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COMPARISON OF THE MASS CONCENTRATION OF SIZE-RESOLVED PARTICULATE MATTER INSIDE A SELECTED FIRE STATION IN POLAND AND IN THE ATMOSPHERIC AIR IN ITS IMMEDIATE SURROUNDINGS

The objective of this study was to evaluate the mass concentration of size-resolved (PM_1, $PM_{2.5}$, PM_4, PM_{10}, PM_{100}) particulate matter (PM) in the indoor air of a selected fire station in Poland and to compare them with the concentrations of the same PM fractions in the atmospheric air. Optical measurements of PM concentrations were conducted for 12 hours a day, simultaneously inside and outside of the fire station, for 14 days in heating and non-heating seasons. In both measurement seasons, the average PM concentrations were higher in the fire station (26–44 μg/m^3) than in the ambient air (9–32 μg/m^3). The proportion of fine particles in the total PM mass was found to be higher in the fire station (83–90%) than in the atmospheric air (40–78%). The findings of conducted analyses substantiate the notion that the concentrations and mass size distribution of PM in the fire station deviates from the concentrations and mass distribution for the urban background, a phenomenon that is attributable to the unique characteristics of the fire station and the prevalence of internal sources within it.

1. INTRODUCTION

Fire stations are distinguished by a distinct microclimate, which, given their function and the nature of the activities undertaken by the personnel present, differs in composition from the microclimate of residential dwellings, offices, commercial establishments, educational institutions, agricultural structures, and industrial facilities [1]. This

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distinction arises from the multifaceted nature of fire stations, which serve not only as operational bases for firefighters but also as places of employment for civilian personnel, including command staff and dispatchers. In addition to serving as a hub for administrative tasks, fire stations are also crucial facilities for physical work, recovery, and rest for firefighters engaged in rescue and firefighting operations. The scope of activities within fire stations is extensive, encompassing a wide range of tasks such as office work, vehicle and combustion equipment cleaning, pre-shift preparation, testing, training in operation, washing, laundry, and culinary activities. Operations-based firefighters spend the majority of their 24-hour shifts in fire stations, while office workers typically spend 8 hours per day in such environments. Regardless of the specific purpose or type of activity, the quality of indoor air is the most critical element of any indoor environment, influencing the comfort, well-being, health, ability to work, and regenerate of its users. Given the multitude of potential pollutants resulting from the diverse range of activities within fire stations, ensuring optimal indoor air quality poses a significant challenge [2].

A review of the extant literature on the subject indicates that the primary sources of air pollution in fire stations include personal protective equipment (helmets, boots, gloves, and special clothing) and fire-fighting equipment utilized during operations and subsequently stored in changing rooms and garages. Additional sources of concern include fire vehicles and combustion equipment, as well as extinguishing agents and other substances employed by firefighters during operations [3]. An important factor influencing the quality of indoor air in fire stations is the occurrence of atmospheric air inflow due to the opening of garage doors during departures and returns from incidents. To optimize the time required to reach an incident, fire stations are often strategically located in city centers or on major thoroughfares, where air quality is frequently compromised due to substantial vehicular traffic. The conditions within the fire station, particularly the presence of multiple sources and the facilitation of air circulation, which enables the movement of pollutants to different rooms, promote a variety of reactions and interactions between pollutants and elements of the internal environment. As a result of the airflow, some pollutants disintegrate, for example, into smaller particles, settle on surfaces, such as desks, or remain unchanged [4, 5].

Among the primary air quality factors in fire stations, suspended particulate matter, along with gases and smoke, constitutes the predominant component of air pollution released during fires, and it is a significant concern due to its potential impact on human health. In addition to fires, firefighters are also exposed to the effects of particulate matter during operations conducted during construction disasters, explosions of flammable gases, vapors, and dust, and bursting of gas cylinders, and pressure boilers, among others. The health implications of PM are determined by its physical properties (size and shape, surface area, electric charge of dust particles, hygroscopicity, and properties related to light scattering and absorption) and chemical properties (elemental composition, presence of inorganic ions, organic compounds, and elemental carbon) [6]. The size of PM in the air inside fire stations, similar to atmospheric air, ranges from nanometers to

millimeters. The classification of PM into distinct fractions or phases is contingent upon these particle sizes [7–9]. Prolonged exposure to elevated concentrations of PM has been demonstrated to augment the risk of respiratory, circulatory, and neurological maladies. This heterogeneous amalgamation of solid particles and liquid droplets suspended in the atmosphere also functions as a medium for other hazardous pollutants that are released during the processes of combustion and pyrolysis. The surface of PM particles can absorb various substances, including polycyclic aromatic hydrocarbons (PAHs), volatile organic compounds (VOCs), hydrogen cyanide (HCN), and other organic and inorganic compounds. The deposition of PM particles in the alveoli of the lungs can impede gas exchange. Furthermore, exposure to coarse, submicron, or ultrafine particles has been demonstrated to elicit an inflammatory response in the respiratory system, induce allergic sensitization, and impair cardiovascular function, among other adverse health effects, including increased bronchial reactivity and coughing. These local reactions have the potential to initiate systemic reactions, underscoring the complexity and far-reaching health implications of airborne particulate matter. It is noteworthy that inflammatory changes within the body can be triggered by even a brief exposure to harmful compounds, underscoring the need for a nuanced understanding of the health implications of airborne particulate matter. While these consequences may be of less clinical significance in young and healthy firefighters, they are significant in older people or people with chronic cardiopulmonary diseases [10].

The most frequently studied pollutants in such buildings are polycyclic aromatic hydrocarbons (PAHs), particulate matter (PM), and diesel particulate matter (DPM) [2]. The PM concentrations in fire stations have been reported in approximately 11 studies, and the most frequently measured fractions are $PM_{2.5}$, PM_4, PM_{10}, and total suspended particles (TSP) [2, 11]. The measurement of PM has been conducted in various areas of fire stations, including truck bays, firefighting PPE storage rooms, common areas, sleeping quarters, kitchens, and offices. The findings have demonstrated that PM concentrations vary depending on the specific location and the type of room. A significant proportion of the studies on PM concentrations in fire stations have centered on the composition of PM and the associated health exposures [4, 5, 11–14].

Recently, there has been a growing trend in the research on PM concentrations in fire stations. More and more PM fractions are being analyzed [5, 11]. Despite the growing interest in the subject, a research gap is the comparison of PM concentrations measured simultaneously in the fire station and the atmospheric air in its immediate vicinity. Conducting such a study would facilitate determining whether the problem of high PM concentrations truly concerns fire stations and would also allow an assessment of the impact of atmospheric air on PM concentrations inside such buildings. In connection with the aforementioned points, this paper aims to determine and compare the PM mass concentration and size composition inside and outside selected fire stations in Poland.

2. EXPERIMENTAL

Measurement site. The studied fire station is located in a typical urban area of Warsaw, Poland (52°17′02.54″N, 20°57′18.30″E) (Fig. 1), approximately 7 km from the city center. Its immediate vicinity consists of tenement houses, apartment blocks, public buildings such as hospitals, offices, and schools, as well as streets with heavy traffic. Within a radius of 2 km from the fire station, there are two main roads, i.e., expressways S7 and S8, with a traffic intensity of 65 000–179 000 vehicles per day [15].

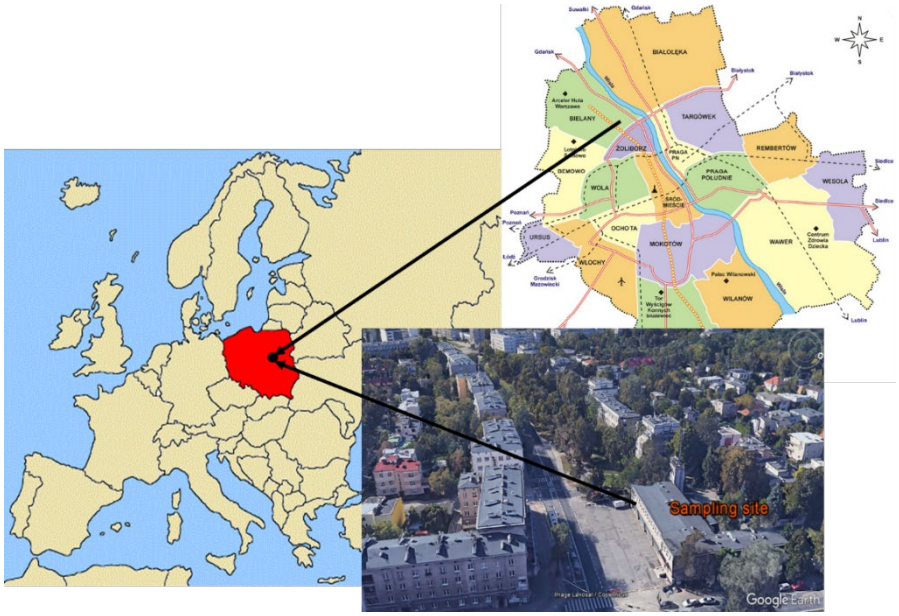

Fig. 1. Measurement site

The air quality near the fire station is determined by road emissions and fuel combustion for heating purposes [16]. The fire station under study is a two-story building constructed in the 1960s. The ground floor comprises a truck bay with a workshop area, a changing room, and an alarm point, while the first floor contains sanitary facilities, living quarters (kitchen, TV room, dining room, and bedrooms), utility rooms, and offices. The garage doors are operated by a mechanical system that opens them upon departure or arrival. Notably, the fire station under study does not have a garage exhaust system, and the building is not equipped with air conditioning, relying instead on natural ventilation. Given that firefighters spend a portion of their time in the clean zone (common room, bedrooms, office space) and a portion of their time in the dirty zone (garage), indoor measurements were taken in the changing room, which is the transitional zone between these two areas. The dimensions of the changing room are approximately 38.55 m^2,

with a height of approximately 4.5 m. The selection of this particular fire station was made because it is representative of a typical Polish fire station. The measurements of PM concentrations for the urban background were conducted at a nearby station situated approximately 2 km in a straight line from the measurement site (52°16′18.17″N; 20°58′29.15″E). The air quality measurement station is located at a height of 15 m AGL (112 m AMSL). The station's location, particularly its elevation, renders the measurement representative of a substantial area. This is because local short-range turbulence is the only phenomenon observed at the station, and concentration jumps are associated with road or pedestrian traffic [17].

Measurement method. The study entailed the automated measurement of the mass concentrations of five PM fractions (PM_1, $PM_{2.5}$, PM_4, PM_{10}, and PM_{100}, alternatively referred to as TSP) in a changing room at a selected fire station and the atmospheric air in its vicinity (urban background). Due to the distinct atmospheric conditions in Poland and the evident seasonal variation associated with heating processes, the study was conducted across two measurement campaigns: heating (08/01/2023–09/02/2023) and non-heating (24/05/2023–25/06/2023). Each measurement campaign involved the execution of 14 measurements. To identify phenomena influencing changes in PM concentrations, measurements were carried out between 8:00 a.m. and 8:00 p.m., i.e., during the period of greatest activity at the fire station. The measurements inside the fire station were performed using an optical method with a DustTrak 8534 DRX dust meter (TSI, Minnesota, USA). The device allows simultaneous real-time mass concentration measurements of PM with aerodynamic diameters of 0.1–100 μm in the range of 0.001–150 mg/m^3. Quality control was guaranteed by a calibration of the device before measurements (October 2020) using a standardized dust sample (Arizona Dust; TSI). Zero calibration was performed before each measurement. The accuracy of the sampler was 5%. Every day, 12-h measurements were performed at a 1 s time resolution, averaging the results every 3 min. The average 12-h concentration was the arithmetic mean of the 160 3-min results. Additionally, at the beginning and end of each measurement day, the same location where the dust meter was placed was used to monitor indoor relative humidity (RH) and temperature (temp) with a portable device (AZ Instrument, SERIE 77,597; Taiwan) (heating season – mean RH: 38%, st. deviation: 6; mean temp.: 21°C, st. deviation: 2; non-heating season – mean RH: 40%, st. deviation: 5; mean temp.: 24 °C, st. deviation: 3). The measuring device was placed approximately in the middle of the wall opposite the door, at a height of approximately 1.5 m from the floor level and at a distance of at least 1.5 m from the wall. This configuration did not affect the functioning of the fire stations, and the device was fortified to mitigate the potential impact of air currents on the recorded concentrations.

The measurement of urban background concentrations was conducted using the PALAS Fidas® 200 meter, a device that adheres to the standards outlined in the EN 16450 [18]

and EN 15267 [19, 20]. The data set encompassed concentrations of five PM fractions: PM_1, $PM_{2.5}$, PM_4, PM_{10}, and PM_{100} , with hourly averages collected for each.

Results analysis. Descriptive statistics were calculated using Excel (version 2024; Microsoft Corporation, USA), and statistical tests were performed using *Jamovi* (version 2.3.28, 2024). The concentrations of five PM fractions were presented as means, medians, and ranges. The nonparametric Mann–Whitney *U* test was used to compare the concentrations of five PM fractions in the indoor air of the fire station and in the ambient air. The statistical significance was defined as $p < 0.05$. Additionally, the mass median aerodynamic diameter (MMAD) and geometric standard deviation (GSD) were determined using regression lines from the log-probability graph of PM size versus cumulative mass distribution. MMAD and GSD are two parameters that characterize particle size distributions (PSDs) [21, 22].

3. RESULTS AND DISCUSSION

Table 1 presents the statistical parameters of five PM fractions examined in the changing room of the selected fire station and the atmospheric air (urban background) in the measurement campaigns. In the indoor air of the fire station, the concentrations of PM fractions ranged from 3 to 919 μg/m^3 during the heating season and from 8 to 495 μg/m^3 during the non-heating season. Concurrently, the mean concentrations of all the PM fractions within the fire station ranged from 39 to 44 μg/m^3 during the heating season and from 26 to 32 μg/m^3 during the non-heating season. Outdoor, the range of PM concentrations during the heating season was from 11 to 391 μg/m^3, and during the non-heating season, it ranged from 1 to 73 μg/m^3. The average PM concentrations for the urban background ranged from 23 to 32 μg/m^3 during the heating season and from 9 to 28 μg/m^3 during the non-heating season. In the context of optical measurements, many researchers believe that the median is a superior representative of the measurement compared to the arithmetic mean. Both values are outlined in Table 1. The arithmetic mean is frequently overestimated by dynamic concentration fluctuations and is associated with the maximum concentration. In the present case study, the medians for both the indoor air of the fire station and the urban background were found to be lower than the average concentrations. The most significant disparities were observed for PM_{100}. Nevertheless, given their comparable orders of magnitude, both values can be regarded as representative.

In general, the concentrations of all PM fractions were found to be elevated in both the fire station and the ambient air during the heating season when compared to the non-heating season. The average percentage increase in PM concentrations during the heating season was approximately 50% for PM_1, $PM_{2.5}$, and PM_4, 45% for PM_{10}, and 37% for PM_{100} inside the fire station, while for urban background approx. 155% for PM_1, 127% for $PM_{2.5}$, 100% for PM_4, 32% for PM_{10} and 14% for PM_{100}. Given the observed

increase in PM concentrations during winter measurements, particularly the heightened levels of fine PM (particles with diameters smaller than 2.5 μm), it can be deduced that PM concentrations within and outside the fire station were influenced by municipal emissions stemming from intensified heating processes during winter. Despite the predominance of urban development in the vicinity of the fire station, characterized by apartment complexes heated by the municipal network, studies conducted by other researchers have documented that the air quality in Warsaw typically deteriorates during winter months compared to summer [23]. This phenomenon can be attributed to the influx of air from neighboring regions (especially villages), where low-rise buildings are predominant [23, 24].

Table 1

Descriptive statistics of a series of 12-h concentrations of PM_1, $PM_{2.5}$, PM_4, PM_{10}, and PM_{100} [μg/m^3] in the changing room of the fire station and its external surroundings (urban background) in the heating and non-heating seasons

Season	Parameter	Fire station					Urban background				
		PM_1	$PM_{2.5}$	PM_4	PM_{10}	PM_{100}	PM_1	$PM_{2.5}$	PM_4	PM_{10}	PM_{100}
Heating	Mean	39	39	40	42	44	23	25	26	29	32
	Median	36	36	36	38	38	23	25	25	26	28
	Minimum	3	4	4	4	4	11	12	13	13	13
	Maximum	291	293	387	787	919	36	51	77	205	391
	SD	21.15	21.47	22.39	27.55	32.45	5.45	6.40	7.74	17.47	33.86
Non-heating	Mean	26	26	27	29	32	9	11	13	22	28
	Median	23	23	24	26	28	6	9	11	20	26
	Minimum	8	8	8	8	8	1	2	3	6	8
	Maximum	192	193	193	236	495	38	42	46	72	73
	SD	12.63	12.71	12.80	13.36	15.87	6.92	7.17	7.58	9.84	10.05

To provide a more nuanced illustration of the differences in PM concentrations inside (I) and outside (O) the fire station, I/O ratios for both measurement periods were determined based on the mean concentrations of all analyzed PM fractions (Table 2). In both seasons, the concentrations of all PM fractions were higher in the fire station than in its external environment. As the I/O ratio values show, these differences are more pronounced in the non-heating season than in the heating season. In the heating season, the highest I/O ratios were recorded for PM_1, and in the non-heating season additionally for $PM_{2.5}$ and PM_4. The I/O ratios confirm the presence of specific PM sources inside the fire station, especially small fractions, such as personal protective equipment stored in the fire station, fire vehicles and their fuel combustion, or testing of combustion equipment in the fire stations, etc. The observed differences in the I/O ratios between the analyzed seasons, i.e., heating vs. non-heating, further support the hypothesis that the activity of internal sources is greater in summer than in winter. The reduction in the contribution of internal sources to PM concentrations in winter is likely attributable to

the impact of poor ambient air quality and the inflow of air from outside, e.g., during the opening of garage doors for departures.

The Mann–Whitney *U* test results for the fire station and urban background demonstrate that the differences in the concentrations of the five PM fractions analyzed at both measurement points under study are statistically significant ($p < 0.001$) (Table 2). When examining the descriptive statistics for the PM concentrations in the fire station and its external environment, it is crucial to consider the dispersion of PM concentrations, which is considerably higher in the fire station compared to the atmospheric air (Table 1). The maximum concentrations observed in the fire station are approximately threefold higher than the urban background levels. The substantial standard deviations (SD) values documented in Table 1 further underscore the significant fluctuations and jumps in PM concentrations within the fire station during both measurement seasons. It can be posited that these momentary fluctuations in PM concentrations are closely associated with the characteristics of the building and the nature of the activities conducted therein. The attainment of maximum concentrations is likely attributable to the phenomenon of resuspension, entailing the collection of dust settled on various surfaces (e.g., firefighting equipment, vehicles, and personal protective equipment) during activities such as the opening of windows and garage doors, the retrieval of uniforms from storage, the execution of cleaning procedures, the testing of equipment, and the initiation and cessation of rescue and firefighting operations. This assertion is supported by findings from earlier studies conducted by the authors [11].

Table 2

Values of I/O ratios in the two measurement seasons
for the fire station and urban background and Mann–Whitney *U* test results

Season	Ratio	PM_1	$PM_{2.5}$	PM_4	PM_{10}	PM_{100}
Heating	I/O	1.7	1.6	1.5	1.5	1.4
	statistical significance (p)	<0.001	<0.001	<0.001	<0.001	<0.001
Non-heating	I/O	3.0	2.4	2.0	1.3	1.1
	statistical significance (p)	<0.001	<0.001	<0.001	<0.001	<0.001

Figure 2 presents the mean percentage shares of individual fractions in the total mass of PM in the fire station and urban background in the heating and non-heating season, averaged over the entire measurement period (14 days). On average, in both measurement seasons, most of the PM mass was accumulated in particles with aerodynamic diameters smaller than 1 μm (31–89%) both inside and outside the fire station under study. A comparison of the shares of this fraction indoors and outdoors reveals that in the heating season, the indoor air exhibited a 10% higher percentage of this fraction compared to the atmospheric air, while in the non-heating season, the indoor air showed a 51% higher percentage. When considering the share of fine PM (particles with an aerodynamic diameter less than 2.5 μm), i.e., the fraction with the greatest impact on

human health, it can be stated that the highest average share of fine particles in the total mass of PM was recorded at fire stations during the heating season (90%), whereas the lowest was recorded for urban backgrounds during the non-heating season (39%).

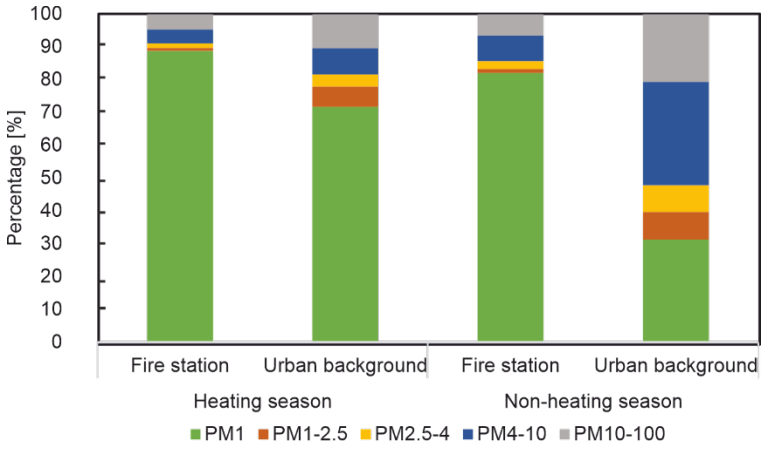

Fig. 2. Average percentage shares of individual particulate matter fractions in the total mass of particulate matter at the fire station and urban background in the heating and non-heating measurement season

The proportion of particles with aerodynamic diameters ranging from 4 to 10 µm in the urban background during the non-heating season was relatively high, and similarly to PM_1, it was 31%.

Table 3

Mass median aerodynamic diameter (MMAD) and geometric standard deviation (GSD) of particle mass size distributions (PSDs) in the fire station and urban background in the heating and non-heating measurement season

Season	Measurement site	MMAD [µm]	GSD
Heating	fire station	1.02	7.75
	urban background	1.71	8.06
Non-heating	fire station	1.30	7.82
	urban background	7.69	8.24

The elevated proportion of coarse PM during the non-heating season, evident in both the fire station and its surrounding environment, may be attributable to lower air humidity, thereby creating conditions conducive to re-suspension, i.e., the re-raising of dust settled on diverse surfaces, which is typified by larger particle sizes. The significant contribution of fine PM to the total PM mass is further substantiated by the low MMAD

values for the fire station in both seasons and atmospheric air in the heating season (Table 3). At the fire station, 50% of the PM mass was concentrated in particles with diameters below 1.02 μm and 1.30 μm in the heating and non-heating season, respectively. In contrast, 50% of the PM mass in the urban background was concentrated in particles with diameters below 1.71 μm in the heating season. A significantly higher value of MMAD was estimated for the urban background in the summer season (7.68 μm). The PM mass size distributions in all of the considered cases were similar – they were bimodal. In all cases, the larger modes ranged from 0.1 to 1 μm, while the smaller modes ranged from 1 to 2.5 μm at the fire station and from 2.5 to 4 μm for the urban background (Fig. 2).

The PM concentrations in the fire station under examination have been compared to the concentrations measured in two other fire stations in Poland. They ranged from 18.3 to 37.3 $\mu g/m^3$ in the fire station equipped with washing equipment and from 27.4 to 32.8 $\mu g/m^3$ in the fire station not equipped with washing equipment [11]. Furthermore, the order of magnitude of PM concentrations obtained in this research is comparable to the order of magnitude of concentrations of the same fractions in a fire station garage located in the northern part of Poland (22–136 $\mu g/m^3$) [12] and approximately three times higher than the PM_{10} concentration in the fire station garage of another Warsaw fire station (11 $\mu g/m^3$) [13]. It should be noted that the selection of studies for comparison was limited to those conducted in Poland, taking into account the similarity of climatic conditions and the utilization of analogous measurement methods, specifically the optical method. However, it is important to acknowledge the potential limitations in the direct comparison of studies due to variations in sampling periods and accuracy. Consequently, the comparisons presented here are intended to provide a general indication rather than definitive conclusions.

4. CONCLUSIONS

A comparative analysis was conducted of the concentrations and mass size distribution of five PM fractions (PM_1, $PM_{2.5}$, PM_4, PM_{10}, and PM_{100}) in the fire station in its immediate vicinity during two measurement seasons, namely heating and non-heating, respectively. Such an analysis has been conducted for the first time, and the following conclusions were derived from the research:

- In both measurement seasons, average PM concentrations in the fire station were higher than in the atmospheric air in its immediate vicinity. In the fire station, they assumed values in the range of 26–44 $\mu g/m^3$, while for the urban background, they ranged from 9 to 32 $\mu g/m^3$.

- In all cases, the predominant share in the total mass of particulate matter was that of fine particles. However, the year-round ratio in the fire station was significantly higher (87%) than for the urban background (58%).
- Based on the average concentrations, statistical tests, PM mass size distribution, and values of MMAD it appears that the concentration and mass size distribution of PM in the fire station differs from the concentrations and mass distribution of the urban background. The microclimate of a fire station is defined by its unique characteristics, including its internal sources of pollution and the nature of the activities that take place within the building. These factors contribute to an elevated proportion of fine PM in the fire station compared to the surrounding atmosphere. This discrepancy, if prolonged, has the potential to adversely impact on the health of individuals who are regularly present in the station.
- Based on the I/O ratio values greater than one, it is concluded that PM concentrations inside the fire station are mainly determined by internal sources, however, the increase in PM concentrations in winter, and thus the decrease in these values, shows that the environment also plays an important role in shaping the fire station microclimate.
- To mitigate the impact of atmospheric air and enhance indoor air quality, it is recommended to implement a systematic wet cleaning method to remove settled dust and minimize resuspension. Additionally, upgrading or replacing ventilation systems and installing air cleaners or filters capable of removing fine particles from indoor air are advised.
- As one of the first studies in this area, the study highlights the need for more comprehensive investigations involving a greater number of fire stations and settings. It should include the analysis of concentrations of other pollutants, such as PM-bound metals, PAHs, and gaseous compounds.

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