EVALUATING THE EFFECT OF A MODIFIED AIR PURIFIER ON AIR QUALITY IN AN APARTMENT IN NIŠ, SERBIA

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Niš, Serbia residents constantly face the severe and pressing issue of air pollution, particularly from suspended particulate matter fractions PM_{10} and $PM_{2.5}$. Conditions worsen significantly during the heating season, as the predominant combustion of wood, pellets, and solid fossil fuels in residential dwellings causes particulate matter concentrations to rise abruptly, exceeding levels more than twice as high as those during the non-heating season. Outdoor pollution easily infiltrates indoors and, together with indoor pollution, drastically degrades the quality of indoor air. Deteriorated indoor air quality poses a significant health risk, as individuals spend a lot of time indoors. This study evaluates the impact of a commercially available air purifier on reducing concentrations of PM_{10} and $PM_{2.5}$ in an apartment in Niš throughout 2024. The analysis reveals that the air purifier´s operation significantly reduces the concentration of suspended particles indoors during both the heating and non-heating seasons for PM_{10} and $PM_{2.5}$. Furthermore, a comparison of indoor and outdoor particulate concentration ratios between the heating and non-heating seasons shows that these ratios are lower during the heating season for both particle fractions.

Key words*: Air quality, Monitoring, Air purifier, Particulate matter*

1. Introduction

The deterioration of outdoor air quality is a serious global problem and a major environmental health concern. It was estimated that in the United States (US) alone air pollution have caused about 160,000 premature deaths in 2010 with a total economic loss of about $175 billion [1]. The US Environmental Protection Agency (EPA) identified "criteria pollutants" as pollutants of concern because of their impacts on health and the environment: particulate matter (PM), ozone (O_3), carbon monoxide (CO), nitrogen dioxide (NO_2), sulfur dioxide (SO_2) [2]. Among all the criteria pollutants, elevated levels of atmospheric particulate matter are regarded as the most harmful to human health. This is especially true for fine particles ($PM_{2.5}$) and ultrafine particles ($PM_{0.1}$). Fine particles can penetrate deep into the lung alveoli, while ultrafine particles can even cross the alveolar-capillary membrane, enter the bloodstream, and reach nearly every cell in the human body [3]. Hence, the ability of particles to penetrate the human body is inversely proportional to their aerodynamic diameter. In addition to size, the toxic potential of particles is significantly influenced by their chemical composition. Namely, after their formation during combustion processes, particles can readily “attract” nearby toxic or even carcinogenic substances, acting as vectors to transport these harmful compounds from the environment into human cells.

In the literature, numerous studies link outdoor air pollution, particularly $PM_{2.5}$ pollution, to chronic diseases and elevated mortality rates. According to a literature review conducted by Kulick et al. [4] prolonged exposure to air pollution, particularly fine particulate matter $PM_{2.5}$, may elevate the risk of stroke onset, and stroke-related mortality. Multiple studies [5–8] have highlighted the harmful impact of prolonged air pollution exposure on the likelihood of developing heart failure and atrial fibrillation, two other serious cardiovascular disorders. Additionally, particles carrying toxic metals, organic compounds, and gases can cause inflammation (most often in the lungs), induce oxidative stress, and activate pro-inflammatory signaling that may even affect distant organs [9]. Prolonged exposure to particulate pollution can even lead to the deposition of particle material around the terminal bronchioles, resulting in chronic focal inflammation and fibrosis, which could predispose individuals to “scar” lung carcinoma [10, 11].

Lelieveld et al. [12] calculated that outdoor air pollution, primarily from $PM_{2.5}$, is responsible for approximately 3.3 million premature deaths annually across the globe, with the majority occurring in Asia. It is worth noting that in this study, the authors begin their analysis with the assumption that all particles are equally toxic, but later incorporate a sensitivity analysis to account for variations in toxicity. In 2022, fine particulate matter ($PM_{2.5}$) was alone attributed to 239,000 annual deaths in the EU [13]. Additionally, over 83% of urban residents in the EU are exposed to pollutant levels that exceed the safety standards outlined in the 2021 World Health Organization air quality guideline values [14].

Air pollution is particularly relevant for Serbia, which, together with other Western Balkan countries, has been an infamous European leader in poor air quality year after year [15]. According to a WHO report [16] on a comprehensive investigation into the impact of air quality on health in Serbia, long-term exposure to air pollution in major cities leads to premature death for a relevant percentage of the population, while short-term exposure increases mortality risk. The WHO’s AirQ+ software [17] was used to calculate the proportion of deaths attributable to air pollution in the main Serbian cities. The analysis of national data shows that nearly 3,600 premature deaths each year are attributable to exposure to $PM_{2.5}$ in 11 studied cities. The investigation collected data on air quality, the population, and its health between 2010 and 2015. Levels of pollutants exceeding the limits set by European Union legislation on air quality were recorded in almost all larger Serbian cities. Simulations of progressive reductions in current $PM_{2.5}$ concentrations suggest significant health benefits from improving air quality in the country.

Individual dwellings and district heating systems with heat capacity below 50 MW are the biggest particulate matter (PM) air polluters in Serbia, as reported in SEPA’s official publication about the state of the air quality in Serbia in 2020 [18]. According to this report, these two groups are responsible for 51% of PM_{10} and 67% of $PM_{2.5}$ overall emissions. In individual households, wood logs and wood products (primarily pellets) are commonly used as heating fuels. Occasionally, coal or even coal pellets are used, mainly because they are cheaper than wood pellets. Recently, the prices of pellets have sharply increased, leading people to even resort to prohibited flammable materials as fuel for economic reasons. While such occurrences are sporadic, the units involved generate very dangerous and even carcinogenic emissions. A further challenge is that these units are difficult to identify within the large group of individual polluters and to sanction the offenders appropriately. An additional reason for elevated emissions is that despite the urge for change, most of the boilers in use are old and not certificated according to appropriate EN standards. Even if heating appliances pass certification testing, the process is conducted under factory-defined air/fuel ratios, which rarely reflect real operating conditions. Numerous studies have shown that deviations from these prescribed ratios lead to excessive emissions [19].

Outdoor pollutants easily infiltrate indoors. There are a number of pathways, but the most frequent are intentional natural ventilation, infiltration through building leaks as well as indoor-outdoor interaction. Since people spend most of their time indoors [20], they are exposed to a combination of particulate matter concentrations from both outdoor and indoor pollutants [21]. The impact of indoor air pollution on human health is complex and remains insufficiently studied, which has drawn increased attention from researchers [22]. Indoor air quality often presents a greater health risk than outdoor air pollution, as many people are exposed to more contaminated air indoors. Unlike outdoor air monitoring, comprehensive indoor air monitoring programs are rarely implemented in the Republic of Serbia, even though such data is crucial for calculating the air pollution exposure of tenants. Exposure can negatively affect human health, comfort, and productivity. The most effective strategy for maintaining healthy indoor air quality involves identifying and eliminating pollution sources while ventilating with clean outdoor air. Venting during the winter months is impossible due to elevated outdoor air pollution, making a portable, consumer-grade air purifier the most viable solution. There is a rising trend in the use of these devices [23], but systematic scientific studies on their efficacy remain sparse.

From the introduction section, it can be concluded that outdoor and indoor pollution presents a serious problem in Serbia, that continuous monitoring of indoor pollution is crucial for estimating tenants' exposure, and that portable air purifiers can provide an *ad hoc* solution to the growing problem of indoor air pollution. These issues motivated the present study.

There is currently no recognized standard procedure for the calibration of low-cost sensors (LCS) [24]. The sensors can be calibrated in the laboratory, before deployment, or in the field by comparing their results to those from reference-grade instruments. There is a need to perform both field and laboratory calibration for LCS, as good correlation with reference instruments in the lab does not always correspond to equally good performance under field conditions. LCS is sensitive to fluctuations in environmental conditions such as changes in temperature, RH, wind direction and speed, and other interacting pollutants.

Hence, the main aim of this study is to demonstrate that air pollution data from portable measuring devices, after adequate calibration against certified reference samplers and automatic air quality monitoring stations, provide reliable information about indoor and outdoor air pollution. For our study, we selected the city of Niš, as it is among the most air-polluted cities in Serbia. According to the data presented on the Serbian Environmental Protection Agency website [16], Niš has been in air quality category III (polluted air) for the last 5 years (2019-2023) due to exceeding the annual limit values prescribed for the concentration of suspended particles PM_{10} and $PM_{2.5}$ in the ambient air. Particulate air pollution peaks during the heating season (October to April) due to the predominant use of biomass and fossil fuels for heating. During that period, the residents of Niš are exposed to more than twice the concentrations of suspended particles PM_{10} and $PM_{2.5}$ compared to the non-heating period [25, 26].

The market provides a wide range of air purification (AP) devices intended for use in apartments and offices [27, 28]. The implementation of natural ventilation does not enhance indoor air quality (IAQ) when the outdoor environment is polluted. As a result, the demand for air purifiers has been rising in recent years. Another aim of our study is to show that a consumer-grade air purifier, modified to provide prefiltered outdoor air indoors, can significantly lower indoor PM concentration.

2. Materials and methods

2.1. Sampling location

Sampling was performed in the city of Niš. The city of Niš, the administrative center of the Nišava district, is located in southeastern Serbia within the Niš basin. It is situated between the branches of the Svrljiške mountains, Suva Planina, and Jastrebac, at the confluence of the Nišava River with the South Morava. The city covers an area of 596.7 km² and, according to the 2022 census, has a population of 182,797, making it Serbia's third most populous city. Niš experiences a moderate-continental climate with warm summers and moderately cold winters. The average annual temperature is around 12°C, with July being the warmest month (average 22.5°C) and January the coldest (average 0.2°C). The average annual air pressure is 971.7 mbar, with averge relative humidity of 72%. The lowest humidity occurs in August (60.6%), while the highest is in December (82%) [29]. The predominant winds, in order of frequency, are east, northwest, north, and northeast. Winds blow on average for 81–105 days per year, with an average speed slightly below 3 m/s. The winter period is often characterized by temperature inversions and calm weather, which limit the dispersion of air pollutants during periods of stillness or weak winds [29].

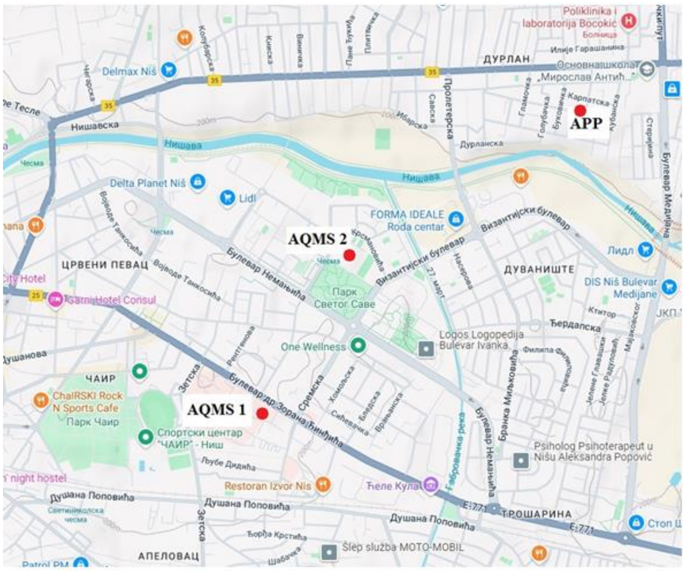


Figure 1. The location of the selected apartment (APP) and AQMS (Air Quality Monitoring Stations) on the Nis city map

The city location, with dwellings concentrated within a valley, favors the accumulation of particulate pollution due to minimal natural ventilation. This issue has worsened due to intensive dwelling construction in the northern part of the city, which prevents the natural inflow of fresh air from the surrounding hills. As a result, an artificial barrier has been created, obstructing the natural ventilation of a large part of the city.

All particulate matter concentration measurements for this study were conducted in an apartment situated in a neighborhood predominantly composed of private houses that use wood and fossil fuels for heating. The chosen apartment (referred to as APP) is located within a 2 km radius of Air Quality Monitoring Station 1 (AQMS1) and 1.3 km from Air Quality Monitoring Station 2 (AQMS2), as illustrated in Fig. 1.

2.2. Measurement campaigns, and equipment used

We conducted a comparative analysis of 1-hour mean PM_{10} and $PM_{2.5}$ concentrations measured indoors, using the PAQMON 1.0 low-cost PM monitoring device [30], and the corresponding outdoor PM_{10} and $PM_{2.5}$ concentrations recorded by GRIMM EDM180 monitors [31] at AQMS1 and AQMS2. These comparison campaigns were performed during the heating season, from January 17th, 2024 to March 9th, 2024, and during the non-heating season, from June 15th, 2024 to August 29th, 2024.

The selected apartment, with a volume of 65 m³, features a carpeted floor with wooden window frames and doors.. The layout includes a living room with an integrated kitchen, two bedrooms, and a bathroom. Heating is provided by one Hisense Energy Pro 4.2 kW inverter air conditioning unit (living room) and one Midea 4.1 kW multi-split air conditioning system with two indoor units (for two bedrooms). The apartment housed two adults and two preschool-aged children. In the non-heating season, the windows were typically slightly ajar, when the air conditioner in the apartment was not working. During the heating season, the windows were closed during the measurement campaign. The air conditioning system provided heating during the winter season. The apartment has a total window surface area of 4 m².

For air purification, a modified portable Xiaomi Mi 2H air purifier [32] was used. In its original design, the purifier draws polluted air from the room through perforated side panels, filters the indoor air using a cylindrical high-density triple-layer HEPA filter (Toray, JPN), and injects the filtered air through an opening at the top. For this study, adjustments were made to the original design. A significant portion of the side perforations was sealed with adhesive tape, allowing air intake solely through a side-mounted flexible hose. The hose was connected to a ventilation duct extending along the entire vertical axis of the house. This modification enabled the air purifier to draw in outside air, filter it, and inject it indoors. In this way, in addition to filtering particles from the air, the system introduces fresh air, contributing to a reduction in CO_2 levels within the space. The device was placed on a cabinet, with its top edge at a height of approximately 2 meters. The modified device and its position inside the living room are shown in Fig. 2.

Figure 2. The modified Xiaomi Mi 2H air purifier: front and side view

For continuous monitoring of PM_{10} and $PM_{2.5}$ concentrations, a PAQMON 1.0 low-cost PM monitoring device was installed in the living room. The PAQMON 1.0 employs an Arduino Mega 2560 microcontroller [33] as its control board, with a NOVA SDS011 sensor module [30] used to measure PM_{10} and $PM_{2.5}$ concentrations, ranging from 0 to 1000 µg/m³.

During the first week of the measurement campaigns, two LVS3 reference samplers [34, 35], equipped with PM_{10} and $PM_{2.5}$ heads, were co-located with the PAQMON 1.0 monitor in the living room. This arrangement was necessary to determine the correction factor for the PAQMON 1.0 [30, 36]. The LVS3 samplers operated at a calibrated flow rate of 38.3 l/min, which was verified using certified flow meters at the start of each measurement campaign.

2.3. Correction factor calculation

The particulate matter (PM) data collected by the PAQMON 1.0 device were corrected using a slightly modified version of the method proposed by Ramachandran et al. [36]. The PM concentrations measured by the PAQMON 1.0 were adjusted by applying a correction factor calculated using Equation (1):

$$F = \frac{1}{n}\sum_{i=1}^{n}\frac{G_i}{K_i} \tag{1}$$

Where F represents the correction factor, n is the number of measurement days, G_i is the 24-hour average PM concentration for i-th day as measured by the LVS3 sampler, and K_i is the corresponding 24-hour average PM concentration recorded by the PAQMON 1.0 on the same day. Each 1-hour PM result obtained by the PAQMON 1.0 device was multiplied by this correction factor. The 1-hour PM results obtained by the PAQMON 1.0 were multiplied by this correction factor. The computed correction factor values are summarized in Tab. 1.

Table 1. Summary of the correction factor (F)

Location	F for PM_{10}	F for $PM_{2.5}$
Apartment (heating season)	1.10	1.25
Apartment (non-heating season)	1.20	1.30

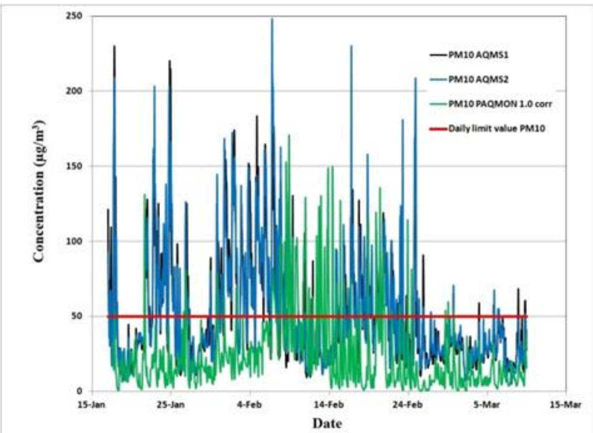
As shown in Tab. 1, the PAQMON 1.0 monitor underestimates PM concentrations compared to the reference gravimetric method, with a deviation of 10–30% for both PM_{10} and $PM_{2.5}$ fractions. These results are consistent with the correction factor values reported in previous studies [30], which involved the use of PAQMON 1.0 devices to monitor indoor PM levels in Niš. These findings emphasize the necessity of applying correction factors to low-cost PM sensors by referencing gravimetric measurements for accurate data interpretation.

3. Results and discusion

3.1. Results of the comparative measurements in the heating season

Comparative measurements in Niš in the heating season were performed, from January 17th, 2024 to March 9th, 2024. During the 53-day observation period, AQMS1 recorded 22 days where PM_{10} concentrations exceeded the daily limit value of 50 μg/m³ and 21 days where $PM_{2.5}$ concentrations exceeded the daily limit value of 25 μg/m³, corresponding to 42% and 40% of the observed days, respectively. Similarly, AQMS2 registered 23 days with PM_{10} levels above the daily limit and 20 days with $PM_{2.5}$ levels exceeding the limit, representing 43% and 38% of the days, respectively.

To assess the effect of an air purifier on indoor air quality, the device was deactivated from February 7th to February 14th, 2024. The evaluation of the purifier's impact on indoor air quality was based on the ratio of particulate matter concentrations (PM_{10} and $PM_{2.5}$) inside the apartment to those in the outdoor environment, during both the periods when the air purifier was operational and when it was turned off. Figure 3 presents the comparative measurements of PM_{10} and $PM_{2.5}$ concentrations, while Tab. 2 summarizes the statistical results of these measurements.



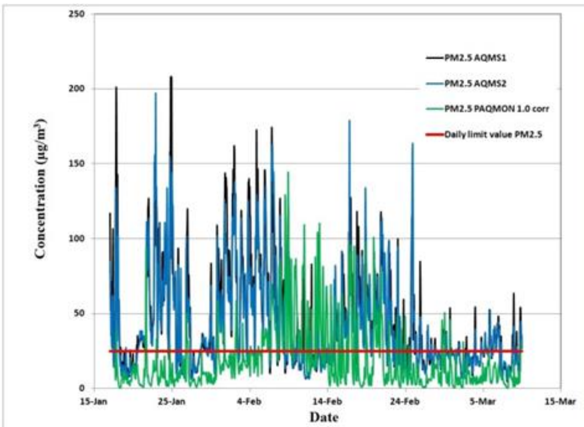


Figure 3. Line diagram of 1-hour mean PM concentrations in the heating season

Based on the data presented in Tab. 2, during the period when the air purifier was operational, the average concentration ratio of PM_{10} between the indoor environment and the outdoor air was 0.35 (APP/AQMS1) and 0.34 (APP/AQMS2). For $PM_{2.5}$, the corresponding concentration ratios were 0.31 (APP/AQMS1) and 0.33 (APP/AQMS2). Conversely, during the period when the air purifier was inactive, the average concentration ratio of PM_{10} in the apartment relative to the outdoor air increased to 1.43 (APP/AQMS1) and 1.35 (APP/AQMS2), while for $PM_{2.5}$, the ratios were 1.45 (APP/AQMS1) and 1.61 (APP/AQMS2).

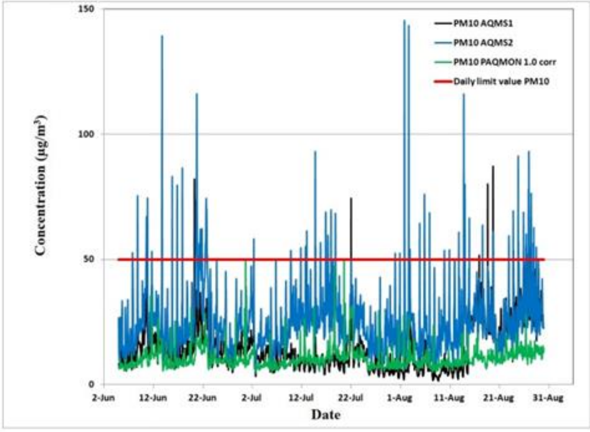
The analysis shows that the air purifier operation significantly reduces the concentration of suspended particles in the apartment, during the heating season, for both observed fractions, PM_{10} and $PM_{2.5}$. The results for the entire measurement period in the heating season show that the average concentration ratio of PM_{10} in the apartment relative to the outdoor air is 0.46 (APP/AQMS1) and 0.45 (APP/AQMS2), while for $PM_{2.5}$, the ratios were 0.31 (APP/AQMS1) and 0.36 (APP/AQMS2).

Table 2. Summary of the average PM mass concentrations (μg/m^3), and standard deviation (SD), for the measurement campaign conducted in the heating season

	PM	**Average**	**SD**	**PM**	**Average**	**SD**
AIR PURIFIER ON		[μg/m^3]	[μg/m^3]		[μg/m^3]	[μg/m^3]
AQMS1 (GRIMM EDM 180)	PM_{10}	51.9	38.1	$PM_{2.5}$	46.5	36.0
AQMS2 (GRIMM EDM 180)	PM_{10}	52.5	38.9	$PM_{2.5}$	43.0	32.8
PAQMON 1.0 CORRECTED	PM_{10}	18.1	17.4	$PM_{2.5}$	14.2	15.3
	PM	**Average**	**SD**	**PM**	**Average**	**SD**
AIR PURIFIER OFF		[μg/m^3]	[μg/m^3]		[μg/m^3]	[μg/m^3]
AQMS1 (GRIMM EDM 180)	PM_{10}	37.3	27.4	$PM_{2.5}$	30.1	24.8
AQMS2 (GRIMM EDM 180)	PM_{10}	39.5	27.0	$PM_{2.5}$	27.0	20.6
PAQMON 1.0 CORRECTED	PM_{10}	53.4	36.9	$PM_{2.5}$	43.5	28.8

3.2. Results of the comparative measurements in the non-heating season

Comparative air quality measurements in Niš during the non-heating season were conducted from June 05th, 2024 to August 29th, 2024. Throughout the 85-day observation period, no exceedances of the daily limit values for suspended particulate matter (PM_{10} and $PM_{2.5}$) were recorded at the automatic monitoring stations in Niš. To evaluate the impact of the air purifier on indoor air quality, the device was turned off between June 10th and June 17th, 2024, as well as from August 1st to August 7th, 2024. The effect of the air purifier was assessed by comparing the ratio of PM_{10} and $PM_{2.5}$ concentrations inside the apartment with those in the outdoor air during periods when the air purifier was operational and inactive. The results of these comparative measurements for PM_{10} and $PM_{2.5}$ are displayed in Fig. 4, and the summary statistics are presented in Tab. 3.



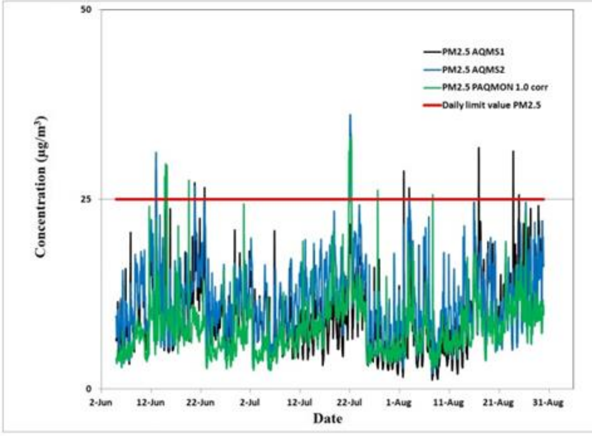


Figure 4. Line diagram of 1-hour Average PM concentrations in the non-heating season

Based on the data in Tab. 3, when the air purifier was active, the average concentration ratio of PM_{10} between the indoor and outdoor environments was 0.71 (APP/AQMS1) and 0.80 (APP/AQMS2). For $PM_{2.5}$, the respective concentration ratios were 0.41 (APP/AQMS1) and 0.68 (APP/AQMS2). Conversely, when the air purifier was inactive, the average PM_{10} concentration ratios were 0.80 (APP/AQMS1) and 0.43 (APP/AQMS2), while the $PM_{2.5}$ ratios rose to 0.91 (APP/AQMS1) and 0.77 (APP/AQMS2).

During the entire measurement period in the non-heating season, the average concentration ratios of PM_{10} in the apartment relative to outdoor air were 0.72 (APP/AQMS1) and 0.42 (APP/AQMS2), while the $PM_{2.5}$ ratios were 0.82 (APP/AQMS1) and 0.69 (APP/AQMS2).

Table 3. Summary of the average PM mass concentrations (µg/m³), and standard deviation (SD), for the measurement campaign conducted in the non-heating season

AIR PURIFIER ON	PM	Average [µg/m³]	SD [µg/m³]	PM	Average [µg/m³]	SD [µg/m³]
AQMS1 (GRIMM EDM 180)	PM_{10}	14.7	10.0	$PM_{2.5}$	9.7	4.6
AQMS2 (GRIMM EDM 180)	PM_{10}	25.1	12.4	$PM_{2.5}$	11.6	4.6
PAQMON 1.0 CORRECTED	PM_{10}	10.4	4.1	$PM_{2.5}$	7.8	3.7
AIR PURIFIER OFF	**PM**	**Average** [µg/m³]	**SD** [µg/m³]	**PM**	**Average** [µg/m³]	**SD** [µg/m³]
AQMS1 (GRIMM EDM 180)	PM_{10}	12.5	8.8	$PM_{2.5}$	9.6	5.2
AQMS2 (GRIMM EDM 180)	PM_{10}	23.4	16.7	$PM_{2.5}$	11.3	5.2
PAQMON 1.0 CORRECTED	PM_{10}	8.3	3.3	$PM_{2.5}$	8.7	4.8

The analysis demonstrates that air purifier operation significantly reduces the concentration of suspended particles in the apartment during the non-heating season for both PM_{10} and $PM_{2.5}$.

Additionally, when comparing the indoor/outdoor concentration ratios of suspended particles during the heating and non-heating seasons, it was observed that these ratios were lower for both particle fractions during the heating season. This discrepancy is primarily attributed to the fact that outdoor concentrations of suspended particles during the heating season are approximately twice as high as those observed during the non-heating season. Furthermore, during spring and summer, with moderately high outdoor temperatures, the apartment is ventilated more frequently, particularly in the morning and throughout the day, whereas ventilation is minimized during the heating season due to reduced window openings.

4. Conclusions

Eliminating all sources of indoor air pollution across various environments is often impractical, and relying solely on natural ventilation is not an effective solution when outdoor air is also polluted. In such cases, air purification technologies are widely recognized as effective tools for maintaining clean indoor air. This study evaluates the effectiveness of a commercially available air purifier in reducing suspended particulate matter concentrations in an apartment in Niš during both the heating and non-heating seasons. The results demonstrate that the air purifier significantly reduces indoor concentrations of PM_{10} and $PM_{2.5}$ in both seasons. Additionally, a comparison of indoor-to-outdoor particulate concentration ratios reveals that these ratios are lower during the heating season for both particle fractions. The research presented in this paper serves as a preliminary introduction to an upcoming study on the application of air purifiers in residential spaces. The results highlight the need for a detailed investigation of all factors affecting the efficiency of air purification in indoor environments using commercially available air purifiers. We plan to expand the research to a larger number of apartments, selecting those with similar characteristics in terms of area, number of floors, and number of occupants, while focusing on non-smoking households. Various types of commercially available air purifiers will be tested, along with apartments featuring different types of carpentry. Such a study will examine the impact of different air purifier models on PM levels, ensuring that each selected model is tested in every apartment. Additionally, the research will include chemical analysis of PM samples, as well as particle composition analysis.

Acknowledgment

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