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Performance assessment of NOVA SDS011 low-cost PM sensor in various microenvironments

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Abstract Over the last 10 years, as a possible alternative to the conventional approach to air quality monitoring, real-time monitoring systems that use low-cost sensors and sensor platforms have been frequently applied. Generally, the long-term characteristics of low-cost PM sensors and monitoring have not been thoroughly documented except for a few widely used sensors and monitors. This article addresses the laboratory and field validation of three low-cost PM monitors of the same type that use the NOVA SDS011 PM sensor module over a 1-year period. In outdoor environments, we co-located low-cost PM monitors with GRIMM EDM180 monitors at the National Air Quality Monitoring stations. In indoor environments, we co-located them with a Turnkey Osiris PM monitor. Several performance aspects of the PM monitors were examined: operational data coverage, linearity of response, accuracy, precision, and inter-sensor variability. The obtained results show that inter-monitor R values were typically higher than 0.95 regardless of the environment. The tested monitors demonstrate high linearity in comparison with PM_{10} and $PM_{2.5}$ concentrations measured in outdoor air with reference-equivalent instrumentation with R^2 values ranging from 0.52 up to 0.83. In addition, very good agreement (R^2 values ranging from 0.93 up to 0.97) with the gravimetric PM_{10} and $PM_{2.5}$ method is obtained in the indoor environment ($30 < RH < 70\%$). High RH (over 70%) negatively affected the PM monitors' response, especially in the case of PM_{10} concentrations (high overestimation).

Keywords Air pollution · Monitoring · Particulate matter · Low-cost PM monitor · NOVA SDS011 PM sensor

Introduction

It is well-documented that elevated levels of particulate matter (PM) adversely affect human health. Long-term exposure to PM_{10} and $PM_{2.5}$ can cause respiratory and cardiovascular disease and increase all-cause mortality (Pope et al., 2006, 2009; Schwartz, 2004). Evidence published by the WHO/Europe confirmed the importance of outdoor air pollution as a risk factor for health and linked fine particles $PM_{2.5}$ and cardiovascular and respiratory ill health (WHO, 2020). Long-term exposure to $PM_{2.5}$ can also trigger atherosclerosis, adverse birth outcomes, and childhood respiratory diseases and is potentially linked

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with neurological development, cognitive function, and diabetes (WHO, 2020). The EU limit values for PM_{10} in the ambient air for the protection of human health are provided in Council Directive 2008/50/EC (European Union, 2008). The directive prescribes a daily limit value of 50 μg/m^3, not to be exceeded more than 35 times per calendar year, and an annual limit value of 40 μg/m^3. The same directive (European Union, 2008) prescribes that annual average $PM_{2.5}$ level cannot exceed 20 μg/m3 after 2020. PM limits and targets for 24 h and annual averages significantly differ from one country to another, as shown in (Jovašević et al., 2015). In terms of health impact assessment studies, it is mandatory to characterize the concentration, particle size distribution, and chemical composition of PM in indoor microenvironments as people spend most of their time indoors (Franck et al., 2011). PM in indoor air originates from outdoor infiltration and additional indoor sources, such as cooking, smoking, heating devices, and dust resuspension (Morawska et al., 2017; Wallace, 2006).

Outdoor monitors underestimate the personal exposure to toxic compounds contained in $PM_{2.5}$ in comparison with personal and indoor monitors (Adgate et al., 2007). Extensive research has been conducted to characterize PM mass concentrations in the indoor environment. Gravimetric methods are still the basis of the European and US reference methods for PM_{10} and $PM_{2.5}$ monitoring, but other monitoring techniques that can provide equivalent results to the PM reference method may be used (Tasic et al., 2012). The development of new low-cost PM sensors, monitors, and low-cost PM-based monitoring networks has enabled researchers to collect data and monitor real-time measurement processes with much higher time resolution. The quality of the data collected in this way could be questionable due to the lack of information on the degree of concordance of the results with the results of the reference PM monitors. This is crucial for assessing the usability of the results obtained by using low-cost PM monitors when conducting health impact studies. The long-term characteristics of low-cost PM sensors and monitors have not been documented well, except for a few widely used sensors and monitors (Alfano et al., 2020).

Most of the low-cost PM monitors use the Mie scattering principle (Mishchenko, 2009) by utilizing a semiconductor laser as a light source and a measuring cell where the scattered light is led directly and via a mirror onto a detector (Venkatraman et al., 2021). The information available from the datasheets of the most popular PM low-cost sensors is summarized in (Giordano et al., 2021; Venkatraman et al., 2021). Another useful discussion of the measurement principles of low-cost sensors is provided in (Giordano et al., 2021).

This research addresses the laboratory and field validation of three new low-cost PM monitors of the same type that use the NOVA SDS011 PM sensor module (NovaFitnes, 2021) over a 1-year period in different indoor and outdoor environments. Another goal of our research is to establish a simple procedure for the correction of the low-cost PM monitor results by comparing them with the PM concentrations obtained using the reference gravimetric method. The NOVA SDS011 PM sensor (Liu et al., 2019) was chosen for installation in low-cost PM monitors and for further tests after long-term testing in laboratory conditions (Tasic et al., 2018), where it displayed good characteristics in terms of temperature stability and reliability (operational data coverage).

Materials and methods

Sampling locations and measurement campaigns

The indoor and outdoor PM measurement campaigns were carried out in two cities in Serbia, which represent different hot spots of PM air pollution: from industry (Bor) and from traffic and local heating (Niš). In the city of Bor, the main source of air pollution, together with SO_2 gas, heavy metals in PM, and aero sediments, is the copper smelter (Tasic et al., 2010). In contrast, in the city of Niš, the main sources of PM particles are traffic and local heating (Kovacevic et al., 2015). Accordingly, the selected cities are expected to be quite different in terms of concentration, composition, and particle size distribution of PM particles.

Several measurement campaigns were conducted in the period from January 15, 2021, to January 15, 2022, in both heating and non-heating periods of the year, with the aim of further exploring the impact of seasonal changes, particle size distribution, and PM concentration levels on PM monitor readings. The evaluation of the low-cost PM sensors' characteristics in indoor air was carried out at two laboratories: the Mining and Metallurgy Institute (MMI) in Bor (44°03′37″N, 22°06′07″E) and the Faculty of Occupational Safety (FOS) in Niš, University of Niš (43°18′42″N, 21°53′11″E), as shown in Fig. 1. The examination of the PM monitor characteristics in outdoor air was carried out through colocation with the Grimm EDM180 PM monitors at the following National Air Quality Monitoring Stations (NAQMS): Public Health Institute (PHI) Niš (43°18′57″N, 21°54′ 51″E) and Town Park (TP) Bor (44°04 33″N, 22°05′58″E), as shown in Fig. 1.

Sampling equipment and data collection — indoor air

The monitoring equipment settings in indoor air were the same for both laboratories used in the sampling campaigns. Two European reference low-volume samplers, LVS3 (Sven/Leckel LVS3), were co-located with the direct reading aerosol monitoring device, Turnkey OSIRIS Particle Monitor Model 2315 (Tasic et al., 2012), and three PAQMON 1.0 PM monitors (marked P1, P2, and P3). Turnkey OSIRIS PM monitors had also been used for the assessment of indoor and outdoor PM concentrations in the previous studies (Briggs et al, 2008; Gulliver & Briggs, 2007; Keuken et al., 2010a, b; Kim et al., 2008; Tasic et al., 2012; Tasic et al., 2015).

PAQMON 1.0 PM monitor (Fig. 2) uses an Arduino Mega 2560 microcontroller (Arduino, 2021) as a control board. A NOVA SDS011 sensor module (Liu et al., 2019) is used for measurements of the PM_{10} and $PM_{2.5}$ mass concentrations in the range from 0 to 1000 μg/m^3. A DHT22 sensor module (Sparkfun, 2021) is used for temperature (−10 to + 40 °C) and relative humidity (20 to 90% RH) measurements. The measurement results are stored as text files on a microSD card and displayed on an LCD display, as shown in Fig. 2. The predefined measuring interval is one second while the averaging interval is set to 1 min. If needed, the averaging interval could be set up in the range from 5 s up to 1 h. Results of measurements can be simply downloaded to a PC over a standard USB serial port. The typical

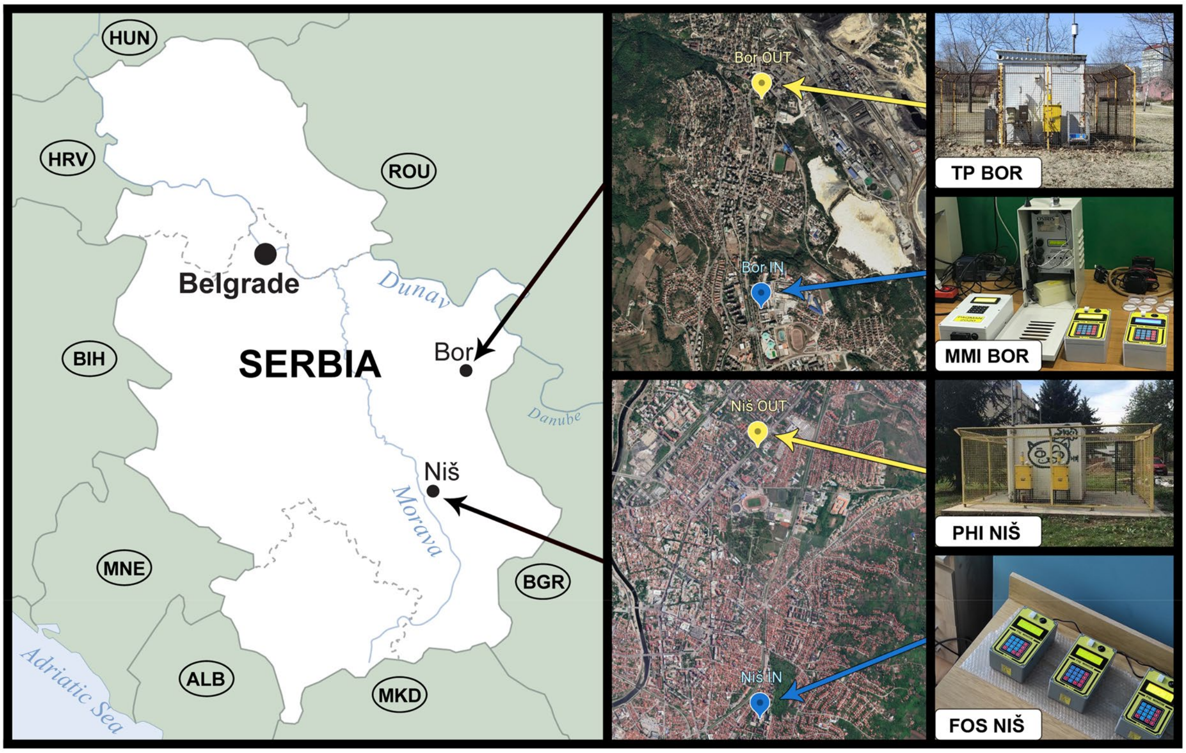

Fig. 1 Measurement sites and colocation setups

Fig. 2 PAQMON 1.0 low-cost PM monitor

instrument zero ranged from 0.1 to 0.4 μg/m^3 for both PM fractions. The instrument does not currently have the ability of zero adjust. Adjustment of the slope coefficient of the working curve is possible for both PM fractions.

Two LVS3 reference samplers carrying PM_{10} and $PM_{2.5}$ impactors were placed in the center of the laboratories. There were 1–2 regular occupants in the laboratories, which have very similar capacities of 20–25 m^3. The laboratories have window surfaces of 1.5 and 2 m^2 and only one door, which was usually closed, while the floor of the laboratories was covered with laminate. During the heating season, laboratories are heated from a central heating system via radiators. There are no mechanical ventilation or air conditioning systems in the laboratories, so ventilation is provided simply by opening the windows or the doors. During the measurement campaign in the laboratory, the windows and doors were usually closed. Twenty-four-hour average PM_{10} and $PM_{2.5}$ mass concentrations were obtained using the LVS3 reference samplers. The OSIRIS monitor provides 15 min while PAQMON 1.0 monitors provide 1-min average PM_{10} and $PM_{2.5}$ mass concentrations. For the calculation of the daily averages of PM, a minimum capture of 90% of 15-min and 1-min averages was required; otherwise, the value was considered as missing. The flow rate of the LVS3 samplers (38.3 l/min) and the OSIRIS monitor (0.6 l/min) was calibrated using certified flow meters at the beginning of each measurement campaign.

Sampling equipment and data collection — outdoor air

The PM monitoring equipment settings in outdoor air were the same for both outdoor sites used in the study. Two European reference samplers, Lifetek PMS (Lifetek, 2021), and three PAQMON 1.0 PM monitors were co-located at NAQMS TP Bor and PHI Niš with the Grimm EDM180 PM monitoring system, which provides 1-h average PM mass concentrations.

Measurement campaigns in Bor

During the heating season (October to March), the indoor PM samples were collected in the laboratory at MMI Bor from April 9 to April 18, 2021. In the non-heating season (April to September), the indoor PM samples were collected in the same laboratory from June 7 to June 21, 2021. During the heating season, the outdoor PM samples were collected at NAQMS TP Bor from March 23 to April 9, 2021. In the non-heating season, the outdoor PM samples were collected at NAQMS TP Bor from July 30 to August 9, 2021.

Measurement campaigns in Niš

During the heating season, the indoor PM samples were collected in the laboratory at FOS Niš from February 21 to March 9, 2021. In the non-heating season, the indoor PM samples were collected in the same laboratory from May 14 to May 24, 2021. During the heating season, the outdoor PM samples were collected at NAQMS PHI Niš from December 23 to January 11, 2022. In the non-heating season, the outdoor PM samples were collected at NAQMS PHI Niš from May 24 to June 7, 2021.

Gravimetric analysis of PM samples

Quartz fiber filters (Whatman QMA 47-mm-diameter filters) were used throughout this study for gravimetric sampling. Samples were collected on a daily basis (3 PM–3 PM), whereby 112 samples were collected in total, 56 samples per each PM fraction. Pre-conditioning and post-conditioning of the filters were undertaken in the MMI Bor laboratory following the requirements of EN 12341 standard. PM mass concentrations were calculated using the average weights of filters. The detection limit was 2.2 μg/m^3, calculated as three times the standard deviation of the net mass of field blanks divided by the nominal air sample volume.

Statistical analysis

Data sets were analyzed to assess the overall agreement between PM levels obtained with different PM monitors and sampling techniques. Several statistical evaluation measures were used to quantify the differences between the obtained PM concentrations. The 1-h average, standard deviation (SD), coefficient of variation (CV), accuracy, precision, mean bias error (MBE), root mean square error (RMSE), inter monitor variability (IMV), and correlation coefficients (R^2) between reference instruments and corrected results of the tested PM monitors were calculated (Zamora et al., 2020). All analyses were completed using SPSS Statistics 17.0 and Microsoft Office Excel 2010.

Accuracy is the degree of closeness between the measured value obtained by a PM monitor and the reference value. The accuracy for each colocation period was calculated using Eq. (1) (Liu et al., 2019; Zamora et al., 2020), where *REF* is the mass concentration of reference instrument (Grimm 180 EDM for outdoor air or OSIRIS for indoor air) and Unit$_i$ is the average mass concentration measured by i-th PM monitor during the colocation period.

$$Accuracy_{campaign} = 100 - \left|\frac{REF - Unit_i}{REF}\right| \times 100 \tag{1}$$

The overall accuracy was calculated by averaging accuracies from each colocation period Eq. (2).

$$OverallAccuracy = \frac{1}{n}\sum_{i=1}^{n} Accuracy_{campaign} \tag{2}$$

We also calculated the mean bias error (MBE) using Eq. (3) to assess if the instruments consistently overestimated or underestimated the PM mass concentration. It should be noted that Eq. (3) is applied to 1-h average PM mass concentrations.

$$MBE = \frac{1}{n}\sum_{i=1}^{n}\frac{REF - Unit_i}{REF} \times 100 \tag{3}$$

The coefficient of variation (CV), as the measure of the spread of data points around the average, was calculated using Eq. (4), where $\boldsymbol{\sigma}$ is the standard deviation and μ is the mean of the 1-h averaged measurements.

$$CV = \sigma/\mu \tag{4}$$

The precision of the two PM monitors (AP) was calculated using Eq. (5). A precision error of 0% between two units would indicate that the units measured identical values (Zamora et al., 2020).

$$Precision = \left|\frac{Unit_1 - Unit_2}{Average\left(Unit_1, Unit_2\right)}\right| \tag{5}$$

The coefficients of determination (R^2) were calculated between the PM monitors (presented as Unit-R^2) and units vs. the REF (presented as REF-R^2). The root mean squared error (RMSE) was calculated using Eq. (6), where REF_i and Unit$_i$ are the corresponding i-th 1-h average PM concentrations from a colocation period with N hours. A value of 0 would indicate a perfect agreement between REF and the unit (Zamora et al., 2020). The overall RMSE was calculated by averaging values from each colocation period.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} \left(REF_i - Unit_i\right)^2}{N}} \quad (6)$$

Inter-monitor variability (IMV) is related to how close the measurements from three units of the same monitor type are to each other. For a set of three monitors, the IMV is reported as a percentage and is calculated using Eq. (7) (Liu et al., 2019):

$$IMV(\%) = \left| \frac{Mean_{highest} - Mean_{lowest}}{Mean_{average}} \right| \times 100 \quad (7)$$

where $\text{Mean}_{\text{highest}}$ is the highest of the three monitors' average concentrations,, $\text{Mean}_{\text{lowest}}$ is the lowest of the three monitors' average concentrations, and $\text{Mean}_{\text{average}}$ is the average of the three monitors' average concentrations.

Results and discussion

Correction factor calculation

To calculate the temporal distribution of PM mass concentrations more accurately, the results of PM monitors were corrected following the slightly modified method of Ramachandran et al. (2003). As previously mentioned, 24-h gravimetric samples were collected concurrently with the PM monitors' measurements. The results of PM monitors were scaled using a specific correction factor Eq. (8):

$$F = \frac{1}{n} \sum_{i=1}^{n} \frac{G_i}{S_i} \quad (8)$$

where F is the correction factor, Gi is the 24-h mean gravimetric PM concentration for i-th day of measurements, Si is the corresponding 24-h mean PM concentration obtained by automatic PM monitor for the i-th day of measurements, and n is the number of days. Each 1-h result of the PM monitors was multiplied by this correction factor. The correction factor for each monitor and each PM fraction is shown in Table 1.

According to the data shown in Table 1, all tested PM monitors show lower results compared to those obtained using the reference method. It is noticeable that the correction factors are in most cases higher in the outdoor air than in the indoor air. This can be attributed to the greater influence of meteorological factors on outdoor PM readings than in indoor microenvironments (Wallace et al., 2021; Wu et al., 2022). The average value of the correction coefficient for the PM_{10} fraction is 1.18, while in the case of $PM_{2.5}$, this value is 1.20. The values of correction factors obtained in our research are quite consistent both for laboratory and field measurements. Furthermore, the $PM_{2.5}$ correction factors for outdoor measurements are in good agreement with the results obtained previously (Liu et al., 2019). In contrast, widely used low-cost $PM_{2.5}$ monitor PurpleAir, with Plantower PMS5003 sensor (Wallace et al., 2021), overestimates $PM_{2.5}$ values up to 40% in outdoor air. Similarly, other experimental results suggested that most light-scattering instruments, such as TSI Dust Trak, overestimated PM_{10} and $PM_{2.5}$ levels by about 2–2.5 times, respectively, compared with the reference instruments (Tasic et al., 2012). Therefore, the characteristics of each type of low-cost sensor have to be checked, because they vary regardless of the similar principle of operation. These results strongly suggest that the correction of PM results obtained from low-cost sensors is crucial for the usability of measurement results.

Table 1 Summary of the correction factors (HS, heating season; NHS, non-heating season)

Campaign	PM_{10}			$PM_{2.5}$		
	P1	**P2**	**P3**	**P1**	**P2**	**P3**
MMI BOR HS indoor	1.10	1.10	1.20	1.10	1.15	1.20
TP Bor HS outdoor	1.15	1.20	1.20	1.30	1.20	1.25
MMI Bor NHS indoor	1.10	1.15	1.10	1.15	1.20	1.20
TP Bor NHS outdoor	1.20	1.30	1.15	1.20	1.15	1.30
FOS Niš HS indoor	1.10	1.15	1.10	1.15	1.20	1.20
PHI Niš HS outdoor	1.30	1.20	1.20	1.20	1.25	1.25
FOS Niš NHS indoor	1.15	1.20	1.20	1.15	1.20	1.15
PHI Niš NHS outdoor	1.30	1.20	1.15	1.20	1.20	1.25

Analysis of results from measurement campaigns in Bor

Summaries of the mean PM mass concentration (µg/m^3), standard deviation (SD), coefficient of variation (CV), accuracy (%), mean bias error (MBE), root mean square error (RMSE), and inter-monitor variability (IMV) for the measurement campaigns in Bor and Niš are given in Tables 2 and 3, respectively.

Based on the results shown in Table 2, it can be concluded that the highest values of mean concentrations, SD and RMSE, were obtained for the PM_{10} fraction in outdoor air during both the heating and non-heating seasons. CV values were fairly uniform in both the heating (mean 0.55) and non-heating seasons (mean 0.64), as was the accuracy of the measurements. MBE values varied from case to case in the range from −8.6 to 17.2% (P3), but they were consistent only in the case of PM_{10} measurements in outdoor air when the results of all monitors exceeded the reference values. For the sake of illustration, Fig. 3 shows the diagram of the hourly values of PM concentrations in the measurement campaign for outdoor air in Bor during the non-heating season.

Analysis of results from measurement campaigns in Niš

Based on the results shown in Table 3, it can be concluded that the highest values of mean PM concentrations, SD, and RMSE were obtained for the outdoor air PM_{10} and $PM_{2.5}$ fractions in the heating season. It should be mentioned that the mean PM concentration measured during both indoor and outdoor campaigns in the heating season in Niš was quite high, higher than national limits for mean daily PM_{10} (50 µg/m^3) and $PM_{2.5}$ (25 µg/m^3)

Table 2 Summary of the mean PM mass concentrations (µg/m^3), standard deviation (SD), coefficient of variation (CV), accuracy (%), mean bias error (MBE), root mean square error (RMSE), and inter-monitor variability (IMV) for the measurement campaigns conducted in Bor (HS, heating season; NHS, non-heating season)

BOR campaigns	Unit	Mean (µg/m^3)	SD (µg/m^3)	CV	Accuracy (%)	MBE (%)	RMSE (µg/m^3)	IMV (%)
PM_{10} — MMI BOR NHS indoor	**P1**	10.94	7.44	0.68	99.34	10.84	3.21	6.70
	P2	10.37	6.82	0.66	94.20	5.71	3.36	
	P3	11.10	9.78	0.88	99.19	0.16	1.70	
$PM_{2.5}$ — MMI BOR NHS indoor	**P1**	8.84	5.55	0.63	94.97	2.36	2.36	7.69
	P2	8.63	5.52	0.64	92.67	−0.62	2.17	
	P3	8.72	6.54	0.75	93.66	−5.83	1.40	
PM_{10} — TP BOR NHS outdoor	**P1**	19.58	11.53	0.59	94.53	12.05	9.33	10.92
	P2	18.54	10.68	0.58	89.52	6.13	9.22	
	P3	20.66	11.48	0.56	99.74	17.16	8.96	
$PM_{2.5}$ — TP BOR NHS outdoor	**P1**	8.91	5.12	0.58	88.13	−4.35	3.07	20.71
	P2	9.58	5.26	0.55	94.79	2.90	2.68	
	P3	8.20	4.33	0.53	81.15	−8.01	3.80	
PM_{10} — MMI BOR HS indoor	**P1**	13.12	9.78	0.75	97.50	10.87	4.33	6.17
	P2	13.12	8.69	0.66	97.52	12.93	5.02	
	P3	12.65	11.32	0.89	94.00	−3.17	2.73	
$PM_{2.5}$ — MMI BOR HS indoor	**P1**	11.40	5.72	0.50	94.94	4.20	3.30	11.29
	P2	10.85	5.77	0.53	90.35	−2.00	3.30	
	P3	10.74	6.99	0.65	89.42	−8.62	2.30	
PM_{10} — TP BOR HS outdoor	**P1**	22.64	10.09	0.45	95.41	11.95	11.12	5.70
	P2	22.41	8.93	0.40	94.49	11.14	10.35	
	P3	22.99	11.06	0.48	96.92	10.64	9.67	
$PM_{2.5}$ — TP BOR HS outdoor	**P1**	13.04	5.13	0.39	96.91	0.35	3.77	10.88
	P2	14.54	6.03	0.41	91.96	10.78	3.87	
	P3	14.04	7.09	0.50	95.68	6.79	5.00	

Table 3 Summary of the mean PM mass concentrations, standard deviation (SD), coefficient of variation (CV), accuracy (%), mean bias error (MBE), root mean square error (RMSE), and inter-monitor variability (IMV) for the measurement campaigns conducted in Niš (HS, heating season; NHS, non-heating season)

NIŠ campaigns	Unit	Mean (μg/m^3)	SD (μg/m^3)	CV	Accuracy (%)	MBE (%)	RMSE (μg/m^3)	IMV (%)
PM_{10} — FOS NIŠ NHS indoor	**P1**	19.89	45.99	2.31	90.29	3.80	13.73	9.31
	P2	18.50	43.89	2.37	97.94	−2.03	12.18	
	P3	19.08	45.23	2.37	94.74	−3.66	12.66	
$PM_{2.5}$ — FOS NIŠ NHS indoor	**P1**	15.65	25.71	1.64	92.84	6.14	6.74	7.09
	P2	14.58	23.98	1.64	99.86	0.97	5.97	
	P3	15.31	27.20	1.78	95.17	−0.92	7.86	
PM_{10} — PHI NIŠ NHS outdoor	**P1**	13.54	5.52	0.41	98.96	2.69	3.37	10.58
	P2	14.61	5.24	0.36	91.00	12.54	3.49	
	P3	14.90	6.13	0.41	88.86	14.11	4.26	
$PM_{2.5}$ — PHI NIŠ NHS outdoor	**P1**	10.70	4.37	0.41	91.97	14.67	2.55	8.83
	P2	10.82	4.64	0.43	90.67	15.42	2.43	
	P3	10.40	5.04	0.48	94.93	8.21	2.53	
PM_{10} — FOS NIŠ HS indoor	**P1**	33.30	29.92	0.90	97.85	8.90	6.71	7.33
	P2	31.72	30.09	0.95	97.11	−1.62	6.70	
	P3	34.14	33.80	0.99	95.28	1.56	8.68	
$PM_{2.5}$ — FOS NIŠ HS indoor	**P1**	26.80	25.97	0.98	98.34	−4.35	5.43	5.38
	P2	25.82	25.70	1.00	94.75	−9.25	5.70	
	P3	26.43	26.54	1.00	96.97	−8.63	5.89	
PM_{10} — PHI NIŠ HS outdoor	**P1**	54.74	54.85	1.00	98.98	−3.49	24.66	7.74
	P2	56.68	55.40	0.98	97.51	0.68	25.28	
	P3	59.11	56.36	0.95	93.12	5.19	26.91	
$PM_{2.5}$ — PHI NIŠ HS outdoor	**P1**	54.47	55.23	1.01	99.39	−2.31	24.24	6.04
	P2	52.14	52.16	1.00	96.30	−6.09	22.46	
	P3	51.27	48.86	0.95	94.69	−6.36	21.36	

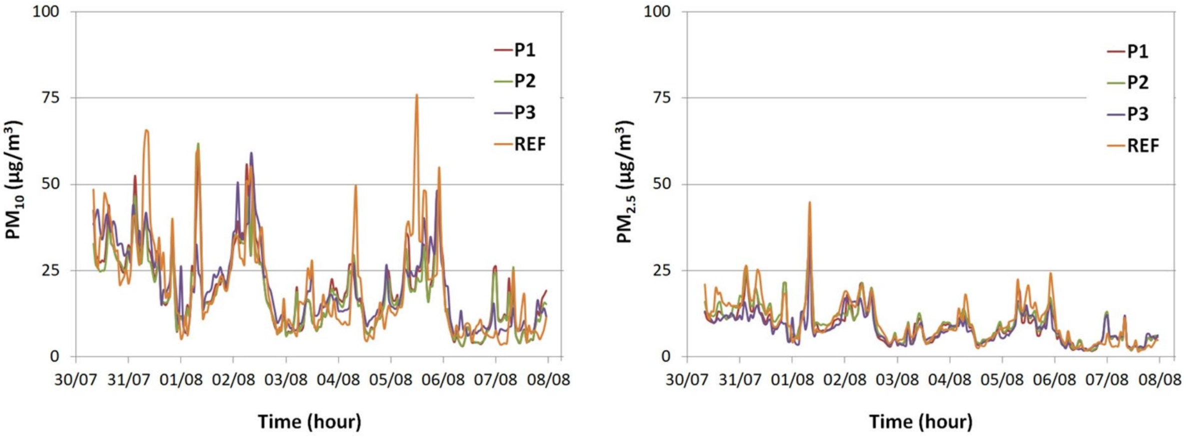

Fig. 3 The 1-h mean outdoor PM mass concentrations measured at TP Bor in NHS

outdoor air concentrations. CV values were fairly uniform in the heating season (mean 0.98), while in the non-heating season they ranged from 0.36 to 2.37 (for P2, PM_{10} fraction). The accuracy of PM monitors was over 90% except in the case of P3 monitor for PM_{10} fraction during the outdoor campaign in NHS.

The MBE values varied from case to case in the range from − 9.2 to 15.4% (P2). These were more consistent in the case of indoor air $PM_{2.5}$ measurements, but the results of all PM monitors in this case underestimate the reference values. For the sake of illustration, Fig. 4 shows PM concentrations observed in Niš in the indoor air in the HS.

Furthermore, in accordance with the results shown in Tables 2 and 3, it is clear that all PM monitors show very similar mean PM concentrations, SD, CV, and RMSE values. The IMV values in the Bor campaigns ranged from 5.3 to 11.3 with one exception of 20.7 ($PM_{2.5}$ outdoor NHS), whereas in the Niš campaigns, IMV ranged from 5.3 to 10.6, which is fairly comparable with the results obtained previously (Liu et al., 2019). The same conclusion applies to the accuracy obtained in our research and in (Liu et al., 2019).

Analysis of results obtained for R^2

Table 4 presents R^2 values obtained between the PM monitors and the reference instruments during the entire period of measurements. Values of R2 shown in Table 4 were generally higher for indoor air, mostly because of the minor effect of meteorological parameters (especially T and RH) on PM monitor readings.

As expected, the lowest values of R^2 between the PM monitors were observed for the outdoor measurements of PM concentrations 0.70 (between P2 and P3) in Bor, and 0.92 (between P1 and P3) in Niš. The lowest values of R^2 between the PM monitors and REF were 0.52 (between P3 and REF) in Bor and 0.58 (between P3 and REF) in Niš. The highest values of R^2 between the PM monitors were 0.990 (between P1 and P2) in Bor, and 0.998 (between P1 and P2) in Niš, both obtained from indoor air.

The highest values of R^2 between the PM monitors and REF were 0.975 (between P3 and REF) in Bor, and 0.958 (between P3 and REF) in Niš, both obtained from indoor air, as well. The results are consistent with those obtained for outdoor PM measurements in Poland (Badura et al., 2018) and Norway (Liu et al., 2019).

Notes concerning the T and RH influence on PM measurements

The percentage of 1-h mean RH values over 80% was 27% and 11% during measurement campaigns in Bor in HS and NHS, respectively. The percentage of 1-h mean RH values over 80% during measurement campaigns in Niš was 21% and 0% in HS and NHS, respectively. Average T and RH during outdoor air measurements in Bor were 7.6 °C and 66.3% in HS and 24.6 °C and 58.1% in NHS, respectively. Average T and RH during outdoor air measurements in Niš

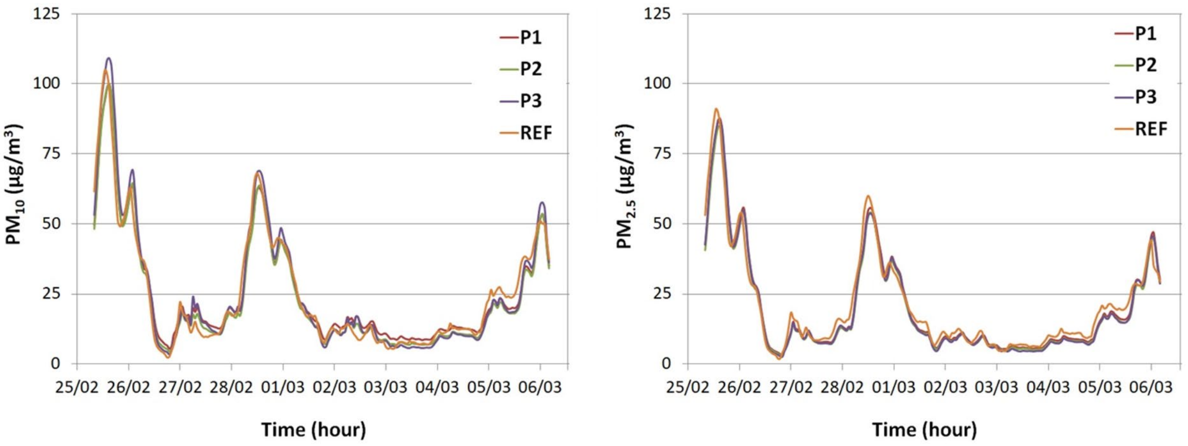

Fig. 4 The 1-h mean indoor PM mass concentrations measured at FOS Niš in HS

Table 4 Summary of the R^2 values between the PM monitors and the reference instruments

BOR **campaigns**	Unit	R^2 **P1**	R^2 **P2**	R^2 **P3**	R^2 **REF**	NIŠ **campaigns**	Unit	P1 **R^2**	P2 **R^2**	P3 **R^2**	REF **R^2**
PM_{10} — MMI BOR NHS indoor	**P1**	1	0.975	0.953	0.920	**PM_{10} — FOS NIŠ NHS indoor**	**P1**	1	0.992	0.988	0.952
	P2	0.975	1	0.967	0.948		**P2**	0.992	1	0.996	0.949
	P3	0.953	0.967	1	0.970		**P3**	0.988	0.996	1	0.958
$PM_{2.5}$ — MMI BOR NHS indoor	**P1**	1	0.984	0.930	0.928	**$PM_{2.5}$ — FOS NIŠ NHS indoor**	**P1**	1	0.991	0.984	0.952
	P2	0.984	1	0.955	0.958		**P2**	0.991	1	0.992	0.944
	P3	0.930	0.955	1	0.973		**P3**	0.984	0.992	1	0.951
PM_{10} — TP BOR NHS outdoor	**P1**	1	0.953	0.721	0.599	**PM_{10} — PHI NIŠ NHS outdoor**	**P1**	1	0.977	0.937	0.645
	P2	0.953	1	0.704	0.628		**P2**	0.977	1	0.928	0.644
	P3	0.721	0.704	1	0.624		**P3**	0.937	0.928	1	0.581
$PM_{2.5}$ — TP BOR NHS OUT	**P1**	1	0.942	0.733	0.807	**$PM_{2.5}$ — PHI NIŠ NHS outdoor**	**P1**	1	0.959	0.916	0.734
	P2	0.942	1	0.714	0.833		**P2**	0.959	1	0.932	0.777
	P3	0.733	0.714	1	0.765		**P3**	0.916	0.932	1	0.760
PM_{10} — MMI BOR HS indoor	**P1**	1	0.965	0.972	0.940	**PM_{10} — FOS NIŠ HS indoor**	**P1**	1	0.998	0.998	0.950
	P2	0.965	1	0.981	0.948		**P2**	0.998	1	0.998	0.952
	P3	0.972	0.981	1	0.975		**P3**	0.998	0.998	1	0.952
$PM_{2.5}$ — MMI BOR HS indoor	**P1**	1	0.990	0.980	0.935	**$PM_{2.5}$ — FOS NIŠ HS indoor**	**P1**	1	0.997	0.998	0.958
	P2	0.990	1	0.976	0.951		**P2**	0.997	1	0.998	0.955
	P3	0.980	0.976	1	0.973		**P3**	0.998	0.998	1	0.952
PM_{10} — TP BOR HS outdoor	**P1**	1	0.923	0.869	0.516	**PM_{10} — PHI NIŠ HS outdoor**	**P1**	1	0.996	0.987	0.805
	P2	0.923	1	0.935	0.597		**P2**	0.996	1	0.990	0.801
	P3	0.869	0.935	1	0.630		**P3**	0.987	0.990	1	0.786
$PM_{2.5}$ — TP BOR HS outdoor	**P1**	1	0.973	0.899	0.660	**$PM_{2.5}$ — PHI NIŠ HS outdoor**	**P1**	1	0.997	0.986	0.818
	P2	0.973	1	0.909	0.726		**P2**	0.997	1	0.986	0.819
	P3	0.899	0.909	1	0.548		**P3**	0.986	0.986	1	0.812

were 9.1 °C and 69.6% in HS and 21.4 °C and 51.6% in NHS, respectively.

The effect of T and RH on PM monitor readings needs to be taken into consideration when using low-cost particle sensors (Crilley et al., 2018; Wallace et al., 2011; Jayaratne et al., 2018; Venkatraman Jagatha et al., 2021). PM mass concentrations measured with any light scattering instrument increase with relative humidity due to the increase of the average particle size associated with condensational growth of its hygroscopic components (Chakrabarti et al., 2004; Fischer and Koshland, 2007; Badura et al., 2018; Liu et al., 2019).

The PM results were not corrected for T and RH influence because this investigation falls outside the scope of this paper; the influence of T and RH on the readings of the NOVA SDS011 sensor will be the subject of our future paper.

Based on our experimental research with the NOVA SDS011 sensor conducted in the previous 2 years in the outdoor air in Bor (the results have not been published yet), in the case of $RH > 80\%$, the PM_{10} readings highly overestimate the values obtained by the reference instrument (GRIMM EDM180). This also applies to $PM_{2.5}$ readings but is much less pronounced than in the case of PM_{10} readings.

For the sake of illustrating the influence of the outdoor environment on PM results, Fig. 5 shows the scatter plots of PM concentrations observed in the Bor outdoor air in the HS. The left portion of Fig. 5 shows lower values of R^2 in the case of PM_{10} results (influence of RH on readings) in comparison with the R^2 values obtained for $PM_{2.5}$ (Fig. 5, right portion).

Also, Fig. 6 shows the scatter plots of PM concentrations observed in the Niš indoor air in the HS. Figure 6, left portion, presents R^2 in the case of PM_{10}

results while the R^2 values for $PM_{2.5}$ are shown on the right. Both portions of Fig. 6 show excellent matching of PM results for both indoor PM_{10} and $PM_{2.5}$ fractions as well as excellent precision (AP).

Analysis of results obtained for the precision between the PM monitors

Table 5 shows the AP between the PM monitors obtained in this study. The ambient regulatory instruments must exhibit precision below 0.1 (Zamora et al., 2020). During the entire measurement period, precision between PM monitors P1 and P2 was below or equal to 0.1 with one exception (outdoor $PM_{2.5}$ TP Bor HS). The P3 monitor exhibited variable precision with P1 and P2 in the range from 0.04 up to 0.27, with the lowest values observed for PM2.5 fraction in the indoor air, but with no consistency required for the regulatory instruments.

Operational data coverage and other remarks

The operation of all tested PM monitors was stable and reliable during the entire duration of the measurements, without blockages and without missing data. In the last 3 years, we have tested more than 20 NOVA SDS011 PM sensors and implemented them in different types of PM monitoring devices. Our experience with NOVA SDS 011 is positive, considering the exceptional durability and stability of the sensors' PM readings in the indoor air. Not many investigations have been conducted so far in the outdoor air. There were only a few malfunctions of the sensor fan, which became quite loud, so it needed to be replaced.

Kuula et al. (2020) reported that the NOVA SDS011 sensor can be inaccurate for PM_{10} measurements, which was also concluded by (Budde et al., 2018). Regardless, the NOVA SDS011 sensor has the potential to measure $PM_{2.5}$ concentrations fairly accurately (Badura et al., 2018; Liu et al., 2019). The present research showed that for the indoor $PM_{2.5}$ concentrations in the range 0–200 μg/m^3, with appropriate correction of the PM results obtained from low-cost PM monitors by comparing them with the results obtained from the reference instruments, and for a specific T range 10–30 °C and RH range 10–70%, the tested PM monitors can be sufficiently accurate for quantitative measurements of $PM_{2.5}$ mass concentrations in indoor air.

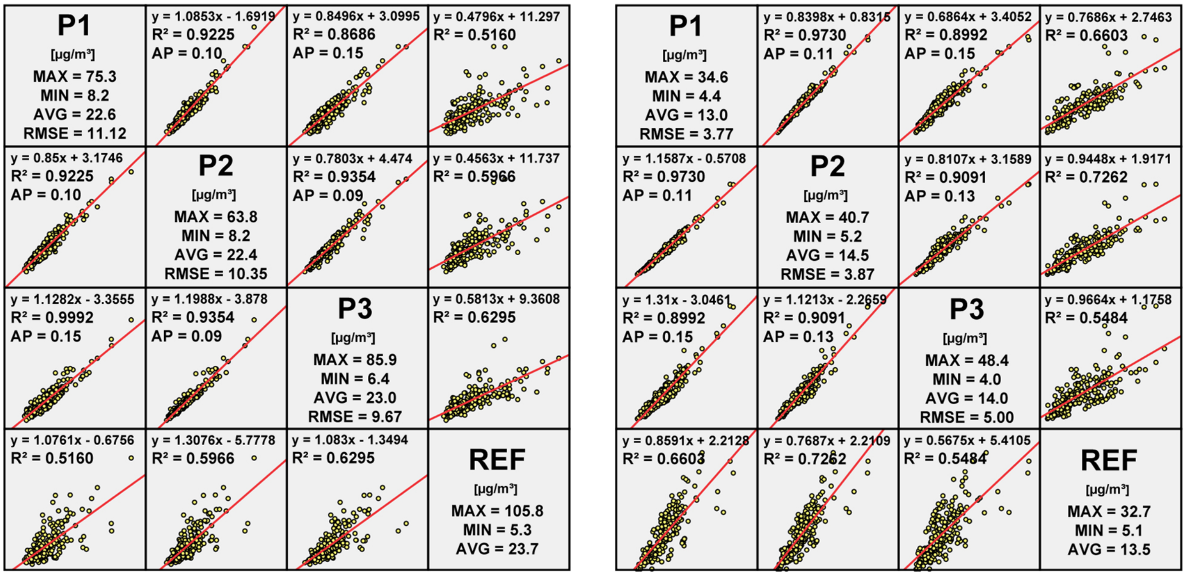

Fig. 5 Scatter plots of the 1-h mean outdoor PM mass concentrations measured at TP Bor in HS (PM_{10} on the left, $PM_{2.5}$ on the right)

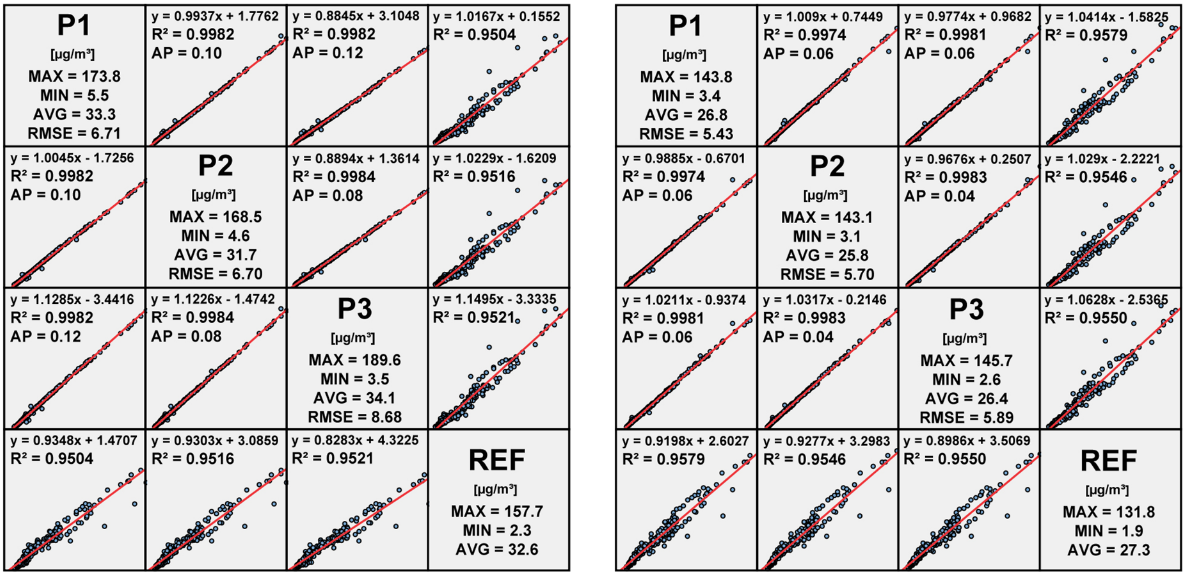

Fig. 6 Scatter plots of the 1-h mean indoor PM mass concentrations measured at FOS Niš in HS (PM_{10} on the left, $PM_{2.5}$ on the right)

Table 5 Summary of precision (AP) between the PM monitors

BOR **campaigns**	Unit	AP **P1**	AP **P2**	AP **P3**	NIŠ **campaigns**	Unit	AP **P1**	AP **P2**	AP **P3**
PM_{10} — MMI BOR	**P1**	0	0.08	0.18	**PM_{10} — FOS NIŠ**	**P1**	0	0.09	0.16
NHS indoor	**P2**	0.08	0	0.15	**NHS indoor**	**P2**	0.09	0	0.09
	P3	0.18	0.15	0		**P3**	0.16	0.09	0
$PM_{2.5}$ — MMI BOR	**P1**	0	0.05	0.15	**$PM_{2.5}$ — FOS NIŠ**	**P1**	0	0.08	0.09
NHS indoor	**P2**	0.05	0	0.12	**NHS indoor**	**P2**	0.08	0	0.08
	P3	0.15	0.12	0		**P3**	0.09	0.08	0
PM_{10} — TP BOR	**P1**	0	0.07	0.26	**PM_{10} — PHI NIŠ**	**P1**	0	0.10	0.12
NHS outdoor	**P2**	0.07	0	0.27	**NHS outdoor**	**P2**	0.10	0	0.09
	P3	0.26	0.27	0		**P3**	0.12	0.09	0
$PM_{2.5}$ — TP BOR	**P1**	0	0.10	0.18	**$PM_{2.5}$ — PHI NIŠ**	**P1**	0	0.04	0.12
NHS OUT	**P2**	0.10	0	0.22	**NHS outdoor**	**P2**	0.04	0	0.12
	P3	0.18	0.22	0		**P3**	0.12	0.12	0
PM_{10} — MMI BOR	**P1**	0	0.07	0.16	**PM_{10} — FOS NIŠ**	**P1**	0	0.10	0.12
HS indoor	**P2**	0.07	0	0.17	**HS indoor**	**P2**	0.10	0	0.08
	P3	0.16	0.17	0		**P3**	0.12	0.08	0
$PM_{2.5}$ — MMI BOR	**P1**	0	0.06	0.14	**$PM_{2.5}$ — FOS NIŠ**	**P1**	0	0.06	0.06
HS indoor	**P2**	0.06	0	0.10	**HS indoor**	**P2**	0.06	0	0.04
	P3	0.14	0.10	0		**P3**	0.06	0.04	0
PM_{10} — TP BOR	**P1**	0	0.10	0.15	**PM_{10} — PHI NIŠ**	**P1**	0	0.05	0.10
HS outdoor	**P2**	0.10	0	0.09	**HS outdoor**	**P2**	0.05	0	0.06
	P3	0.15	0.09			**P3**	0.10	0.06	0
$PM_{2.5}$ — TP BOR	**P1**	0	0.11	0.15	**$PM_{2.5}$ — PHI NIŠ**	**P1**	0	0.05	0.11
HS outdoor	**P2**	0.11	0	0.13	**HS outdoor**	**P2**	0.05	0	0.11
	P3	0.15	0.13	0		**P3**	0.11	0.11	0

Conclusions

In the last decade, as a possible alternative to the conventional approach to air quality monitoring, real-time monitoring systems that use low-cost sensors and sensor platforms have been applied. Despite their frequent use, mainly in the monitoring of outdoor PM concentrations, long-term characteristics of low-cost PM sensors have not been thoroughly documented except for a few widely used sensors and monitors. This research focused on the laboratory and field validation of three low-cost PM monitors of the same type that use the NOVA SDS011 PM sensor module over a 1-year period, aiming to provide an insight into their characteristics in different indoor and outdoor environments.

The lowest values of R^2 between the PM monitors and the reference instruments were obtained for outdoor air while the highest values were obtained for indoor air with R^2 values ranging from 0.93 up to 0.97 ($30 < RH < 70\%$). High RH values (over 70%) negatively affected the PM monitors' response, especially in the case of PM_{10} concentrations (high overestimation). Almost during the entire measurement period, precision between PM monitors P1 and P2 for both PM_{10} and $PM_{2.5}$ fractions was below or equal to 0.1, which is required for the regulatory instruments, while the P3 monitor exhibited more variable precision compared with P1 and P2. The accuracy of the PM monitors was mostly over 90%. Based on all the facts mentioned above, it can be concluded that the NOVA SDS011 sensor module is suitable for indicative measurements of PM particles in indoor air. All tested PM monitors showed very similar mean PM values, SD, CV, and RMSE values. Further testing of this low-cost sensor will be conducted in order to determine the best model for correction the influence of humidity, temperature, and other meteorological factors on outdoor PM readings.

Author contribution AB: conceptualization, investigation, data collection, writing — original draft, lead author. VT: data collection, gravimetric analysis lead, writing — original draft. NŽ: study planning, data curation, formal analysis. IL: data collection, instrument preparation and operation. MB: data collection, writing — review and editing. NM: data collection, methodology. DT: data collection, formal analysis, visualization.

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Data availability The datasets used or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors declare no competing interests.

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