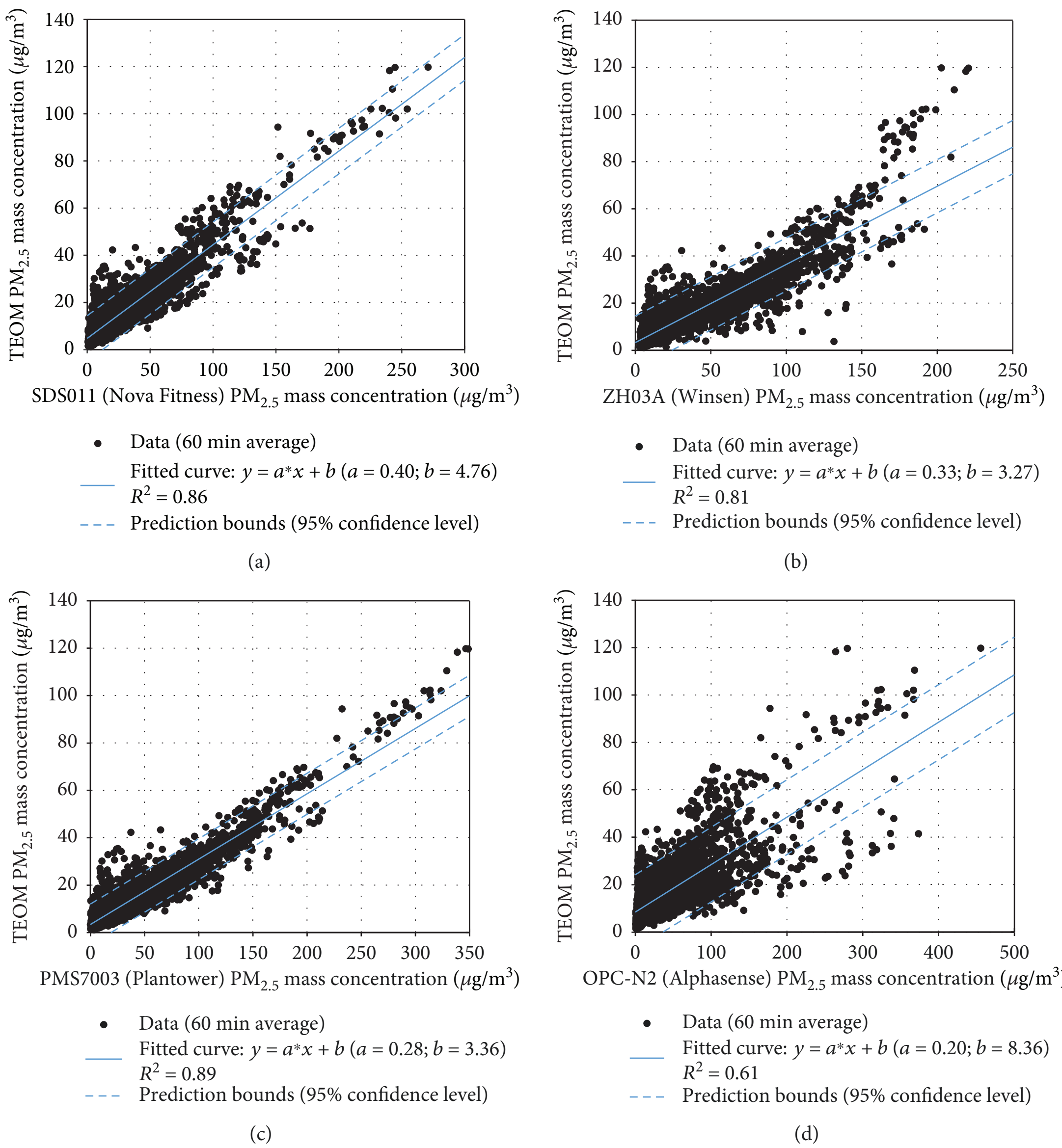


Figure 5: Results of linear fittings for 1-hour averaged data: (a) SDS011 (Nova Fitness), (b) ZH03A (Winsen), (c) PMS7003 (Plantower), and (d) OPC-N2 (Alphasense).

vicinity. During this research campaign, TEOM was highly linearly correlated with this measuring station: Pearson's correlation coefficient was at the level of 0.91 and coefficient of determination at the level of 0.81 for 1-hour averages (see Figure S4). For this reason, TEOM was considered a sufficient source of information about $PM_{2.5}$ changes and sufficient to assess the linearity of sensor outputs.

Table 3 presents the coefficients of determination (R^2) from linear regression fittings between TEOM and sensor outputs. The best results were obtained for Plantower sensors, for all adopted averaging times. The level of 0.83 to 0.87 was achieved for short-time averages (1 min and 15 min). R^2 values nearly 0.9 were calculated for 1-hour means, and the level of 0.9 was exceeded for daily averages. It should be noted that Plantower outputs with "AE" correction factors were highly correlated to data without that factor (Pearson's correlation coefficients at the level of 0.99), but their relationship to TEOM was somewhat lower.

Previously reported evaluations of earlier versions of Plantower sensors showed also quite high linear correlations with comparison instruments: $R^2 > 0.57$ for 1-hour data and $R^2 > 0.66$ for 24-hour data from air quality monitor with PMS3003 [30], $R^2 > 0.71$ for 1-hour data and $R^2 > 0.77$ for daily data for instrument with PMS5003 sensor [31], and $R^2 > 0.8$ for 1-hour averages and $R^2 > 0.88$ for 24-hour data, when PMS1003 sensors were used [29].

Nova Fitness SDS011 sensors showed also high linearity to TEOM data. Coefficients of determination for 1 min, 15 min, and 1-hour data were at the level of about 0.8. The R^2 value around 0.9 was obtained for 24-hour averages.

In case of Winsen ZH03A sensors, only unit no. 3 was observed to be stable during the whole measurement period.

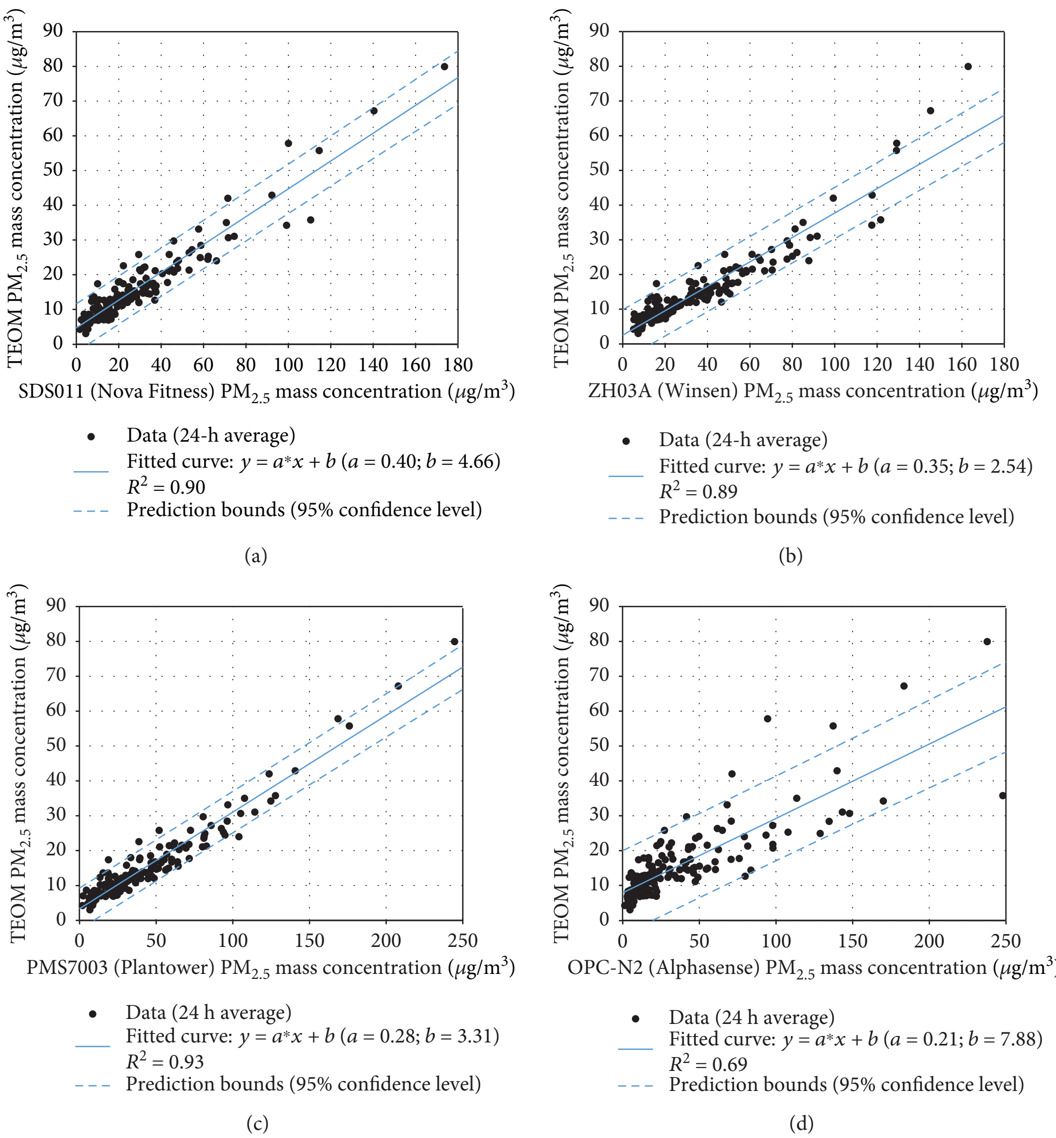


FIGURE 6: Results of linear fittings for 24-hour averaged data: (a) SDS011 (Nova Fitness), (b) ZH03A (Winsen), (c) PMS7003 (Plantower), and (d) OPC-N2 (Alphasense).

R^2 values were equal to 0.74 and 0.77 for 1 min and 15 min mean, respectively. The R^2 level of 0.8 was achieved for 1-hour time scales and nearly 0.9 for 24-hour averages. Unit no. 2 was used only to 24 December 2017, and the fitting results were a little bit lower than in the previous case. Overall, fitting results for ZH03A were satisfactory, but above the level of about 60 μg/m^3 data significantly deviated from the linear model (see Figure 5(b)).

Alphasense OPC-N2 sensors demonstrated only moderate linear relationship with TEOM. R^2 values reached the level of 0.5–0.7 for 24-hour averages and 0.4–0.6 for shorter time scales. OPC-N2 sensors were characterized with some variability between units, and quality of fittings for sensor no. 1 was slightly better than for other units. The relationship between TEOM and OPC-N2 devices was more similar to power-law function, but the quality of such fittings was also moderate because of large dispersion of data. Nonlinear characteristics of OPC-N2 sensors and moderate correlation with control measurements were also reported in [37].

In case of all PM sensors, characteristic temporary peaks were observed for data averaged in short-time scales. For that reason, it was assumed that sensor outputs should be smoothed by averaging for at least 15 minutes when they are used for ambient air monitoring. This period of time should be sufficient to detect short-term pollution events. Averaging in longer time periods (1 hour, 24 hours) could be also useful, particularly to preserve consistency with data from typical governmental measurement stations. Examples of relationships between TEOM and PM sensors are presented in Figures 5 and 6 for 1-hour and 24-hour averaging, respectively. Only results from units with the highest R^2 values were presented.

Tables S1–S4 in the Supplementary Material present the computed parameters of linear models for all averaging

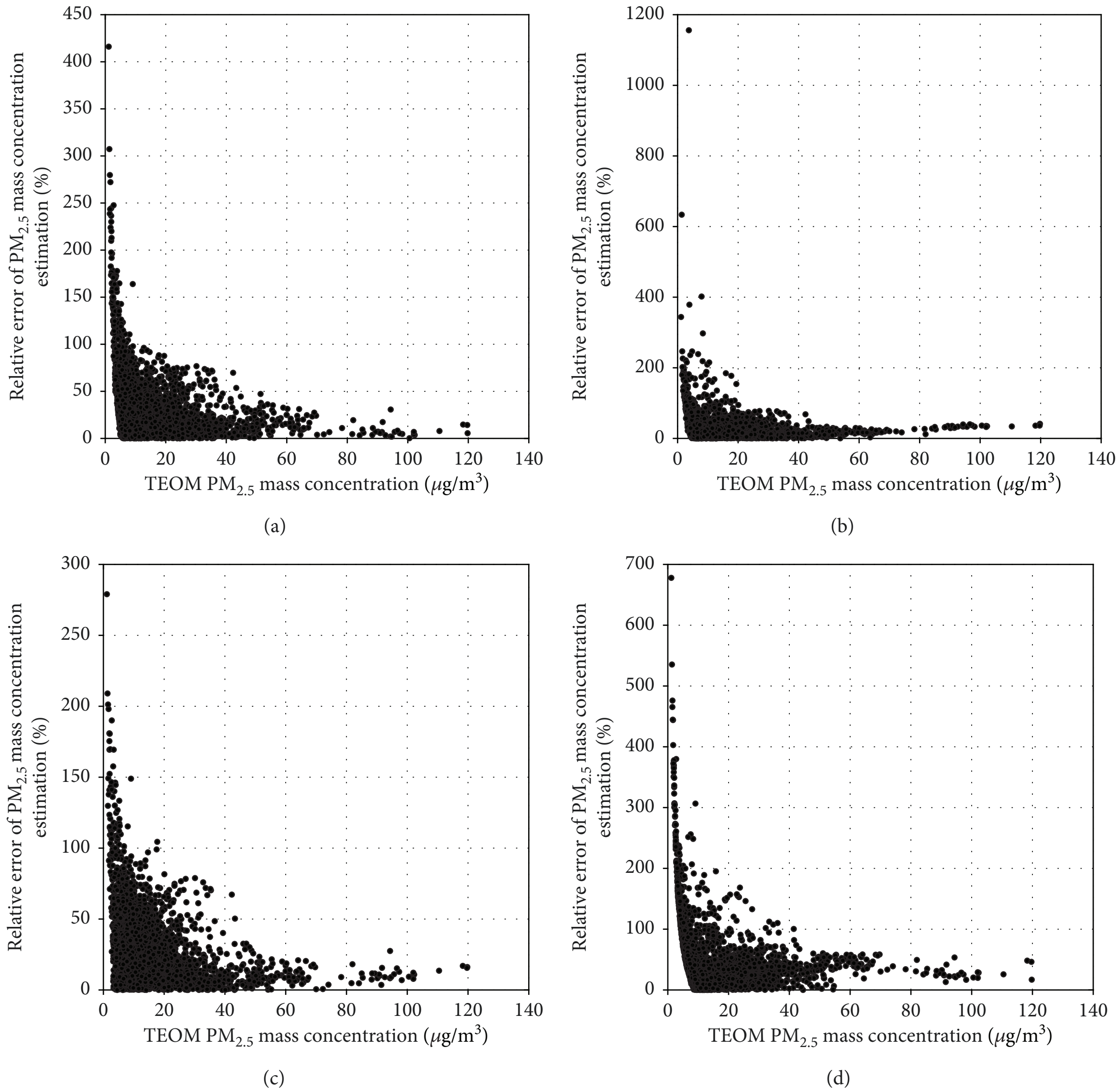
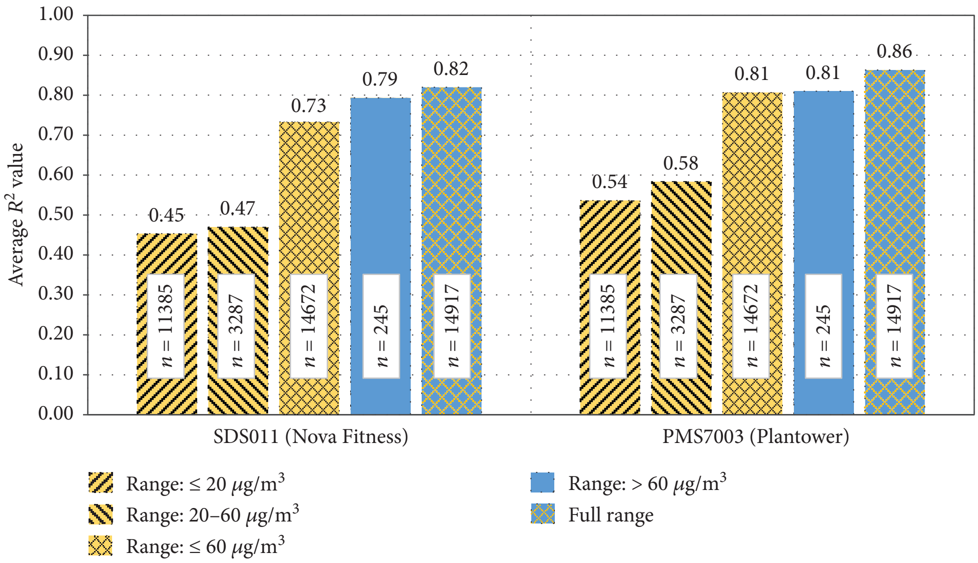


FIGURE 7: The distribution of relative error of $PM_{2.5}$ estimation over the mass concentrations measured by TEOM in case of (a) SDS011 (Nova Fitness), (b) ZH03A (Winsen), (c) PMS7003 (Plantower), and (d) OPC-N2 (Alphasense). Please note the different scales on the y-axes.

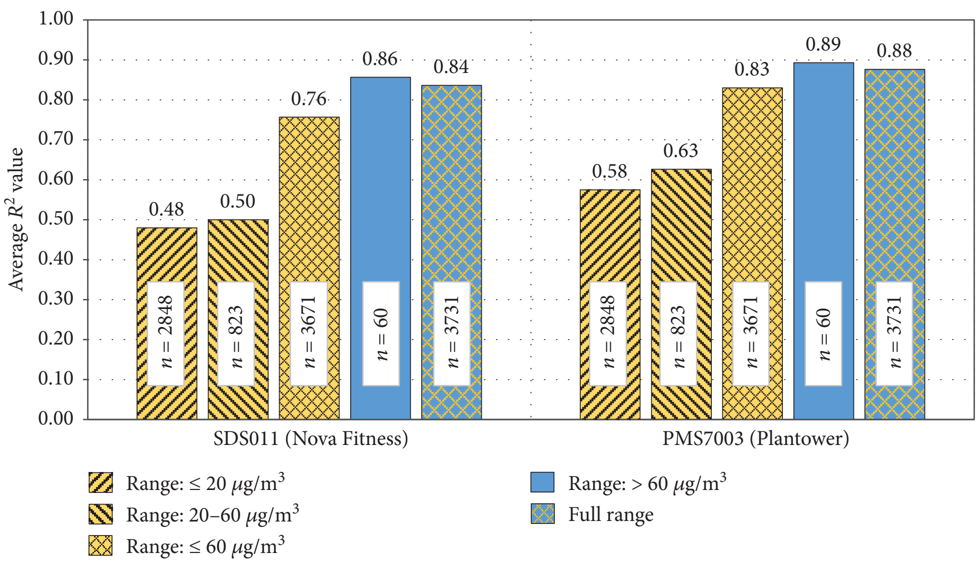
periods. Slopes of regression and intercepts were very similar for all units of sensors with the lowest intramodel variability: PMS7003 and SD011. In case of the ZH03A sensor, some differences in intercepts were observed between units no. 2 and no. 3. Two copies of OPC-N2 (no. 1 and no. 2) were characterized with very similar parameters of regression, but unit no. 3 had value of slope quite distinct from others. Additionally, the slopes for most sensors were the same for short-term averaging (1 min/15 min), hourly averaging, and daily averaging. Only small differences in intercepts were noticed for different averaging times.

4.4. Influence of $PM_{2.5}$ Concentration Range on Sensor Performance. Figure 7 presents the distribution of the relative error of $PM_{2.5}$ estimation by means of calibrated low-cost sensors. 1-hour averaged data for selected units was plotted for clarity. Generally, the biggest relative errors were observed for $PM_{2.5}$ concentrations below 20–30 μg/m^3—the error values were up to a few hundred percent. Between 20 μg/m^3 and 60 μg/m^3, the errors were mostly below 90%–100% (only OPC-N2 showed errors up to 170%). Above the level of 60 μg/m^3, relative errors were between ~0% and 31% in case of SDS011 (12% on average) and PMS7003 (11% on average). Some higher errors were observed for the stable unit of Winsen ZH03A (3%–41%; 25% on average). The OPC-N2 counter was characterized with relative errors between 13% and 58% (37% on average).

Figure 8 presents the comparisons of R^2 values from regression fittings for adopted ranges of $PM_{2.5}$ concentration, low (≤20 μg/m^3), medium (20–60 μg/m^3), and high (>60 μg/m^3), and also for combined ranges. Only sensors with low intramodel variability and highly



(a)



(b)

Figure 8: Averaged coefficients of determination (R^2) for SDS011 and PMS7003 sensors in different concentration ranges for (a) 15 min and (b) 1-hour averages. n in the text box inside the bar indicates the number of samples used for fitting.

correlated to TEOM were taken into that analysis (i.e., SDS011 and PMS7003). Averaged R^2 values from three units are presented for readability.

In case of both tested sensors, irrespective of averaging time, the quality of fittings was only moderate when sensors were measuring low levels of $PM_{2.5}$ (R^2 at the level of 0.4–0.5 for SDS011 and R^2 around 0.5–0.6 for PMS7003). This range of concentrations was characterized with a large dispersion of registered data. Only slightly better results were reached for the range of medium concentrations. However, the increase in R^2 parameter was noticeable when data from low and medium ranges were used together in regression analysis—R^2 reached the level of 0.7 for SDS011 and 0.8 in case of PMS7003. Relatively high R^2 values were also calculated for a range with higher $PM_{2.5}$ concentrations—R^2 around 0.8 for 15 min data and near 0.9 for 1 h averages. This range of data was mainly responsible for the overall quality of sensors fittings, but it should be noted that in the whole study more than 75% of TEOM data was below 20 μg/m^3 and only 1.5% was bigger than 60 μg/m^3 (mainly after 01 January 2018). Therefore, further measurements are necessary to confirm the results of the conducted analysis.

The dependency of fitting quality on the studied range of $PM_{2.5}$ concentrations was also discussed in [27, 32]. Poor agreement of low-cost sensors with collocated instruments was observed at low ambient $PM_{2.5}$ concentration levels (<20/40 μg/m^3), and the improvement of fitting was noticed for wider ranges of concentrations (up to 250 μg/m^3) [27]. The fitting quality depends also on the precision and accuracy of the control instrument used for comparison. This

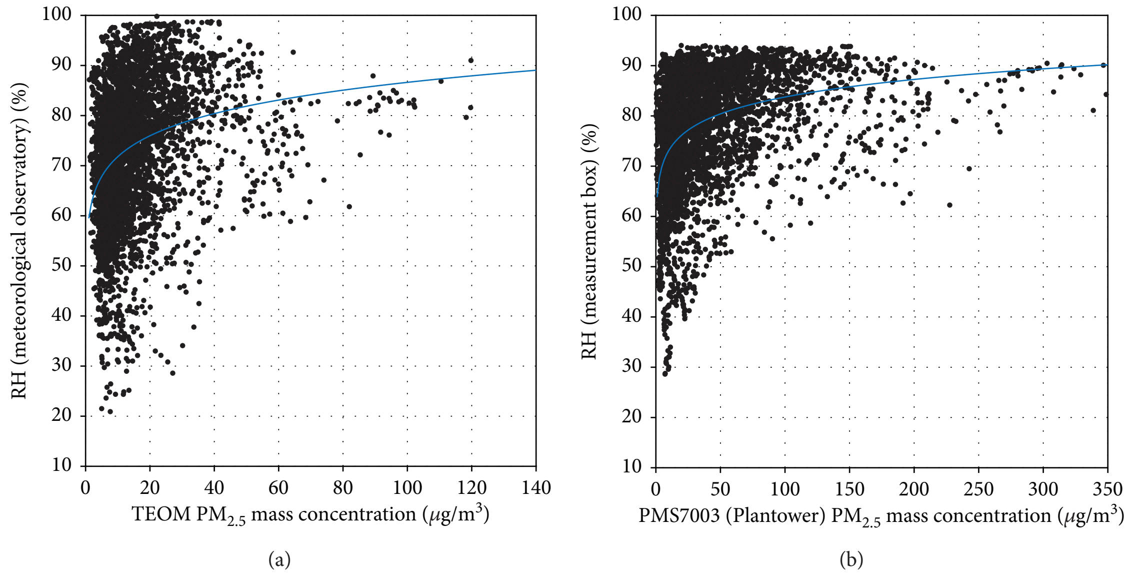


FIGURE 9: Distribution of $PM_{2.5}$ outputs on relative humidity (RH): (a) TEOM 1400a vs. RH at the meteorological observatory and (b) PMS7003 sensor vs. RH in the measurement box. 1-hour averaged data was plotted for clarity.

issue is particularly important in case of low-level concentrations and short-time sampling. In case of this measuring campaign, TEOM might be responsible for some of the inaccuracies. In this type of device, large fluctuations of signal may occasionally occur [42], which can lead to erroneous measurements.

Generally, the results of analysis showed that calibration by collocation is not a simple task. A long period of time might be necessary for acquisition of a sufficiently wide range of particulate matter concentrations. In some circumstances, calibration actions can take weeks or months for ambient air monitoring systems. Measuring properties of the control instrument also affect the results of such comparison.

Regardless of the fact that correlations with the TEOM instrument in the range of low $PM_{2.5}$ concentrations were only modest, the analysis showed that PM sensors could be reasonably good at indicating high levels of $PM_{2.5}$. Thus, they may become a valuable tool to inform the public about increased air pollution events.

4.5. Influence of Air Humidity Level on Sensor Performance. During the measuring campaign, strong diurnal variations of relative humidity and temperature were observed. Generally, lower temperatures and higher RH levels occurred at night. Many elevated $PM_{2.5}$ concentrations happened also at night, and household heating systems could have made a big contribution to that situation. Figure S5 in the Supplementary Material presents examples of such episodes.

The daily distribution of measured $PM_{2.5}$ concentrations (see Figure S6 in the Supplementary Material) showed that the highest values of $PM_{2.5}$ occurred in the mornings (6–9 UTC) and in the evenings (18–20 UTC), when RH values were also usually high (compare with Figure S7). This co-occurrence of elevated RH and $PM_{2.5}$ concentrations may explain the relatively high outputs from low-cost PM sensors at high RH levels. An example of the relationship between RH values and $PM_{2.5}$ data from TEOM and low-cost sensor is presented in Figure 9. Similar relationships were observed for all tested sensors. It should be noted that RH registered inside the measurement box did not reach the highest values registered at the meteorological observatory. This is due to slightly higher temperature inside the box, which results from the heat emitted by electronic circuits during their work.

High levels of RH had, however, an impact on performance of some sensors. In the case of Nova Fitness SDS011, higher dispersion of data between units was observed already above 80%, and beyond 90% differences in data sets were even more visible. Figure S2 in the Supplementary Material presents those differences.

The other aspect of assessment of the humidity impact was based on a comparison of parameters of linear functions for all considered RH ranges. Examples of such comparison are presented in Figure 10. It was noticed that in some cases slopes of linear equations can vary significantly when the RH level is elevated.

For SDS011 (Figure 10(a)), the value of slope changed from a level of 0.47 for RH below 80% to 0.41 for RH range 80%–90% and around 0.37 when RH was higher than 90%. Therefore, the overestimation of outputs was observed when measurements were conducted in very humid air.

A similar situation was even more visible in the case of OPC-N2 (see Figure 10(d)). Slope changed from 0.38, for RH under 80%, to 0.14 when RH was higher than 90%. The impact of high ambient RH was also noticed in [36]—OPC-N2 demonstrated significant positive artefacts during measurements in humid air (>85%).

In the case of ZH03A, changes of slope values were less significant (see Figure 10(b)). The slope was equal around 0.35–0.36 up to 90% RH, and above that level the value of 0.33 was computed. PMS7003 was characterized with stable slope value for all ranges of RH (see Figure 10(c)). For both

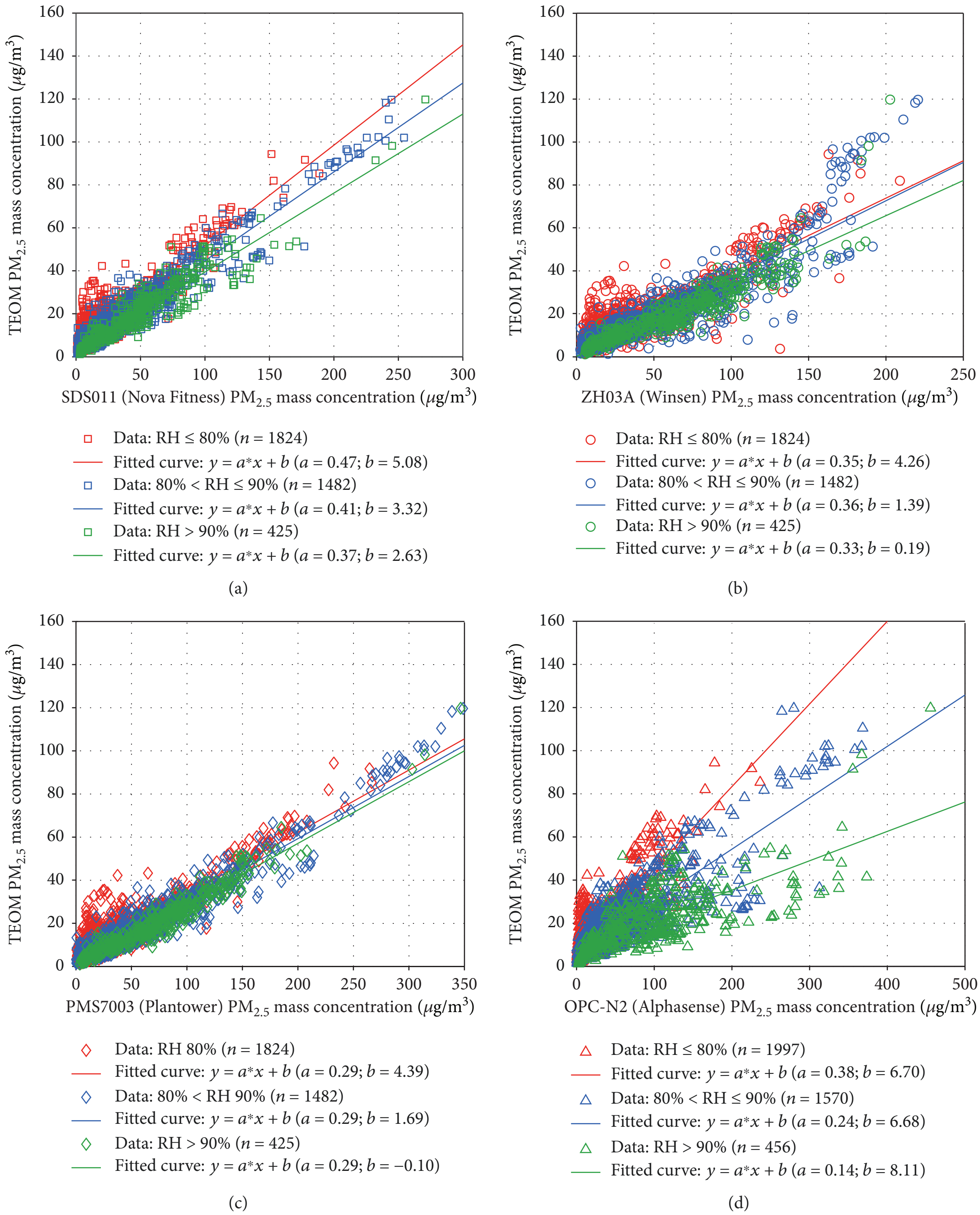


FIGURE 10: Results of linear fittings in different relative humidity (RH) ranges for 1-hour averaged data: (a) SDS011 (Nova Fitness), (b) ZH03A (Winsen), (c) PMS7003 (Plantower), and (d) OPC-N2 (Alphasense). *n* in the brackets indicates the number of samples used for fitting.

sensor models, small alterations of intercepts were observed when the RH level was changing.

To sum up, the analysis showed the necessity of the use of correction factors for high humidity levels in the case of some PM sensors. Such action has been proposed for OPC-N2 in [36]. Similar corrections could be also beneficial for Nova Fitness SDS011 devices.

5. Conclusions

Many models of low-cost PM sensors are available these days on the market. The conducted comparison of four models of PM sensors and TEOM analyser demonstrated that optical PM sensors generally follow the trend of $PM_{2.5}$ changes in atmospheric air. However, some temporary peaks were observed for the raw short-term data in the case of all tested sensors. Data filtering or smoothing for at least 15 minutes may be advantageous in that situation and should not affect the ability to detect short-term pollution events.

An important thing that should be noted is that the raw outputs from the off-the-shelf devices may significantly overestimate the $PM_{2.5}$ concentrations (a factor of 2.5–5 might be observed, as the results of this study showed). It may be due to the fact that sensors are calibrated by the manufacturer using particles with properties completely different than particulate matter in the monitored air. For this reason, calibration (or recalibration) of PM sensors should be made in the final environment of measurements. The most common method of such calibration is based on the use of the data from the collocated higher-class instrument.

As the results of this study showed, that kind of action could be in some ways be complicated. Sensors like OPC-N2 (Alphasense) or ZH03A (Winsen) were characterized with relatively high intramodel variability. On the other hand, SDS011 (Nova Fitness) and PMS7003 (Plantower) were precise in terms of reproducibility between units. This feature could be very useful when a large amount of sensors is to be used, e.g., in dense monitoring networks. Calibration factors from one unit can be used for others in such case.

The other aspect of calibration is related to linearity of sensor responses. OPC-N2 units exposed only a moderate linear relationship with TEOM (the average R^2 value at the level of 0.5–0.6). The results for linear fittings were much better for PMS7003, SDS011, and ZH03A sensors. In particular, PMS7003 sensors reached R^2 higher than 0.8 for short-time averaging times and exceeded 0.9 for daily averages.

The conducted data analysis showed also that a wide range of $PM_{2.5}$ concentrations is desirable to properly describe sensor characteristics. The situation when the particulate's concentration range is narrow could lower the quality of fittings of sensor data and increase the calibration efforts. The duration of collocated calibration is site-specific, but it should last at least a few weeks to acquire a sufficient amount of data.

This research was conducted under different meteorological conditions. PM sensors worked both at temperatures below 0°C and at temperatures above 30°C, and no problems with functioning were noticed. Malfunction was only observed for two copies of ZH03A sensors, and particle accumulation could be responsible for that situation.

During the measurement period, the relative humidity varied from 27% to the level of above 90%. Some impact of high relative humidity (RH > 80%) was observed in the case of SDS011 and OPC-N2 sensors. Larger dispersion of SDS011 outputs was noticed in very humid air, and substantial change of slopes of linear models occurred for both devices. The use of correction factors for high humidity levels should be advantageous for those sensors.

Overall, the study showed that low-cost optical PM sensors could be effective tools for ambient air quality monitoring. The results of this research can help the authors of measuring systems and users of low-cost PM sensors in choosing the appropriate conditions for sensor work and calibration.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

Acknowledgments

This work was cofinanced within the specific subsidy granted for the Faculty of Environmental Engineering, Wroclaw University of Science and Technology, by the Ministry of Science and Higher Education (statutory project No. 0402/0130/17). The work was partially financed by the European Union and cofinanced by NFOSiGW within LIFE+ Program, Project LIFE-APIS/PL-Air Pollution and biometeorological forecast and Information System (LIFE12 ENV/PL/000056).

Supplementary Materials

Location of measurement stations, comparisons of data from TEOM 1400a and BAM analyser, and examples of daily distribution of temperature, relative humidity, and $PM_{2.5}$ concentration during the measuring campaign. Additional tables with parameters of linear regression fittings were also included. *(Supplementary Materials)*

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