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INDOOR AND OUTDOOR AIR QUALITY: ANALYSIS OF SUSPENDED PARTICLES IN RESIDENTIAL SPACES IN BOR, SERBIA

Abstract: *This study examines the levels of suspended particles (PM_{10} and $PM_{2.5}$) in residential settings in Bor, Serbia, alongside simultaneous outdoor measurements of PM. The project lasts 2 years and involves 30 apartments per year, selected based on criteria such as window type, connection to central heating, non-smoking status, distance from major pollution sources, and prevailing wind direction. Results from the winter measurement campaign (heating season) in 15 apartments, presented here, show that indoor PM concentrations vary significantly depending on ventilation habits, window type, and proximity to pollution sources. Measurements were conducted over 45 days during the heating season, and residents maintained activity diaries to document household activities. The average PM_{10} concentration in apartments was 18.2 μg/m³, while the average $PM_{2.5}$ concentration was 12.0 μg/m³. The average indoor/outdoor concentration ratio was 0.58 for PM_{10} and 0.68 for $PM_{2.5}$. The final results of this project will support the development of recommendations aimed at reducing indoor air pollution in urban homes across Serbia.*

Keywords: air quality, monitoring, suspended particles, measurement

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INTRODUCTION

Air pollution, particularly involving particulate matter (PM), has emerged as a significant environmental and public health concern globally. Fine particles such as PM_{10} (particles with diameters ≤ 10 μm) and $PM_{2.5}$ (particles with diameters ≤ 2.5 μm) are especially hazardous due to their ability to penetrate deep into the respiratory system, leading to various health issues. These particles have been linked to increased risks of cardiovascular and respiratory diseases, lung cancer, and premature mortality, especially in vulnerable populations such as children, the elderly, and individuals with pre-existing conditions (Gladović et al., 2023).

While outdoor air pollution has been extensively monitored, indoor air quality (IAQ) has only recently gained the attention it deserves. Given that people spend up to 90% of their time indoors, indoor exposure to PM represents a substantial public health risk. Indoor PM concentrations are influenced not only by outdoor air infiltration but also by indoor sources such as heating, cooking, and smoking. In urban and industrial areas, studies have shown that indoor PM levels can often rival or exceed those measured outdoors (Radović et al., 2024).

The city of Bor in eastern Serbia is one of the country's most prominent industrial centers, primarily due to its large-scale copper mining and smelting operations. This industrial activity has long been associated with poor air quality. Studies from recent years have confirmed that Bor frequently exceeds national and European Union air quality standards, particularly for outdoor SO_2 and PM_{10} concentrations and content of As, Pb, and Cd in PM_{10} samples (Serbula et al., 2013; Tasić et al., 2010; Tasić et al., 2012; Tasić et al., 2017), while some studies have investigated PM levels in public buildings or outdoor urban areas, there is a lack of systematic data on PM concentrations in residential settings in Bor.

To address the existing knowledge gap concerning indoor air quality in Bor, a scientific research initiative was launched in January 2025. This project, funded by the Center for the Promotion of Science (CPN), involves a collaborative effort between the Mining and Metallurgy Institute Bor (MMI Bor) and the civil society organization "Građanska čitaonica Evropa." The primary objective is to quantify the concentrations of PM (PM_{10} and $PM_{2.5}$) within residential environments and assess the extent to which indoor air quality is influenced by Bor's well-documented ambient air pollution.

The project is scheduled to span a two-year period and will involve air quality measurements in 30 residential units per year, selected from the broader central area of Bor. Based on responses to a preliminary citizen survey, 60 apartments will be chosen - 30 equipped with wooden window frames and 30 with PVC or aluminium joinery.

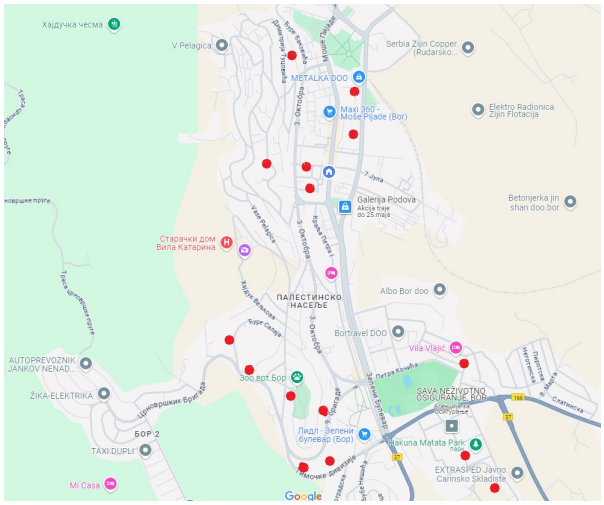

Figure 1. *Location of the first 15 selected apartments in the city of Bor*

Inclusion criteria include connection to the central heating system and occupancy by non-smoking residents. In each apartment, measurements will be conducted over two 40–50 day periods: one during the heating season and the other during the non-heating season.

Residents will be actively engaged in the study through participation in the measurement process within their homes. They will be asked to maintain a detailed activity diary during the monitoring periods, which will be instrumental in evaluating their exposure to particulate matter and understanding the influence of routine household activities on indoor PM concentrations.

The research team will analyze both the measured PM levels and the self-reported activity data to identify correlations and potential causal relationships.

Through seasonal sampling and comprehensive data analysis, the study aims to elucidate patterns and interrelations between indoor and ambient PM levels. It also seeks to enhance public awareness regarding the health implications of indoor air pollution. By integrating scientific expertise and civic participation, the initiative promotes a collaborative model for environmental monitoring and public health research. The empirical data generated will contribute to the broader scientific understanding of indoor air pollution in industrial urban contexts and support the formulation of evidence-based mitigation strategies.

Ultimately, the findings will inform both policymakers and residents, offering insights into how to improve living conditions and reduce health risks associated with prolonged exposure to particulate matter indoors.

METHODOLOGY

This paper presents the results of measurements of PM concentrations (PM_{10} and $PM_{2.5}$) conducted in 15 residential apartments in the city of Bor, during the period from March 1 to April 17, 2025. Figure 1 shows the locations of the 15 selected apartments on the map of the city of Bor. Among the 15 selected apartments, eight featured PVC window frames, whereas the remaining seven had wooden frames.

Figure 2. *PM monitor installed in the apartment*

PM measurements in indoor air

In each apartment, an automatic PM monitor (Božilov et al., 2022) was installed to continuously measure PM_{10} and $PM_{2.5}$ concentrations, along with indoor temperature and relative humidity (Figure 2).

The PM monitors recorded one-minute average values for all observed parameters, while hourly averages were used for the analyses presented in this paper. Prior to deployment in real-world settings, all PM monitors were tested under laboratory conditions at the MMI Bor to verify measurement accuracy. During the calibration process, the results from each device were compared with those obtained using the reference gravimetric method for determining PM concentrations (Ramachandran et al., 2003), in order to identify potential deviations and apply necessary corrections.

PM measurements in ambient air

The automatic monitoring station (AMS) Bor-Town Park measurements were used to compare the average hourly values of PM concentrations measured in apartments with PM concentrations in ambient air. At this measuring point, PM concentrations are measured with an automatic Grimm EDM 180 analyzer, and 1-hour average values of outdoor PM concentration can be downloaded from the official website of the Serbian Environmental Protection Agency (SEPA): https://sepa.gov.rs/

RESULTS AND DISCUSSION

The average values of the measurement results are presented in Table 1. During the measurement campaign conducted in the heating season, no exceedances of the daily limit value for PM_{10} (50 µg/m³) or $PM_{2.5}$ (25 µg/m³) were observed in any of the monitored apartments. The average ambient concentrations of PM_{10} and $PM_{2.5}$ during the measurements campaign were 31.3 µg/m³ and 17.6 µg/m³, respectively. The average ambient concentration ratio of $PM_{2.5}$ and PM_{10} during the campaign was 0.56.

Table 1. *Average values of PM concentrations and PM indoor/outdoor (I/O) ratios during the heating season*

No.	PM_{10} (µg/m³)	$PM_{2.5}$ (µg/m³)	PM_{10} I/O	$PM_{2.5}$ I/O
N30	25.0	14.1	0.80	0.80
N42	23.2	12.0	0.74	0.68
N49	20.8	17.0	0.66	0.97
N2	20.1	11.1	0.64	0.63
N45	19.1	13.5	0.61	0.77
N31	18.3	12.4	0.58	0.71
N43	18.2	12.9	0.58	0.73
N46	17.6	11.9	0.56	0.67
N40	16.6	12.1	0.53	0.79
N34	16.5	12.5	0.53	0.71
N44	16.2	11.1	0.52	0.63
N47	16.3	9.8	0.52	0.56
RZ	16.1	11.3	0.51	0.64
N35	16.0	9.4	0.51	0.53
N41	12.9	9.1	0.41	0.52
average	**18.2**	**12.0**	**0.58**	**0.69**
min	12.9	9.1	0.41	0.52
max	25.0	17.0	0.80	0.97
stdev	3.1	2.0	0.10	0.11

The measurement results summarized in Table 1 suggest that indoor sources of suspended particles were either negligible or absent in the studied apartments. Similar PM concentration levels were reported in the study (Tasić et al., 2015) during the heating season, where measurements were conducted in the offices of MMI Bor. The average concentrations of PM_{10} and $PM_{2.5}$ in the offices during the measurement campaign were 20.3 µg/m³ and 10.9 µg/m³, respectively.

Another study of PM_{10} concentrations conducted in four apartments in Bor (Tasić et al., 2013) reported similar PM_{10} levels during the heating season. The average indoor and ambient concentrations of PM_{10} during the measurement campaign were 26.13 µg/m³ and 52.6 µg/m³, respectively. The average PM_{10} I/O ratio was 0.55. These findings are consistent with the results reported by Pekey et al. (2010) for Kocaeli (Turkey) during the cold season, where the PM_{10} I/O concentration ratio was 0.56, and by Diapouli et al. (2008) for a typical residence in the center of Athens, where the PM_{10} I/O ratio was approximately 0.61.

Table 2 presents the Pearson correlation coefficients (r) between indoor and outdoor (I/O) PM concentrations during the heating season. The average correlation coefficient for I/O PM_{10} concentrations is 0.33, while the average *r* value for I/O $PM_{2.5}$ concentrations is 0.51. These results indicate a higher infiltration of $PM_{2.5}$ from the outdoor environment into the apartments.

Table 2. *Pearson correlation coefficients (r)between I/O PM concentrations during the heating season*

No.	PM_{10} I/O corr. coef.	$PM_{2.5}$ I/O corr. coef.
N30	0.45	0.60
N42	0.22	0.42
N49	0.27	0.31
N2	0.32	0.53
N45	0.22	0.46
N31	0.40	0.61
N43	0.36	0.64
N46	0.40	0.68
N40	0.35	0.55
N34	0.45	0.60
N44	0.45	0.55
N47	0.20	0.52
RZ	0.25	0.36
N35	0.27	0.34
N41	0.40	0.48
average	**0.33**	**0.51**
min	0.20	0.31
max	0.45	0.68
stdev	0.09	0.11

Figure 2 shows the PM concentrations measured during the heating season in one of the selected apartments in Bor. The apartment is occupied by two retirees who follow their regular daily routines. Episodes of elevated PM concentrations in this apartment occur during cooking and while cleaning the apartment (vacuuming and dusting). This apartment is located less than 500 meters from the AMS Bor Town Park, from which hourly average ambient PM concentrations and meteorological data were obtained. Additionally, the apartment is situated next to a busy street where heavy-duty vehicle traffic is allowed. Despite these factors, the average I/O ratios for PM_{10} and $PM_{2.5}$ during the measurement campaign were 0.58 and 0.71, respectively. Although the apartment is over 50 years old, it has relatively well-preserved wooden window frames, which likely contributed to the observed Pearson correlation coefficients between I/O PM concentrations during the campaign: 0.40 for PM_{10} and 0.61 for $PM_{2.5}$.

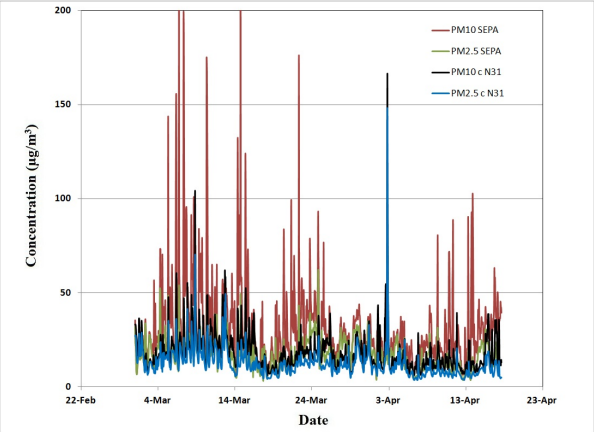

Figure 2. *An example of PM concentrations in one of the apartments in Bor during the heating season*

CONCLUSION

In conclusion, the findings suggest that indoor PM concentrations in the analyzed apartments in Bor during the heating season were largely influenced by the infiltration of outdoor particles, as well as by the occupants' cooking and cleaning activities. The average I/O ratios of 0.58 for PM_{10} and 0.68 for $PM_{2.5}$, along with higher correlation coefficients for $PM_{2.5}$ ($r = 0.51$) compared to PM_{10} ($r = 0.33$), indicate a more efficient penetration of finer particles into indoor environments.

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