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INDOOR PM_{10} AND $PM_{2.5}$ IN RESIDENTIAL APARTMENTS IN BOR, SERBIA: NON-HEATING SEASON ANALYSIS

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Abstract

This study examines indoor PM_{10} and $PM_{2.5}$ concentrations in residential apartments in Bor, Serbia, during the non-heating season, aiming to assess the relative contributions of indoor and outdoor sources. Measurements were conducted in 30 apartments across two independent campaigns carried out in May–June and August–September. Indoor concentrations were normalized using corresponding outdoor values and expressed as indoor/outdoor (I/O) ratios to enable comparison between the datasets. The results indicate a clear difference between the two periods. During May–June, median I/O ratios were approximately 1.08 for PM_{10} and 1.16 for $PM_{2.5}$, suggesting a dominant influence of indoor sources. In contrast, during August–September, median values decreased to approximately 0.63 for PM_{10} and 0.94 for $PM_{2.5}$, indicating a stronger contribution of outdoor air. These differences were statistically significant ($p < 0.05$) and were further supported by graphical analysis, which revealed broader and right-skewed distributions in May–June compared to more compact distributions in August–September. The findings demonstrate that indoor particulate matter concentrations during the non-heating season are strongly influenced by seasonal changes in ventilation and occupant behavior, with transitional periods showing increased importance of indoor emission processes.

Keywords: indoor air quality, particulate matter, indoor–outdoor relationships, residential exposure.

INTRODUCTION

Particulate matter (PM) is recognized as one of the most significant air pollutants due to its well-established impacts on human health, including respiratory and cardiovascular diseases, lung cancer, and premature mortality [1]. Particulate matter fractions such as PM_{10} and $PM_{2.5}$

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are particularly important because of their ability to penetrate deeply into the respiratory system and contribute to adverse health outcomes.

Although outdoor air pollution has been extensively studied, indoor air quality has gained increasing attention in recent decades, primarily because people spend the majority of their time indoors [2]. As a result, indoor exposure to particulate matter often represents a substantial portion of total human exposure.

Indoor PM concentrations are governed by a complex interaction between outdoor air infiltration and indoor emission processes. Activities such as cooking, cleaning, and resuspension of settled dust can significantly increase indoor particle levels, sometimes resulting in concentrations that exceed those measured outdoors [3,4]. The relationship between indoor and outdoor concentrations is commonly expressed through the indoor/outdoor (I/O) ratio, which provides insight into the relative importance of infiltration and indoor sources [5].

Bor (Serbia) represents a specific industrial environment influenced by long-term mining and metallurgical activities, which strongly affect ambient air quality [6]. While outdoor particulate matter levels in this region have been widely investigated, indoor environments in residential settings remain less systematically studied.

Recent research has shown that indoor PM concentrations in such environments are strongly influenced by ventilation patterns, building characteristics, and occupant behaviour. In response to this knowledge gap, a citizen science initiative was established, enabling residents to participate directly in indoor air quality monitoring by hosting measurement devices and providing contextual information on their daily activities.

The non-heating season represents a particularly dynamic period, characterized by changes in ventilation regimes and variations in occupant behavior, which may significantly influence indoor PM concentrations. Transitional periods, in particular, may exhibit enhanced variability due to the combined effects of indoor sources and fluctuating air exchange rates.

The aim of this study is to investigate differences in indoor PM_{10} and $PM_{2.5}$ concentrations between two periods of the non-heating season, May–June and August–September, using normalized indoor/outdoor ratios in order to better understand the dominant processes governing indoor air quality in residential environments.

In addition to its scientific objectives, the citizen science framework enabled broader engagement of the local community in environmental monitoring and awareness. By involving residents directly in the measurement process, the study captured real-life indoor exposure conditions that are often difficult to reproduce under controlled experimental settings. Such an approach also allowed for the collection of contextual information on daily activities, which is essential for interpreting short-term variations in indoor particulate matter concentrations. Furthermore, the participatory nature of the project contributed to increasing public understanding of air quality issues in an industrial environment such as Bor, while simultaneously providing a dataset that reflects both environmental conditions and human behaviours. This integration of instrumental measurements and user-reported data represents an important step toward more comprehensive assessments of indoor air quality.

MATERIALS AND METHODS

Indoor particulate matter concentrations were measured in 30 residential apartments in Bor, Serbia, during the non-heating season (Figure 1). The study was designed as two independent sampling campaigns, each including 15 apartments, conducted in May–June (apartments 1–15) and August–September (apartments 16–30). The apartments were selected to represent typical urban residential conditions, with emphasis on non-smoking households and comparable building characteristics.

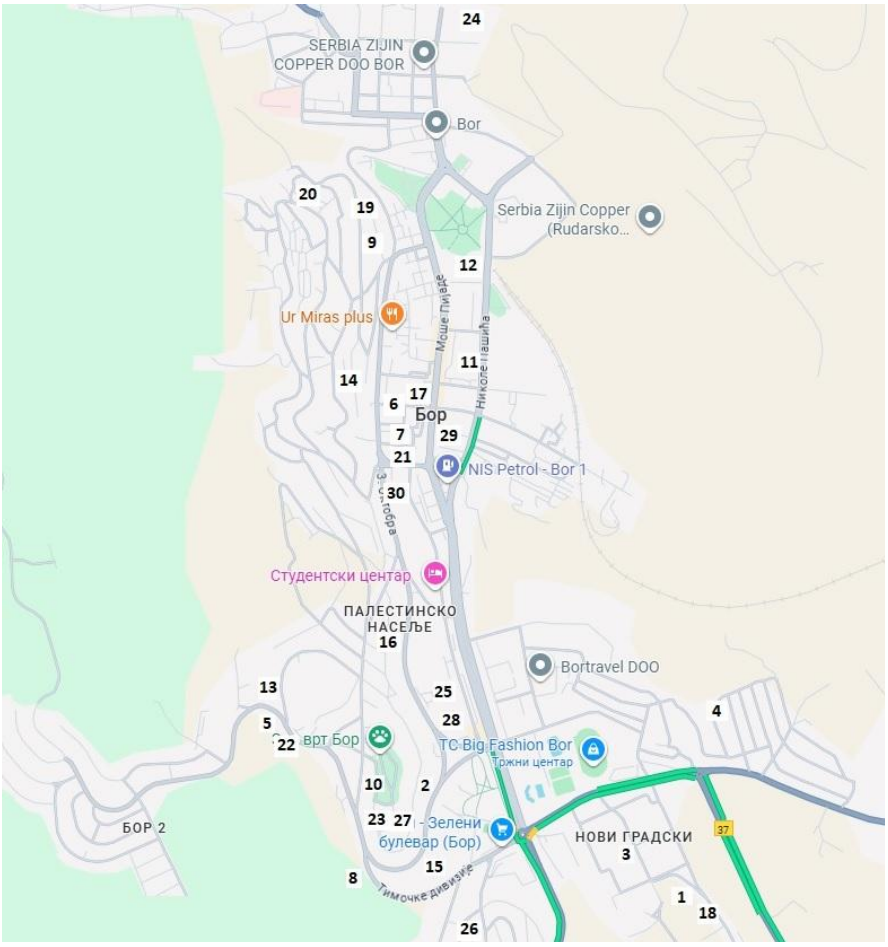

Figure 1 *Spatial distribution of the 30 selected residential apartments in the city of Bor, Serbia*

Indoor PM_{10} and $PM_{2.5}$ concentrations were monitored using compact optical particle sensors (NOVA SDS011 low-cost PM sensor), integrated into automated measuring devices that continuously recorded particulate matter concentrations together with temperature and relative humidity at a temporal resolution of one minute [7]. The performance of this type of sensor has been previously evaluated under different environmental conditions. Prior to deployment, all devices were calibrated under laboratory conditions, and their performance was assessed through comparison with the gravimetric reference method.

Outdoor particulate matter concentrations were obtained from the official automatic monitoring station in Bor (AMS Bor – Town park), where measurements are performed using a Grimm EDM 180 aerosol spectrometer [8]. Average outdoor concentrations corresponding to each sampling period were used for normalization.

The study was conducted within a citizen science framework, where residents hosted monitoring devices in their homes and recorded their daily activities during the measurement period. This approach enabled a more realistic interpretation of indoor particulate matter variability.

To enable comparison between the two independent datasets, indoor concentrations were normalized with respect to outdoor levels and expressed as indoor/outdoor ratios. Given the relatively small sample size and observed variability, a non-parametric statistical approach was applied. Central tendencies were described using median values, while variability was evaluated through the spread of the data. Extreme values were identified based on their deviation from the main distribution and were examined separately to assess their influence on the results [9]. Differences between the two periods were tested using the Mann–Whitney U test at a significance level of 0.05.

RESULTS AND DISCUSSION

An overview of average indoor and outdoor particulate matter concentrations provides a basis for understanding the observed differences between the two sampling periods and their potential influence on indoor air quality.

Average indoor concentrations were:

- PM_{10}: 21.2 µg/m^3 (May–June) and 17.2 µg/m^3 (August–September)
- $PM_{2.5}$: 12.1 µg/m^3 (May–June) and 9.4 µg/m^3 (August–September)

Average outdoor concentrations were:

- PM_{10}: 20.0 µg/m^3 (May–June) and 26.9 µg/m^3 (August–September)
- $PM_{2.5}$: 9.8 µg/m^3 (May–June) and 10.3 µg/m^3 (August–September)

The normalized indoor particulate matter concentrations showed a clear and systematic difference between the two investigated periods of the non-heating season.

For PM_{10}, the median indoor/outdoor ratio during May–June was approximately 1.08, indicating that indoor concentrations were slightly higher than outdoor levels. In contrast, during August–September, the median decreased to approximately 0.63, suggesting that indoor concentrations were predominantly controlled by outdoor air.

A similar trend was observed for $PM_{2.5}$, where the median value during May–June was approximately 1.16, while in August–September it decreased to approximately 0.94, indicating a reduced influence of indoor sources.

These differences are illustrated in Figure 2, where boxplots show a pronounced shift toward higher values during May–June, along with a wider spread of the data. In contrast, the August–September dataset is more compact, with most values clustered below or around unity.

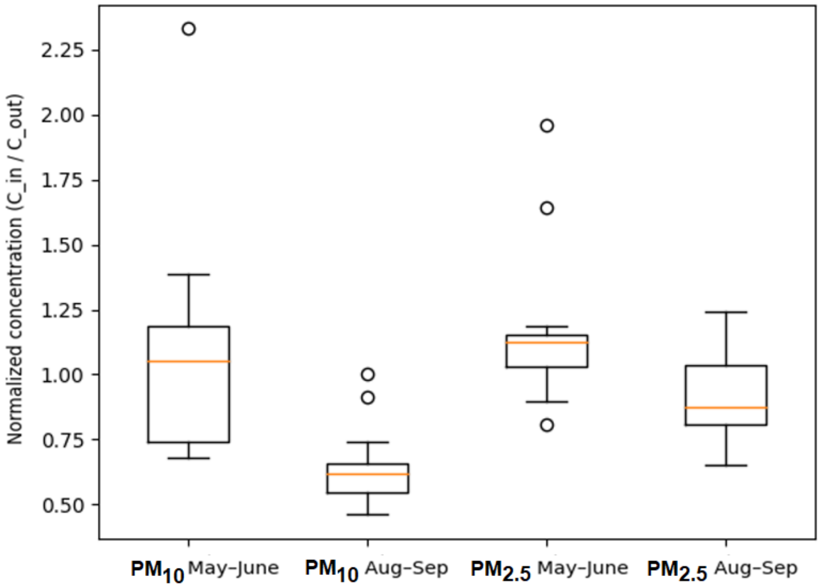

Figure 2 *Boxplots of normalized PM_{10} and $PM_{2.5}$ concentrations (C_in/C_out) for May–June and August–September*

Histogram analysis (Figure 3) further supports these observations. The histogram binning was performed by dividing the range of normalized concentration values into equally spaced intervals. The final number of bins was selected to provide sufficient resolution while maintaining clear visual interpretability of the distributions.

The same binning approach was applied consistently across comparable datasets to enable direct visual comparison. The number of bins was set to $k = 7$, as this provided a clear compromise between distribution resolution and visual interpretability for the given sample size.

The May–June dataset exhibits a right-skewed distribution, with a noticeable fraction of apartments showing I/O ratios greater than 1.0 and, in some cases, exceeding 2.0 for PM_{10}. The August–September dataset, on the other hand, is centered at lower values and shows reduced variability.

An extreme value observed in the PM_{10} dataset during May–June increased variability but did not significantly affect the central tendency. Its exclusion resulted in only minor changes in the distribution, confirming that the observed differences between the two periods are robust. A similar effect was observed for $PM_{2.5}$, where one elevated value slightly influenced the spread without altering the overall trend.

Statistical testing confirmed that the differences between the two periods were significant ($p < 0.05$), indicating that the datasets represent distinct distributions.

The observed behavior can be explained by seasonal variations in ventilation and occupant activities. The May–June period represents a transitional phase during which ventilation conditions may be less stable and indoor activities such as cleaning and resuspension contribute to elevated concentrations. In contrast, the August–September period is associated with more stable ventilation conditions and higher air exchange rates, leading to stronger coupling between indoor and outdoor air.

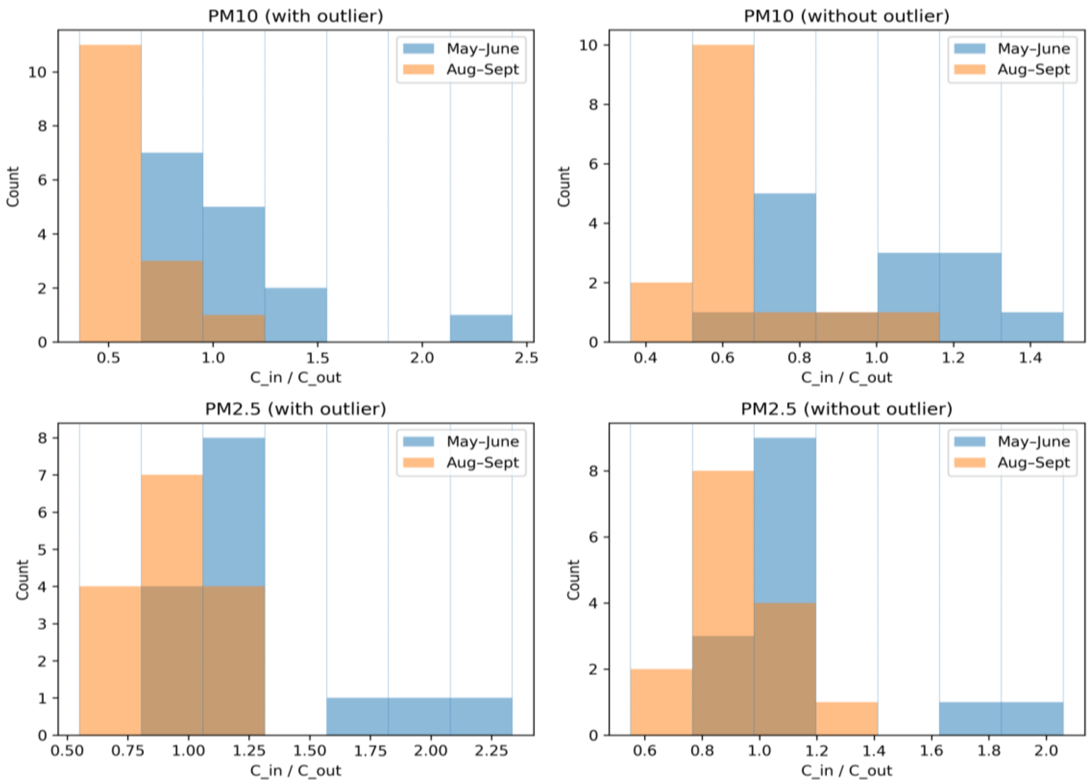

Figure 3 *Histograms of normalized PM_{10} and $PM_{2.5}$ concentrations, illustrating differences in distribution between the two sampling periods*

These findings are consistent with previous studies demonstrating that indoor particulate matter concentrations are controlled by the balance between infiltration and indoor emission processes [3–5].

CONCLUSION

Indoor PM_{10} and $PM_{2.5}$ concentrations in residential apartments in Bor show significant variability during the non-heating season. The May–June period is characterized by a stronger influence of indoor sources, while August–September reflects a greater contribution of outdoor air. The use of normalized indoor/outdoor ratios proved to be an effective approach for comparing independent datasets and identifying dominant processes.

Within the second year of the project, measurements will be extended to an additional 30 apartments, enabling the development of a more comprehensive dataset and allowing direct comparison with results obtained in 2025. This extended dataset will provide a stronger basis for evaluating the temporal stability of indoor air quality patterns in residential environments.

Furthermore, due to space limitations, the present study focuses only on the non-heating season, while the analysis of indoor particulate matter during the heating season will be presented in future publications.

The continuation of measurements within a citizen science framework is expected to contribute to a better understanding of long-term indoor air quality dynamics in industrial urban environments and to support more informed assessment of exposure and associated health risks.

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