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

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Abstract

This study investigates indoor PM10 and PM2.5 concentrations in residential apartments in Bor, Serbia, during the heating season, with the aim of assessing the relationship between indoor and outdoor particulate matter and identifying dominant processes influencing indoor air quality. Measurements were conducted in 30 apartments across two independent sampling periods, hereafter referred to as G1 (March-April) and G2 (October–November), representing different phases of the heating season. To enable comparison between the two datasets, indoor concentrations were normalized using the corresponding average outdoor concentrations measured during each campaign period and expressed as indoor/outdoor (I/O) ratios. The results indicate that normalized PM concentrations remain relatively stable between the two periods, with no statistically significant difference observed. Although PM2.5 shows a tendency toward higher values in G1, this difference does not reach statistical significance after the application of robust outlier treatment. Overall, the findings suggest that during the heating season, indoor particulate matter concentrations are strongly influenced by outdoor air infiltration, while apartment-specific factors contribute to observed variability.

***Keywords**: air quality, monitoring, PM_{10}, $PM_{2.5}$, residential apartments*

1. INTRODUCTION

Particulate matter (PM) is recognized as one of the most significant air pollutants due to its well-documented adverse effects on human health, including respiratory and cardiovascular diseases, lung cancer, and premature mortality [1]. Fine and coarse particle fractions, commonly represented as PM_{10} and $PM_{2.5}$, differ in their physical behavior and health relevance, particularly with respect to their ability to penetrate the respiratory system and persist in indoor environments. While outdoor air pollution has been extensively studied, indoor air quality has gained increasing attention in recent decades, primarily because individuals spend a substantial portion of their time indoors [2]. As a result, indoor exposure to particulate matter often represents a dominant component of total human exposure. Indoor particulate matter concentrations are controlled by a combination of processes, including infiltration of outdoor air, indoor emission sources, and removal mechanisms such as deposition and ventilation. Fine particles ($PM_{2.5}$) typically exhibit higher penetration

efficiency through the building envelope and lower gravitational settling rates, allowing them to remain suspended in indoor air for longer periods. In contrast, coarse particles (PM_{10}) are more strongly influenced by deposition and resuspension processes [3,4]. The relationship between indoor and outdoor concentrations is commonly expressed through the indoor/outdoor (I/O) ratio, which provides a normalized measure of the extent to which indoor concentrations reflect outdoor pollution levels or are influenced by indoor sources [5]. Values close to unity indicate strong coupling between indoor and outdoor air, while higher values suggest the presence of significant indoor emissions. Bor (Serbia) represents a specific industrial environment. Normalized PM10 concentrations did not differ significantly between the G1 and G2 periods, suggesting that coarse particle behavior is governed by relatively stable processes, primarily the balance between outdoor infiltration and indoor depositing and metallurgical activities, which significantly 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, particularly during the heating season, when both outdoor emissions and indoor activities may differ substantially from non-heating periods. In addition to its scientific objectives, this study is part of a citizen science initiative in which residents actively participated in indoor air quality monitoring by hosting measurement devices and providing contextual information on daily activities. This approach enables the collection of data under realistic living conditions and supports a more comprehensive interpretation of indoor particulate matter variability. The aim of this study is to evaluate indoor PM_{10} and $PM_{2.5}$ concentrations during the heating season, to compare two independent measurement periods, and to assess the extent to which indoor air quality is governed by outdoor pollution levels, particle size-dependent processes, and apartment-specific factors.

2. EXPERIMENTAL

Indoor particulate matter concentrations were measured in residential apartments located in the urban area of Bor, Serbia, during the heating season. The study was designed as two independent sampling campaigns, hereafter referred to as G1 (March–April, apartments 1-15) and G2 (October–November, apartments 16-30), each including a separate group of apartments. The measurements were not paired, meaning that different apartments were included in each campaign, which required the use of normalization and appropriate statistical methods to ensure comparability. Indoor PM_{10} and $PM_{2.5}$ concentrations were monitored using compact PM monitoring devices based on the NOVA SDS011 low-cost particulate matter sensor [7]. Outdoor particulate matter concentrations were obtained from the official automatic monitoring station (AMS Bor – Town Park), where measurements are performed using a Grimm EDM 180 aerosol spectrometer [8]. For the purposes of this study, average outdoor concentrations corresponding to each sampling period were used.

3. RESULTS AND DISCUSSION

Average indoor and outdoor particulate matter concentrations provide 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}: 19.0 μg/m^3 (March–April) and 13.6 μg/m^3 (October–November)
- $PM_{2.5}$: 13.0 μg/m^3 (March–April) and 8.6 μg/m^3 (October–November)

Average outdoor concentrations were:

- PM_{10}: 31.3 μg/m^3 (March–April) and 24.3 μg/m^3 (October–November)
- $PM_{2.5}$: 17.6 μg/m^3 (March–April) and 15.9 μg/m^3 (October–November)

Because the two measurement campaigns were conducted under different ambient air pollution conditions, direct comparison of absolute indoor concentrations would not provide meaningful insight into I/O relationships. To address this issue, indoor concentrations were normalized with respect to the corresponding average outdoor concentration for each campaign period.

Given the relatively small sample size and the presence of variability typical for environmental datasets, a non-parametric statistical approach was adopted. This choice avoids assumptions about the underlying distribution of the data, which is particularly important in the presence of skewed distributions or extreme values.

Central tendencies were described using median values, as the median provides a robust measure that is less sensitive to extreme observations than the arithmetic mean. Variability was characterized using the interquartile range (IQR), which represents the spread of the central 50% of the data. Quartiles were defined as follows: Q1- value below which 25% of observations fall; Q3 - value below which 75% of observations fall; IQR = Q3 − Q1.

Outliers were identified using the Tukey criterion, according to which values are classified as outliers if they fall outside the interval: below Q1 − 1.5 × IQR or above Q3 + 1.5 × IQR.

This approach is widely used in exploratory data analysis because it is distribution-independent and robust to extreme values [9]. The analysis of normalized indoor particulate matter concentrations provide insight into the relationship between indoor and outdoor air during the heating season, while minimizing the influence of differing ambient pollution levels between the two sampling periods.

Because the two datasets (G1 and G2) are independent and not paired, the Mann–Whitney U test was used as the primary statistical test for assessing differences between the two periods. This test evaluates whether two independent samples originate from the same distribution without assuming normality. To complement the non-parametric analysis, Welch's t-test was also applied as a sensitivity check. This test is suitable for datasets with unequal variances and provides an additional perspective on the robustness of the results. Normality of the data was evaluated using the Shapiro–Wilk test. The results indicated deviations from normal distribution in several cases, further supporting the use of non-parametric methods as the primary analytical approach. A significance level of 0.05 was adopted for all statistical tests.

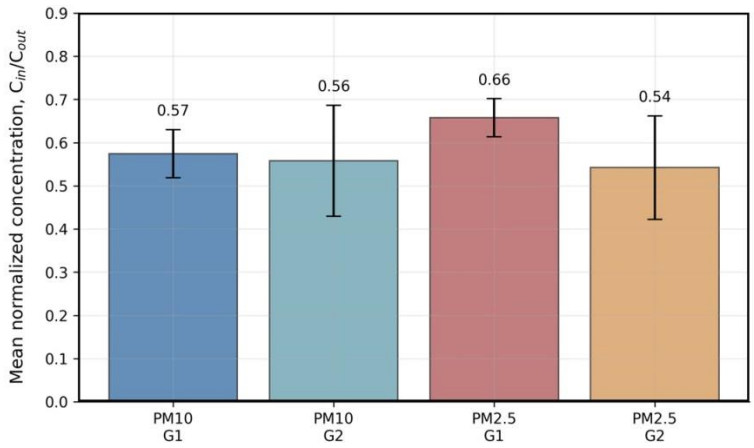


Figure 1. *Mean normalized indoor/outdoor concentration ratios (C_in/C_out) for PM_{10} and $PM_{2.5}$ with approximate 95% confidence interval*

After normalization to the corresponding average outdoor concentrations, PM_{10} exhibited similar indoor/outdoor ratios in both investigated periods. The median values, which represent the central tendency more robustly, were also closely aligned between the two periods. This indicates that the indoor/outdoor relationship for PM_{10} remained relatively stable throughout the heating season, as shown in Figure 1.

Table 1. *Descriptive statistics of normalized indoor PM_{10} and $PM_{2.5}$ concentrations (C_in/C_out) after IQR-based outlier removal*

Fraction/period	n	Mean	SD	Median	Q1	Q3	Min	Max
PM_{10} G1	14	0.574	0.106	0.545	0.515	0.628	0.412	0.799
PM_{10} G2	15	0.558	0.254	0.564	0.333	0.665	0.243	1.148
$PM_{2.5}$ G1	12	0.658	0.078	0.659	0.625	0.706	0.517	0.801
$PM_{2.5}$ G2	15	0.542	0.237	0.535	0.311	0.720	0.220	0.987

Statistical comparison using the Mann–Whitney U test (shown in Table 2) confirmed that the differences between G1 and G2 were not statistically significant. This result suggests that, when expressed in normalized form, PM_{10} concentrations are governed by similar processes in both periods. From a physical perspective, this behavior can be explained by the balance between infiltration of outdoor particles and indoor removal mechanisms.

Table 2. *Statistical comparison of normalized PM concentrations between G1 and G2*

Comparison	Dataset	Mann-Whitney p	Welch t-test p	Interpretation
PM_{10} G1 vs G2	Full data	0.648	0.534	Not significant
PM_{10} G1 vs G2	IQR-cleaned dataset	0.844	0.824	Not significant
$PM_{2.5}$ G1 vs G2	Full data	0.074	0.059	Not significant
$PM_{2.5}$ G1 vs G2	IQR-cleaned dataset	0.124	0.093	Not significant

Although $PM_{2.5}$ showed a tendency toward higher normalized values during G1, statistical testing indicated that this difference did not reach the level of significance, as shown in Table 2. Welch's t-test produced similar results, further supporting the conclusion that the observed differences are not statistically robust. Despite the lack of statistical significance, the consistently higher I/O ratios for $PM_{2.5}$ compared to PM_{10} (for G1) represent an important and physically meaningful result. Fine particles are characterized by higher penetration efficiency through the building envelope and lower deposition rates compared to coarse particles. Consequently, $PM_{2.5}$ is more strongly coupled with outdoor air and remains suspended in indoor environments for longer periods. Graphical analysis provides additional insight into the structure of the data and supports the statistical findings. Boxplots of normalized concentrations show that $PM_{2.5}$ distributions are generally shifted toward higher values compared to PM_{10} (G1), confirming the stronger indoor persistence of fine particles. The spread of the data also differs between the two periods. In particular, the G2 dataset exhibits a wider distribution for both particle fractions, indicating increased variability between apartments. This suggests that apartment-specific factors, such as ventilation behavior, building characteristics, and indoor activities, may play a more significant role than the sampling period itself. Histogram-based distribution analysis further illustrates these differences, as shown in Figure 3. The density shown on the y-axis is calculated by normalizing the frequency of observations within each bin. Specifically, the number of values in each bin is divided by the total number of observations and the bin width, so that the total area under the histogram equals one. This representation allows comparison of distributions independently of sample size and bin width.

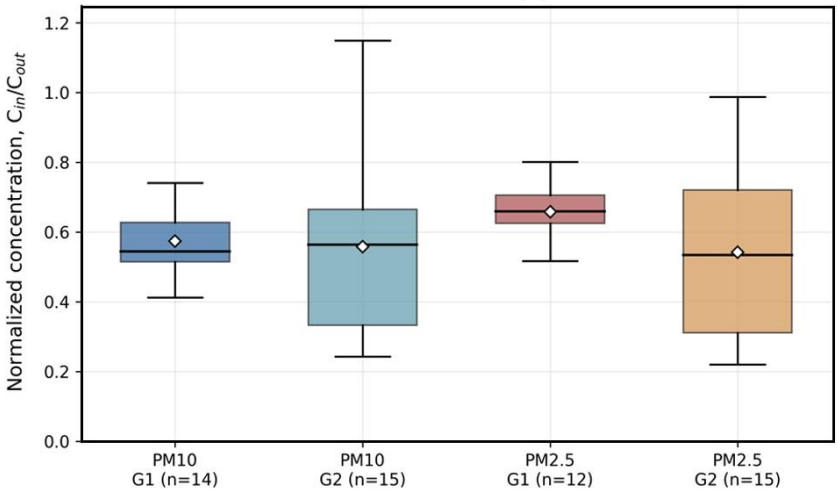


Figure 2. *Boxplots of normalized PM_{10} and $PM_{2.5}$ indoor concentrations (C_in/C_out) for the two heating-season sampling periods (G1 and G2)*

A limited number of elevated values were identified as outliers based on the IQR criterion. These values were analyzed separately to assess their impact on the overall results. The removal of outliers resulted in only minor changes in central tendency measures, particularly for PM_{10}, confirming that the main conclusions are robust. For $PM_{2.5}$, outlier removal reduced variability but did not alter the overall trend of higher normalized values compared to PM_{10}. It is important to emphasize that such outliers should not be interpreted solely as measurement errors. In indoor air quality studies, elevated values may reflect short-term emission events, such as cooking, cleaning, or resuspension of dust, which can significantly influence exposure over short time intervals.

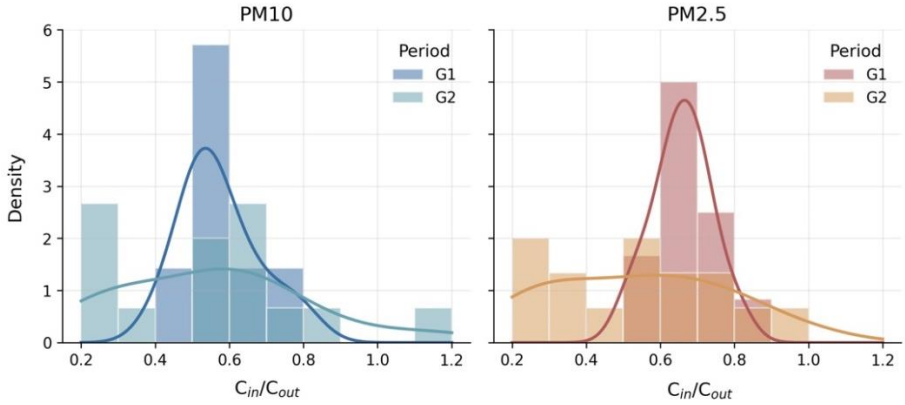


Figure 3. *Distribution of normalized PM_{10} and $PM_{2.5}$ indoor concentrations (C_in/C_out) after IQR-based outlier removal. The histograms illustrate differences in distribution shape and variability between the two heating-season sampling periods (G1 and G2)*

The combined results indicate that, during the heating season, indoor particulate matter concentrations are largely governed by relatively stable physical processes. The absence of significant differences between the two sampling periods suggests that the indoor/outdoor relationship is controlled more by particle behavior and building characteristics than by temporal variation within the heating season. The higher normalized values observed for $PM_{2.5}$ compared to PM_{10} are consistent with well-established physical principles, including higher penetration efficiency and lower deposition rates of fine particles. This behavior implies that outdoor air pollution remains an important driver of indoor $PM_{2.5}$ concentrations, even in the presence of indoor sources. At the same time, the observed variability between apartments highlights the importance of local factors, including occupant behavior and ventilation patterns. These factors can lead to substantial differences in indoor air quality, even under similar outdoor conditions.

4. CONCLUSION

Indoor PM_{10} and $PM_{2.5}$ concentrations in residential apartments in Bor during the heating season exhibit relatively stable behavior when expressed as normalized indoor/outdoor ratios.

Normalized PM_{10} concentrations did not differ significantly between the G1 and G2 periods, suggesting that coarse particle behavior is governed by relatively stable processes, primarily the balance between outdoor infiltration and indoor deposition. Although a tendency toward higher normalized $PM_{2.5}$ values was observed during G1 period, this difference did not reach statistical significance. Therefore, the results do not support the existence of a pronounced temporal difference within the heating season. The continuation of measurements within a citizen science framework is expected to contribute to improved understanding of long-term indoor air quality behavior in industrial urban environments.

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