FACTA UNIVERSITATIS
Series: **Working and Living Environmental Protection** Vol. 21, Nº 3, 2024, pp. 143 - 153
https://doi.org/10.22190/FUWLEP241206013B

Original scientific paper

EVALUATION OF A LOW-COST-SENSOR-BASED PARTICULATE MATTER MONITOR: A COMPARATIVE STUDY

UDC 502.3:504.3.054

Aca Božilov

University of Niš, Faculty of Occupational Safety, Niš, Republic of Serbia

ORCID iD Aca Božilov https://orcid.org/0000-0001-7032-4789

Abstract. *Indoor air quality (IAQ) significantly affects health, productivity, and comfort, particularly in urban environments, where individuals spend over 90% of their time indoors. Indoor air is often more polluted than outdoor air due to various indoor pollution sources. Effective IAQ monitoring is essential but often constrained by the high cost and complexity of traditional gravimetric methods and high-end automatic monitors. Emerging low-cost sensors offer an affordable and scalable alternative.*
This study examines the performance of the PM V1.0 device, equipped with a low-cost NOVA SDS011 particulate matter sensor (PM_{10} and $PM_{2.5}$ fractions). The PM V1.0 was compared against two commercially available monitors: the high-precision Microdust PRO CEL-712 and the budget-friendly Dylos DC1100 PRO. Measurements conducted over 10 days through co-location of the monitors showed strong correlations between the PM V1.0 and the comparison devices, with coefficients of determination (R^2) values exceeding 0.93 for both PM fractions.
These findings validate the PM V1.0 as a reliable, cost-effective alternative for IAQ monitoring. The research highlights the potential of low-cost sensors to improve IAQ monitoring by providing affordable solutions.

Key words: *Indoor Air Quality Monitoring, Particulate Matter (PM_{10}, $PM_{2.5}$), Low-Cost Sensors, NOVA SDS011, Microdust PRO CEL-712, Dylos DC1100 PRO*

1. INTRODUCTION

Urban residents spend more than 90% of their time indoors, making indoor air quality (IAQ) a critical factor for their comfort, productivity, and health [1]. The relationship between IAQ and overall quality of life is complex and can have both short-term and long-term effects. These effects may range from mild discomfort and reduced focus to

Received December 6, 2024 / Accepted December 8, 2024
Corresponding author: Aca Božilov
University of Niš, Faculty of Occupational Safety, Čarnojevića 10a, 18000 Niš, Serbia
E-mail: aca.bozilov@znrfak.ni.ac.rs

respiratory tract irritation, headaches, and more severe conditions, such as respiratory infections and chronic diseases [2].

Indoor air quality is often worse than outdoor air quality, despite the influence of outdoor air on indoor environments. This is because indoor spaces frequently have additional sources of pollution directly linked to activities of the occupants. Given the limited natural purification mechanisms in enclosed spaces, the concentration of pollutants in such environments can be significantly higher, further complicating the issue of pollution [3].

In Serbia, air quality monitoring is primarily focused on outdoor environments and industrial workplaces, in accordance with existing regulations. Unlike industrial workplaces, there are no specific guidelines for monitoring IAQ in non-industrial buildings, such as residential buildings, public facilities, and administrative offices.

Particulate matter (PM), including PM_{10}, $PM_{2.5}$, and $PM_{0.1}$, is used worldwide as a key indicator of air quality due to its association with serious health issues, such as respiratory and cardiovascular diseases [4, 5].

Traditional methods for measuring PM concentrations, such as gravimetric methods, are considered the gold standard but are time-consuming and expensive, with results typically available days after sampling. In contrast, automatic stationary monitors enable real-time monitoring of PM concentrations but are too expensive to purchase and maintain, with prices reaching up to €20,000 [6].

Consequently, PM monitoring, which often involves filter collection and gravimetric analysis or the use of relatively expensive equipment, ultimately limits the spatial and temporal resolution of PM data [7, 8]. To address this, commercially available portable devices are increasingly used as an alternative to automatic stationary monitors. These devices mainly operate on an optical principle, counting particles and converting the count into mass concentrations. Portable PM monitors are significantly smaller than stationary ones, and their prices range from several hundred to several thousand euros, making them more accessible. Devices such as the Microdust PRO CEL-712 by Casella offer similar capabilities for no more than €6,000, while more affordable options (devices), such as the Dylos DC1100 PRO, are available for around €300. However, both types of devices require calibration and adaptation to specific conditions, and their accuracy can be further affected by relative humidity.

Recent technological advancements have led to the development of affordable low-cost sensors, such as the NOVA SDS011, which utilise the principle of laser scattering to detect particulate matter [9]. These sensors allow for high spatial and temporal resolution PM concentration measurements and are often priced below €100. Their small size, low power consumption, and ease of maintenance make them ideal for indoor air monitoring. However, the operation and key characteristics of these sensors have not been thoroughly examined, leaving room for further improvement in this field.

As part of this study, a new device, PM V1.0, was developed based on the NOVA SDS011 sensor to provide a cost-effective solution for monitoring PM_{10} and $PM_{2.5}$ concentrations in indoor environments. Its measurement results were compared with those obtained from commercial devices in different price ranges, such as the Microdust PRO and the Dylos DC1100 PRO. The comparison involved regression and correlation analyses, with the coefficient of determination (R^2) used to assess the consistency of results. The aim of the study was to confirm the potential of low-cost sensors for broader application in proactive indoor air quality monitoring systems.

2. METHODOLOGY

The study was conducted in the Air Quality Management Laboratory at the Faculty of Occupational Safety, University of Niš (FOS). The experiment involved the co-location of three different PM concentration monitors: the tested PM V1.0 device, based on an Arduino platform with a NOVA SDS011 PM sensor, and two commercially available monitors in various price ranges – the Microdust PRO CEL-712 and the Dylos DC1100 PRO. All three devices are shown in Figure 1.

2.1. Description of measuring devices

- **Microdust PRO CEL-712**

The Microdust PRO CEL-712 is a real-time particle concentration monitoring device that utilises the proven forward light scattering principle, providing precise and reliable dust concentration measurements ranging from 0.001 mg/m³ to 250 g/m³ [10]. It was combined with a TUFF sampling pump, which provided a constant flow rate, and additional adapters for inserting polyurethane foam (PUF) filters. An AC/DC adapter powered the device, and a technical modification to the pump's battery charger allowed continuous operation beyond the factory limitation, which enabled continuous and uninterrupted monitoring. Additional adapters and PUF filters (PM_{10} and $PM_{2.5}$ measurements can be made using a PUF size-selective inlet system) facilitated the measurement of PM_{10} and $PM_{2.5}$ concentrations. The collected data were then uploaded to a computer using the Casella Insight Data Management software.

The Microdust PRO monitor was selected as the reference device for measuring PM_{10} and $PM_{2.5}$ particle concentrations due to its calibration capabilities, which make it a reliable reference device for comparing results obtained from the low-cost NOVA SDS011 sensor and the Dylos DC1100 PRO. This device allows pre-measurement linearity adjustments, including ZERO calibration, which ensures a precise setup. It features a unique optical calibration insert, which establishes known instrument sensitivity or SPAN, providing highly accurate and reliable measurements. When inserted into the probe, the calibration insert creates a stable and fixed scattering effect. Similar to factory calibration (using Arizona Road Dust equivalent – ISO 12103-1 A2 (fine) test dust), the insert generates a light-scattering effect equivalent to the factory concentration level. This fixed reference value, indicated on the calibration insert's label, should be entered into the device to confirm the original factory calibration point.

- **Dylos DC1100 PRO**

The Dylos DC1100 PRO (with PC interface) is a low-cost laser particle counter designed to measure particle concentrations in indoor air. It features two particle size channels and measures (counts) and records in real time the numerical concentration of particles with diameters greater than 0.5 μm and 2.5 μm [11]. Continuous operation was achieved using a power adapter, and the device was connected to a personal computer via an RS-232 connector. The accompanying Data Logger software allowed for data acquisition. The particle number concentration (PNC) of PM_{10} and $PM_{2.5}$ was subsequently converted to particle mass concentration (PMC) based on particle size, density, and count (number of particles) using the equation developed by Arling et al. [12].

- **PM V1.0 Device**

The developed PM V1.0 device, based on the Arduino platform and the NOVA SDS011 sensor module [13], is primarily designed for measuring PM_{10} and $PM_{2.5}$ concentrations within a range of 0-999.9 µg/m³, as well as ambient air temperature (-10 to +50 °C) and relative humidity (20–90% RH) by using the DHT22 sensor module [14]. Additional parameters (e.g. CO_2, VOCs, pressure) can be measured by integrating supplementary sensor modules into the device. Unlike most commercially available PM monitors, this device can be powered directly via an AC/DC adapter and it can operate independently for several days owing to an internal high-capacity battery. It allows adjustable measurement averaging intervals ranging from 5 seconds to 1 hour. Pre-determined correction factors can be set for specific environmental conditions, ensuring accurate real-time PM concentration readings displayed on the device. Lightweight, portable, and quiet, the PM V1.0 is well-suited for personal PM exposure monitoring in indoor environments.

Fig. 1 (a) Casella Microdust Pro CEL-712, (b) Dylos DC1100 PRO (with PC interface), (c) PM V1.0 (with NOVA SDS011 sensor module) [10,11]

2.2. Co-location of the devices

All devices were placed on the same table, 10 cm apart (Figure 2), and exposed to identical air pollution conditions for a total duration of 10 days. Over the first five days, $PM_{2.5}$ concentrations were measured, followed by PM_{10} concentrations over the subsequent 5 days, as the Microdust PRO CEL-712 can only measure one fraction at a time depending on the installed filter. Average 15-minute PM concentration values recorded by the devices were compared.

To assess the agreement between the measurements recorded by the low-cost device and the other two devices, the coefficient of determination (R^2) was calculated. The coefficient of determination is a useful metric for assessing the accuracy and reliability of low-cost devices, indicating whether the tested device replicates the measurements of the reference device and whether it can replace it in practice. A higher R^2 value indicates a stronger agreement between the two sets of results.

Fig. 2 Co-location of PM measuring devices in the FOS laboratory

In the context of simple linear regression, the coefficient of determination (R^2) is equal to the square of Pearson's correlation coefficient between the dependent variable (y) and the independent variable (x). It is calculated using the following equation:

$$R^2 = \left(\frac{\sum (x_i - \bar{x}) \cdot (y_i - \bar{y})}{\sqrt{\sum (x_i - \bar{x})^2 \cdot \sum (y_i - \bar{y})^2}} \right), \quad (1)$$

where:

- x_i is the measurement value obtained by the reference device;
- y_i is the measurement value obtained by the tested device;
- $\bar{x}$ is the mean value of the reference device data;
- $\bar{y}$ is the mean value of the tested device data.

This calculation quantifies the degree of alignment between the results obtained by all three devices, providing a basis for determining the potential of the PM V1.0 device as a low-cost alternative for indoor air quality monitoring.

3. Results and Discussion

The results of this study reveal valuable insights into the performance and reliability of the tested PM V1.0 device compared to the commercially available Microdust PRO and Dylos DC1100 PRO monitors. The following sections provide a detailed comparison of the measurement results, emphasizing the correlation between the devices and discussing the implications of these findings for air quality monitoring.

The decision to use 15-minute mean values, despite all devices being capable of measuring 1-minute concentrations, was made for three important reasons. Firstly, averaging over 15 minutes helps facilitate the identification of meaningful trends and patterns that might be obscured by short-term fluctuations. Furthermore, using 15-minute means ensures consistency across the measurements from all devices, providing a fair comparison and reducing the influence of any transient anomalies. Lastly, handling 15-minute averages makes data management more efficient, simplifying the analysis process.

Figures 3 and 4 present the average 15-minute PM_{10} and $PM_{2.5}$ concentrations recorded in the FOS laboratory. These line charts illustrate the consistency and variability in the measurements across the different devices over the test period.

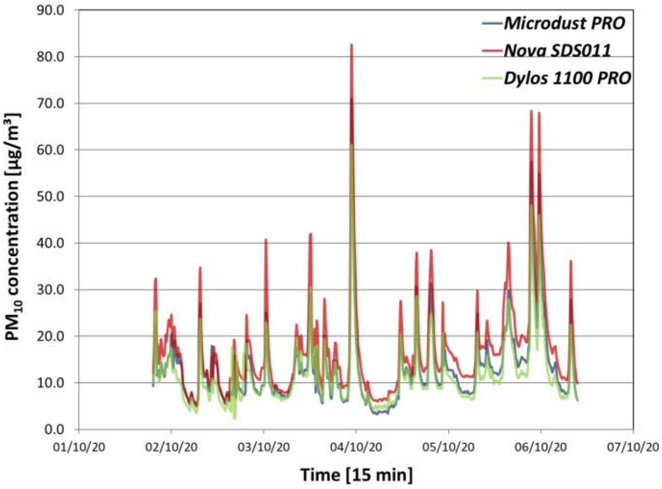

Fig. 3 PM_{10} concentration measurements in the FOS laboratory

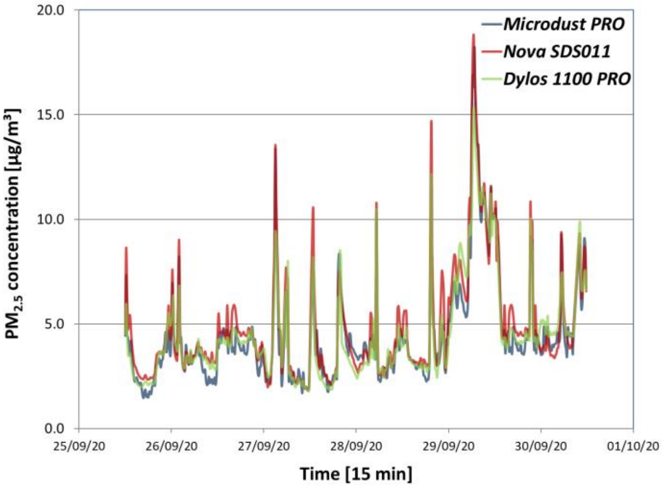

Fig. 4 $PM_{2.5}$ concentration measurements in the FOS laboratory

Figures 5, 6, and 7 show scatter plots comparing PM_{10} concentrations across all devices.

The coefficient of determination ($R^2 = 0.9757$) indicates a very strong linear dependence between PM_{10} concentration measurements obtained using the Microdust PRO device and the NOVA SDS011 sensor.

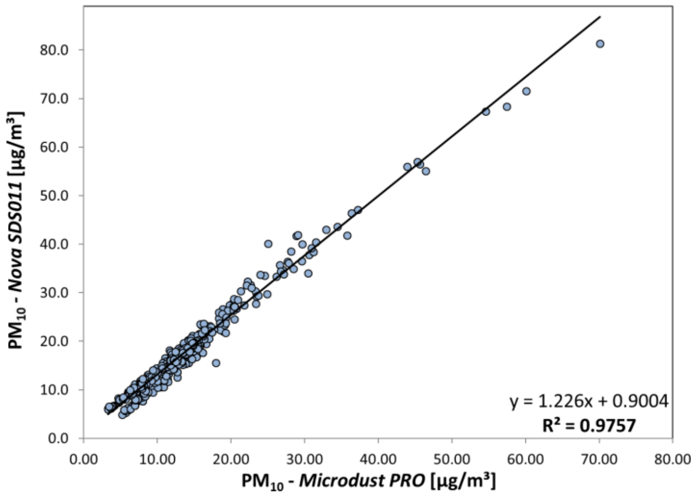

Fig. 5 PM_{10} concentrations – Microdust PRO vs. NOVA SDS011

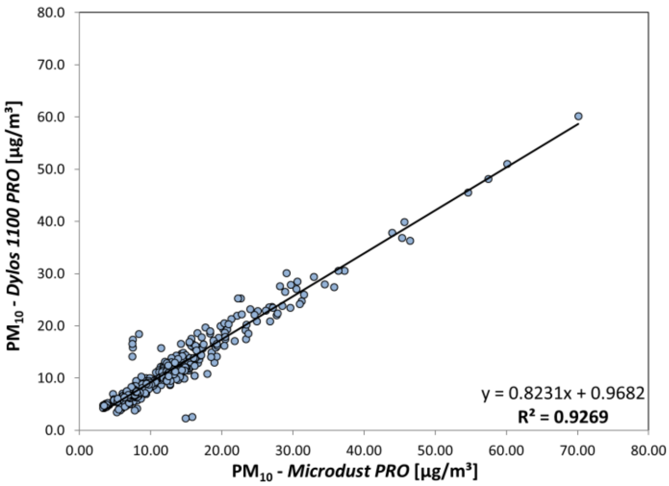

Fig. 6 PM_{10} concentrations – Microdust PRO vs. Dylos DC1100 PRO

The coefficient of determination (R^2 = 0.9269) also suggests a very strong linear dependence between PM_{10} concentration measurements obtained using the Microdust PRO and Dylos DC1100 PRO devices.

The coefficient of determination (R^2 = 0.945) demonstrates that there is a very strong correlation between the PM_{10} concentration measurements obtained using the low-cost NOVA SDS011 sensor and the Dylos DC1100 PRO device, which is also in the low-cost range.

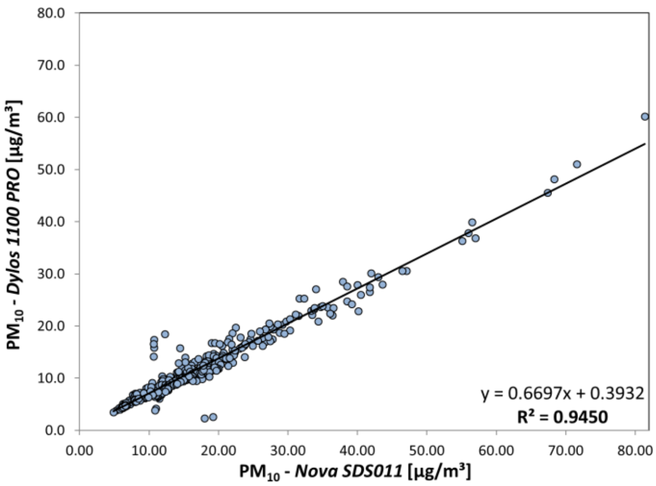

Fig. 7 PM_{10} concentrations – NOVA SDS011 vs. Dylos DC1100 PRO

Figures 8, 9, and 10 show scatter plots comparing $PM_{2.5}$ concentrations across all devices.

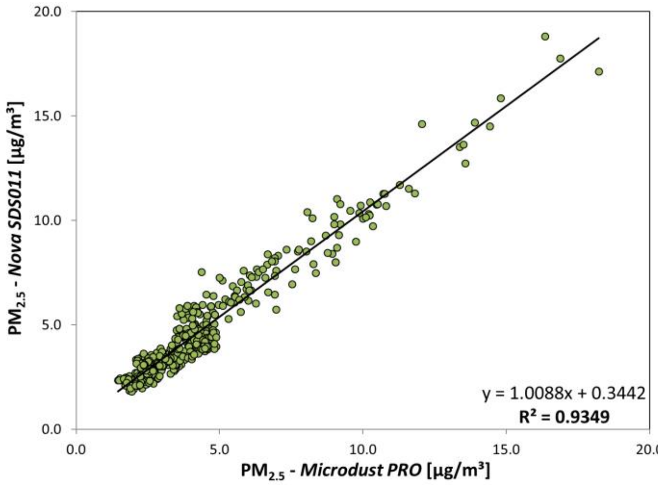

Fig. 8 $PM_{2.5}$ concentrations – Microdust PRO vs. NOVA SDS011

The coefficient of determination (R^2 = 0.9349) indicates a very strong linear dependence between $PM_{2.5}$ concentration measurements obtained using the Microdust PRO device and the NOVA SDS011 sensor.

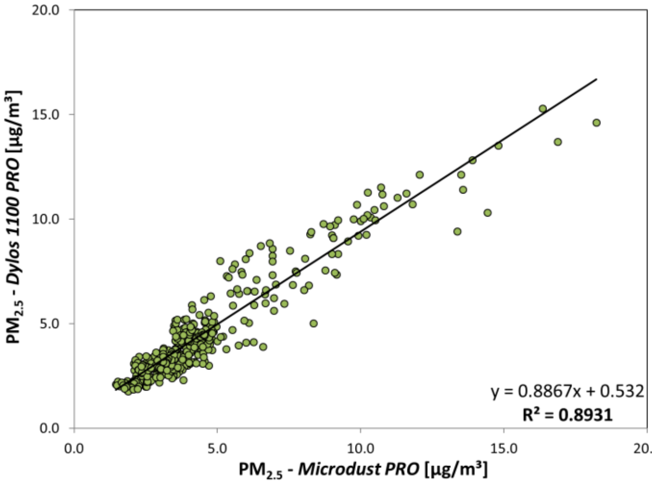

Fig. 9 $PM_{2.5}$ concentrations – Microdust PRO vs. Dylos DC1100 PRO

The coefficient of determination (R^2 = 0.8931) shows a very strong linear dependence between $PM_{2.5}$ concentration measurements obtained using the Microdust PRO and Dylos DC1100 PRO devices, slightly weaker than the dependence observed for PM_{10} concentrations.

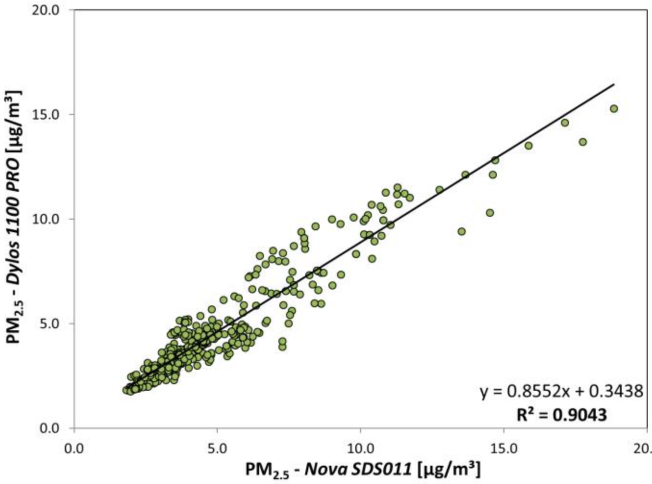

Fig. 10 $PM_{2.5}$ concentrations – NOVA SDS011 vs. Dylos DC1100 PRO

The coefficient of determination (R^2 = 0.9043) reflects a very strong correlation between the $PM_{2.5}$ concentration measurements obtained using the low-cost NOVA SDS011 sensor and the Dylos DC1100 PRO device, albeit slightly weaker than the correlation observed for PM_{10}.

The comparison of PM_{10} and $PM_{2.5}$ measurements between the commercially available Microdust PRO, which falls into a high price range, the more affordable, commercially available Dylos DC1100 PRO, and the NOVA SDS011-based PM V1.0 monitor revealed strong linear correlations, with R^2 values ranging from 0.8931 to 0.9757. The NOVA SDS011 sensor, in particular, showed excellent agreement with the Microdust PRO, especially for PM_{10} concentrations, where the R^2 value was 0.9757. While the Dylos DC1100 PRO exhibited slightly weaker correlations, it still demonstrated reliable performance across both PM fractions, reflecting its consistent performance within its lower price range. Overall, while PM_{10} measurements showed stronger correlations, the results confirm that the developed PM V1.0 monitor can be used as a reliable alternative for monitoring particulate matter, especially in budget-constrained applications. These findings validate the potential of low-cost sensors for air quality monitoring, highlighting their effectiveness, notably in indoor environments and cost-sensitive applications.

4. CONCLUSION

The results of this study demonstrate that low-cost sensors, such as the NOVA SDS011, can provide reliable measurements of particulate matter (PM) concentrations when compared to more expensive instruments. With high coefficients of determination indicating strong correlations, these sensors can be effectively used for monitoring indoor air quality (IAQ), which is crucial for the health and well-being of people who spend over 90% of their time indoors.

The study involved the co-location of low-cost and commercially available monitors, showing strong linear correlations between their measurements. The NOVA SDS011 sensor-based PM V1.0 device, in particular, demonstrated its ability to deliver accurate and consistent PM data at a fraction of the cost of traditional monitoring equipment. Therefore, it is a practical solution for applications where budget constraints limit the use of high-cost devices.

Despite their promising performance, low-cost PM sensors such as the NOVA SDS011 require thorough calibration and validation under various environmental conditions to ensure accuracy. Factors such as humidity, temperature, and the presence of other pollutants can affect sensor performance, and these variables need to be accounted for in future studies.

Moreover, the integration of these sensors into a wider air quality monitoring network could enhance the spatial and temporal resolution of air quality data. This could lead to better-informed public health policies and interventions aimed at reducing exposure to harmful particulate matter.

Ongoing research and development is essential to optimise their performance and expand their application in both indoor and outdoor air quality monitoring. Incorporating additional sensors for parameters such as CO_2, VOCs, and pressure could make devices like the PM V1.0 more versatile and comprehensive. In conclusion, low-cost sensors offer significant advantages in terms of affordability and ease of use, and with continued advancement, they could play a critical role in improving public health by providing detailed and accessible air quality data.

Acknowledgement: *This study was financially supported by the Ministry of Education, Science and Technological Development of the Republic of Serbia, Grant No. 451-03-66/2024-03/200148.*

REFERENCES

1. Kozielska B, Ferdyn-Grygierek J, Slezakova K, Sowa J, Hassan SKM. Editorial: Indoor environmental air quality in urban areas. Front Environ Sci 2024;12. https://doi.org/10.3389/fenvs.2024.1393997
2. Darçın M. Association between air quality and quality of life. Environ Sci Pollut Res 2013; 21: 1954–9. https://doi.org/10.1007/s11356-013-2101-3.
3. Leung DYC. Outdoor-indoor air pollution in urban environment: challenges and opportunity. Front Environ Sci 2015;2. https://doi.org/10.3389/fenvs.2014.00069
4. Fuzzi S, Baltensperger U, Carslaw K, Decesari S, Denier van der Gon H, Facchini MC, et al. Particulate matter, air quality and climate: lessons learned and future needs. Atmos Chem Phys 2015; 15: 8217–99. https://doi.org/10.5194/acp-15-8217-2015
5. Mukherjee A, Agrawal M. World air particulate matter: sources, distribution and health effects. Environ Chem Lett 2017; 15: 283–309. https://doi.org/10.1007/s10311-017-0611-9
6. Shukla K, Aggarwal SG. Particulate Matter Measurement Techniques. Handbook of Metrology and Applications 2022: 1–29. https://doi.org/10.1007/978-981-19-1550-5_133-1
7. Manikonda A, Zíková N, Hopke PK, Ferro AR. Laboratory assessment of low-cost PM monitors. Journal of Aerosol Science 2016; 102:29–40. https://doi.org/10.1016/j.jaerosci.2016.08.010.
8. Watson JG, Tropp RJ, Kohl SD, Wang X, Chow JC. Filter Processing and Gravimetric Analysis for Suspended Particulate Matter Samples. Aerosol Sci Eng 2017; 1:93–105. https://doi.org/10.1007/s41810-017-0010-4.
9. Božilov A, Tasić V, Živković N, Lazović I, Blagojević M, Mišić N, et al. Performance assessment of NOVA SDS011 low-cost PM sensor in various microenvironments. Environ Monit Assess 2022; 194. https://doi.org/10.1007/s10661-022-10290-7
10. CEL-712 Microdust Pro Real-time Dust Monitor – HB4048-03 User Manual, Casella Cell [Online]. URL: https://www.casellasolutions.com/product_support/airsampling/microdustpro/documentation.html [Accessed 8 Nov 2024]
11. DC1100 PRO AIR QUALITY MONITOR with PC INTERFACE [Online] URL: http://www.dylosproducts.com/dcproairqumo.html [Accessed 10 Nov 2024]
12. Arling, J., O'Connor, K., Mercieca, M. Air Quality Sensor Network for Philadelphia. Data Validation, 2010. [Online]. URL: https://www.fijnstofmeter.com/documentatie/Data-Validation.pdf [Accessed 15 Nov 2024]
13. Nova PM SDS011 Dust Particle Sensor for Air Quality Measurement [Online]. URL: http://en.novasensor.cn/?list_16/55.html [Accessed 7 Nov 2024]
14. Sparkfun DHT22 Humidity and Temperature Sensor [Online]. URL: https://www.sparkfun.com/datasheets/Sensors/Temperature/DHT22.pdf, [Accessed 7 Nov 2024]

EVALUACIJA MONITORA KONCENTRACIJA SUSPENDOVANIH ČESTICA ZASNOVANOG NA NISKOBUDŽETNOM SENZORU: KOMPARATIVNA STUDIJA

Kvalitet unutrašnjeg vazduha značajno utiče na zdravlje, produktivnost i udobnost, naročito u urbanim sredinama gde pojedinci provode više od 90% svog vremena u zatvorenom prostoru. Unutrašnji vazduh je često zagađeniji od spoljašnjeg zbog različitih izvora zagađenja u zatvorenim prostorima. Efikasno praćenje kvaliteta unutrašnjeg vazduha je od ključnog značaja, ali je često ograničeno visokim troškovima i složenošću tradicionalnih gravimetrijskih metoda i automatskih monitora visoke klase. Novi niskobudžetni senzori nude pristupačnu i skalabilnu alternativu.

U ovoj studiji ispitane su performanse uređaja PM V1.0, opremljenog niskobudžetnim NOVA SDS011 senzorom za merenje koncentracija suspendovanih čestica (frakcije PM_{10} i $PM_{2.5}$). PM V1.0 je upoređen sa dva komercijalno dostupna monitora: visokopreciznim Microdust PRO CEL-712 i cenovno pristupačnijim Dylos DC1100 PRO. Merenja u trajanju od 10 dana, vršena kolokacijom sva 3 monitora, pokazala su jake korelacije između PM V1.0 i uporednih uređaja, sa vrednostima koeficijenata determinacije (R^2) većim od 0,93 za obe frakcije PM.

Rezultati su potvrdili da je PM V1.0 pouzdana i isplativa alternativa za praćenje kvaliteta unutrašnjeg vazduha. Istraživanje ističe potencijal niskobudžetnih senzora za unapređenje praćenja kvaliteta unutrašnjeg vazduha pružanjem cenovno pristupačnih rešenja.

Ključne reči: *monitoring kvaliteta unutrašnjeg vazduha, suspendovane čestice (PM_{10}, $PM_{2,5}$), niskobudžetni senzori, NOVA SDS011, Microdust PRO CEL-712, Dylos DC1100 PRO*