IMPACT OF EXTENSIVE GREEN ROOF ON THE REMOVAL OF PARTICULATE MATTER

by

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This paper investigates the impact of extensive green roof on ambient PM1, PM2.5, and PM10 concentrations. During summer, particulate matter (PM) concentrations in ambient air were measured above the green roof and reference roof of a school building in the urban environment. The backward trajectory of air mass from the HYSPLIT model was used to access the particle's emission source. The results show that green roof reduces PM concentration in ambient air by up to 67% and improve the air quality index. The larger impact was observed for PM1 particles, which are the most dangerous for human health. The high correlation coefficients for the ratio of PM2.5/PM10 concentrations were found above both roofs, indicating fine particulate dominance. The findings of this paper can help the large-scale adoption of green roofs to mitigate air pollution.

Key words: *air pollution, air quality, air quality index, green roof, particulate matter, vegetation*

Introduction

Air pollution and climate change are closely linked because burning fossil fuels releases air pollutants and GHG. If address short-lived climate pollutants, such as ground-level ozone and black carbon, a component of PM, dual benefits can be achieved: better air quality and climate change mitigation. Many people are exposed to air pollution as the global population becomes more concentrated in urban areas [1, 2]. Air pollution is one of the most serious impacts of rapid industrialization and urbanization. Air quality assessments based on data from monitoring stations managed by national authorities indicate that the concentrations of air pollutants, especially PM, regularly exceed the levels that protect human health [3]. The PM is a mixture of solid particles and liquid droplets of dust, dirt, *etc*. in the air. Depending on the aerodynamic diameter, particulates can be coarse, fine, and ultrafine. Coarse particles have an aerodynamic diameter between 2.5 μm and 10 μm, and include dust, fly ash, pollen, mold, *etc*. Fine particles have an aerodynamic diameter of less than 2.5 μm, including combustion particles and secondarily formed aerosols. Primary particulate matter is emitted from power plants, vehicles, industries, construction sites, mining, *etc.* Secondary PM is formed in the atmosphere through chemical reactions. The PM has been linked with different health problems [4].

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The state-managed system for monitoring air quality in Serbia showed that the concentrations of air pollutants, especially PM, in large cities regularly exceed the levels recommended in the WHO air quality guidelines [5]. Air quality in almost all locations in Serbia where it is measured is assigned the lowest possible score, according to the Serbian Environmental Protection Agency Annual Report on the State of Air Quality in Serbia. The main sources of outdoor air pollution in Serbia include the energy sector (thermal power plants, district heating plants, and individual household heating), the transport sector, waste dump sites, and industrial activities [3]. In the city of Belgrade, the air has been excessively polluted (third category) for many years due to exceeding the limit values for PM2.5 and PM10.

It is recognized that plants can have a positive influence on air quality. Plants can absorb various gaseous pollutants from the air, and PM are deposited on the above-ground parts of the plant. Among different plant species, the potential of PM removal from the environment depends on the leaf's anatomical traits of species, such as the presence of trichomes and hair, wax cover, leaf surface roughness, and stomata number and size [6]. Precipitation events cause PM to be washed off from leaves, recovering their capacity to filter airborne PM [7]. Green infrastructure is recognized as a key element in dealing with climate change issues, given its potential to mitigate GHG emissions as well as improve the environmental health and quality of life of its residents [8]. Green roofs are emerged as a promising solution increase green spaces and well-being in densely populated urban areas. Green roofs have numerous environmental benefits such as the reduction of heat gains and losses through building roofs, the urban heat island effect, stormwater runoff, and noise as well as an increase in biodiversity and green areas in urban areas [9].

In the last 30 years, only 5% of publications have investigated the influence of green roofs on air quality in urban areas [10, 11]. In Chicago 19.8 ha of green roof removed 1675 kg of air pollution, whit O_3 accounting for 52%, 27% for NO_2, 14% for PM10, and 7% for SO_2 [12]. In Singapore, the green roof with crushed stones and gravel, increases mass concentration of PM2.5 and PM10 by 16% and 42%, respectively, while reducing SO_2 by 37% and NO_2 by 21% [13]. In Australia, field measurements were performed to calculate the ambient air pollutant removal of an extensive green roof compared to adjacent identical building with a conventional roof [14]. The big-leaf resistance model was used to estimate the annual removal rate of NO_2, O_3 and PM2.5 for the green roof. The green roof was theoretically capable of removing 2.3 kg of NO_2, 6.9 kg of O_3, and 0.5 kg of PM2.5 per year. The NO_2 detected on the green roof was on occasion higher compared to the conventional roof, while a lower concentration of O_3 was observed on the green roof. There were no statistically significant differences in detected PM2.5 between the two buildings. In the study [15], laboratory measurements were performed to determine the NO_x/O_3 removal of 13 plants commonly used on green roofs. Three species were found to be the most efficient for the NO_2/O_3 uptakes: sedum sexangulare, *Thymus vulgaris, and Heuchera Americana L*. Field measurement of CO_2 concentration at the middle of the green roof plot and the surrounding area showed that during the sunny day, a green roof lower the CO_2 concentration by 2% [16]. Plants reduced the CO_2 concentration in the environment by absorbing CO_2 in the daytime, while during the night time, CO_2 concentration at the green roof plot was slightly higher than that at the surrounding area. The study [17] combines leaf-sampling and ambient air monitoring approaches in quantifying deposition and overall PM reduction by green infrastructure in near-road environments in the UK. The order of PM density was PM1 > PM2.5 > PM10, accounting for 66%, 29%, and 5% of total deposited particles, respectively. There is a lack of experimental research on green roof effect on air pollution in Europe.

Belgrade the capital and larger city of Serbia is often among the most polluted city in the world [18]. According to long-term air quality data collected over 2020, with an annual mean PM2.5 concentration of 24.3 μg/m³, Belgrade was placed in 590th place out of all cities ranked worldwide [19]. In 2020, the annual mean for PM2.5 was five times higher compared to the WHO guidelines and more than two times higher for PM10 [20]. The effects of green roof vegetation on PM concentration have not been studied in Serbia, according to available sources. In this context, this paper investigates the impact of a lightweight green roof with the mineral wool growing substrate on PM concentrations. The results of experimental measurements of PM1, PM2.5, and PM10 concentrations above the green roof and reference roof of the school building during summer days in July 2020 are presented. The ratio between PM2.5 and PM10 concentrations was determined to assess the particle emission source. The backward trajectory of air mass from the hybrid-single particle lagrangian integrated trajectory (HYSPLIT) [21] model was used to access the particle's source of origin.

Methodology

The measurement site is located in the capital city of Serbia, Belgrade. The country belongs to the Cfa type of climate (humid subtropical), according to the Koppen-Geiger climate classification [22]. Belgrade has a problem with the loss and degradation of green spaces while many smaller green spaces within the central city zone were converted into built-up areas [23]. The central urban part of Belgrade has only 2.8% of green areas, compared to barely over 12% in its entire territory with suburban greenery and forests [24]. The field experiment was conducted in a school building located in the New Belgrade municipality of Belgrade. During the last years, the air quality measuring station at New Belgrade showed that air was excessively polluted due to the high concentration of PM, according to a Report on air quality in the Republic of Serbia from the Serbian Environmental Protection Agency [5]. Figure 1 shows the location of the experimental site on Omladinskih Brigada Street. The study site is surrounded by major roads with intensive traffic and eight bus lines. The school building is close to a large business and residential building complex and 700 m away from the E-75 highway.

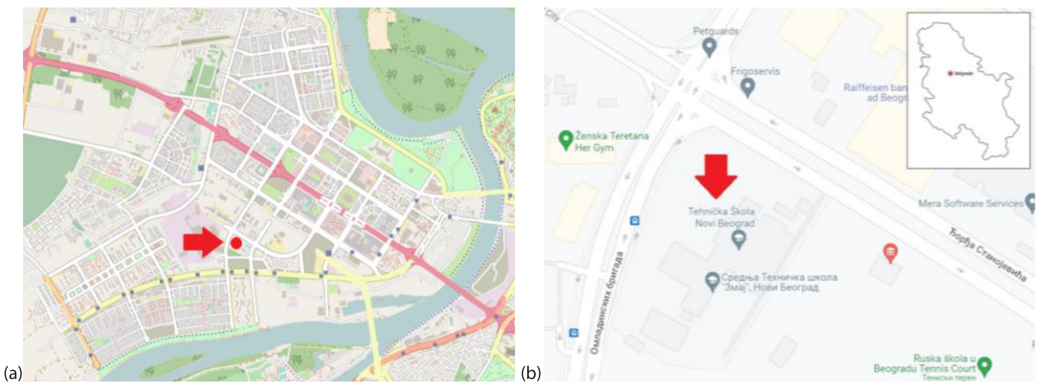


Figure 1. (a) Map of New Belgrade with location of measurement site and (b) location of a school building

In November 2018, 25 m² of the school roof was covered with an extensive green roof system. Measurements were obtained simultaneously from the green roof and the adjacent reference roof. The existing reference roof consists of concrete slabs with a hydro isolation layer and gravel layer on the top. The layer of gravel was removed from one surface area of the roof and a lightweight green roof was installed at the first-floor height approximately 4 m from the ground level. From bottom to top, the green roof consists of four layers: a waterproof layer, a drainage layer, rock mineral wool as a growing substrate, and a vegetation mat. The lightweight green roof can be a good retrofitting solution for existing buildings that have limited load capacity. Figure 2 shows a green roof and a reference roof with monitoring sensors. The green and reference roof has the same area and orientation. A mix of eight Sedum species was chosen for the green roof vegetation mat: *Sedum acre, Album coral carpet sedum, Sedum wall album, Sedum hybridum, Sedum sexangulare, Sedum hispanicum, Sedum floriferum,* and *Sedum Kamtschaticum*. These plant species were selected because they are the most used plants for green roofs worldwide. During the field measurement, the roof was uniformly covered with vegetation. The plant height was between 10 cm and 15 cm.

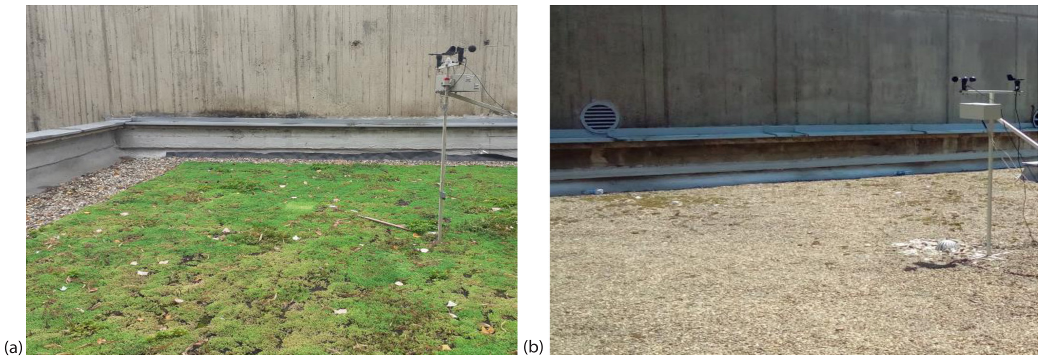


Figure 2. (a) The extensive green roof and (b) reference roof with monitoring sensors

The PM10, PM2.5, and PM1 concentrations in ambient air were obtained from air quality monitoring stations with low cost PMS3003 sensors positioned at the center of the roofs. The PMS3003 is a low cost commercially available particle sensor with a 10 seconds response time. The PM sensor uses a laser scattering principle, which works by measuring light scattered by particles carried in an air stream through a light beam, as shown in fig. 3. Pollution monitoring using different commercial low cost sensors is observed worldwide. It was established that PMS3003 sensors are precise enough for PM monitoring [25, 26]. The sensors were calibrated before the measurements campaign. The real-time mass PM concentrations were measured at 140 cm above the reference roof and green roof. The measurements campaign was performed from 1 until 7 July 2020. Ambient PM concentrations were recorded at a 10 minute time intervals. In this way the PM sensors provide 144 measurements every day. Measurement data were stored in the data acquisition system Keithley DAQ 6510. The technical specifications of the sensor are summarized in tab. 1.

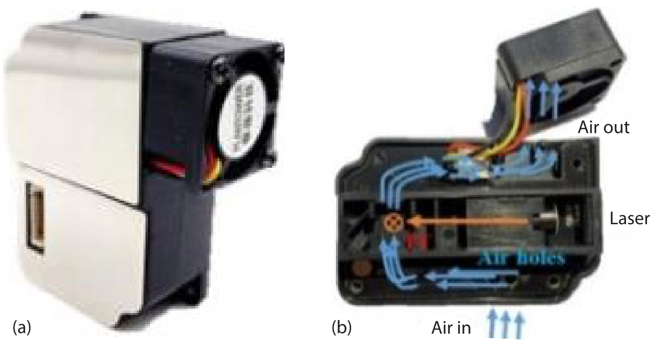


Figure 3. The particulate matter PMS3003 sensor

Table 1. Technical specifications of the sensors

Parameter	Model	Measuring range	Resolution	Accuracy
PM1, PM2.5, PM10 concentration	Plantower PMS3003	0.3-1µm 1-2.5 µm 2.5-10 µm	1 µg/m^3	±10%

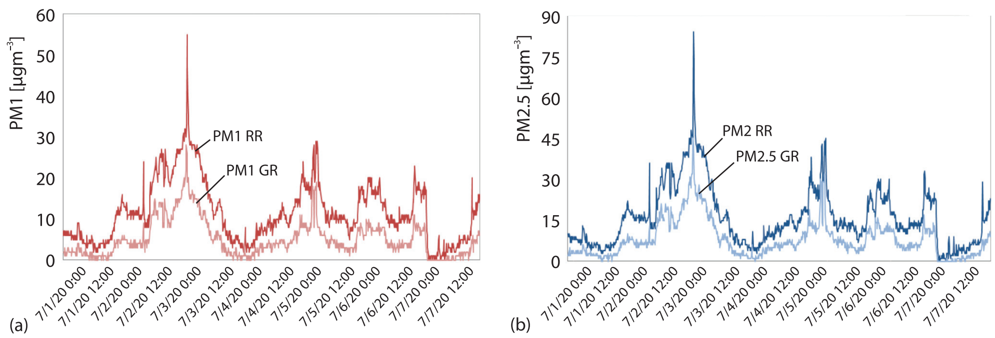
The air quality index (AQI), which reports daily air quality regarding health effects, was calculated according to the USA Environmental Protection Agency (USEPA) method. The USEPA AQI was selected because it is commonly applied AQI in the world. The USEPA uses the five most common ambient air pollutants: PM2.5, PM10, O_3, CO, NO_2, and SO_2. Pollutant with the highest pollution index is considered to express the AQI. Since in this research only PM concentration was measured, the 24 hour mean values for PM2.5 and PM10 concentration were used to calculate the index of pollutant (sub-AQI) using:

$$I_p = \frac{I_{Hi} - I_{Lo}}{BP_{Hi} - BP_{Lo}}\left(C_p - BP_{Lo}\right) + I_{Lo} \tag{1}$$

The breakpoints in the concentration of each pollutant (BP_{Hi}, BP_{Lo}), AQI values corresponding to breakpoints (I_{Hi}, I_{Lo}), and AQI rating based on PM2.5 and PM10 concentration are given in [27]. The lower the AQI value, the lower the level of air pollution. The AQI values at or below 100 are thought of as satisfactory.

Results

Ambient PM concentrations were recorded at 10 minutes time intervals and later mean hourly and finally mean daily PM concentrations were calculated. The measured mass concentrations of PM1, PM2.5, and PM10 in the ambient air above the reference roof and green roof are presented in fig. 4. It was found that above the green roof concentrations of PM were



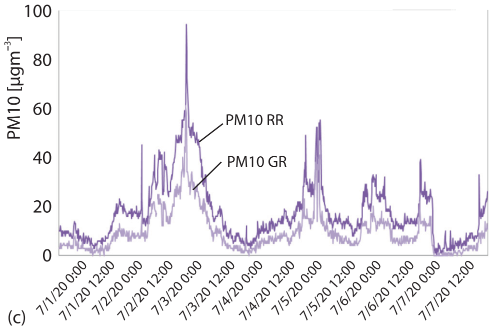


Figure 4. The mass concentration of; (a) PM1, (b) PM2.5, and (c) PM10 above reference roof and green roof; *RR – reference roof, GR – green roof*

lower compared to the reference roof, during the observed period. The mean PM1 concentration above the green roof was 5 μg/m^3, while 12 μg/m^3 above the reference roof. The mean PM2.5 concentration above the green roof was 8 μg/m^3, while 16 μg/m^3 above the reference roof. Above the green roof, the mean PM10 concentration was 10 μg/m^3, while 18 μg/m^3 above the reference roof. In general, the lowest PM concentrations occurred in the afternoon (from 1-3 pm). After 4 pm, the rush hour increased the number of cars and PM concentration. The concentration increased, causing the concentration reach its maximum in the night hours (mainly at around 11 pm). In the site location, the highest concentrations of both coarse and finer PM were recorded on July 3rd, while on July 7th were recorded minimal PM concentrations. It can be observed that the PM mass concentrations followed a trend of ΔPM10 > ΔPM2.5 > ΔPM1.

The results of statistical analysis, including the mean, median, maximum, and standard deviation values of PM1, PM2.5, and PM10 mass concentrations expressed in μg/m^3 in the ambient air are given in tab. 2. The maximum PM1, PM2.5, and PM10 mass concentrations above the reference roof were 55 μg/m^3, 84 μg/m^3, and 94 μg/m^3, respectively, while above the green roof 28 μg/m^3, 45 μg/m^3, and 61 μg/m^3, respectively.

Table 2. Summary statistics of PM concentration [μgm^{-3}] above reference roof and green roof

	Reference roof			Green roof		
	PM1	PM2.5	PM10	PM1	PM2.5	PM10
Mean	12	16	18	5	8	10
Standard deviation	7	11	13	4	7	8
Median	10	14	14	4	6	7
Maximum	55	84	94	28	45	61

Apart from local pollution sources, the PM transport from the highly polluted regions could significantly influence the air quality in the study area. To identify the transportation routes and possible emission sources the HYSPLIT model was used. This analysis was performed with 72 hours backward air mass trajectories, fig. 5, at 300 m, 500 m, and 700 m above ground level to assess the contribution of long-range transport of the PM. The HYSPLIT model indicated that particles had originated from the North Atlantic Ocean and are the result of a combination of different source regions, dust generation mechanisms, atmospheric synoptic conditions, and sink mechanisms [28].

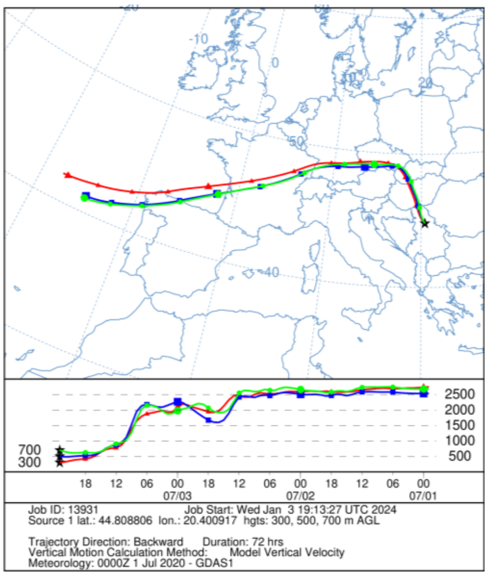


Figure 5. The air mass backward trajectories reaching the site location

The ratio of PM2.5/PM10 mass concentrations shows the relative dominance of fine and coarse particles. A high PM2.5/PM10 ratio (>0.5) suggests that fine particles are major contributors, while a lower PM2.5/PM10 ratio indicates the dominance of coarse particles [29]. Figure 6 shows the PM1/PM10 ratio in the ambient air above the green roof and reference roof. The PM2.5/PM10 ratio in the ambient air above the green roof and reference roof is presented in fig. 7. The higher values of PM1/PM10 and PM2.5/PM10 ratios were found above both roofs during the summer days. This indicates the involvement of finer particles and suggests that traffic emission was one of the dominant sources of PM. The PM10 concentration values were well correlated with PM1 concentration values, with correlation coefficients of 0.9631 for the reference roof and 0.9609 for the green roof. The correlation coefficient between PM10 and PM2.5 concentration values is 0.9875 for the reference roof and 0.9842 for the green roof. The high value of the correlation factor suggests that PM1, PM2.5, and PM10 came from similar emission sources [30].

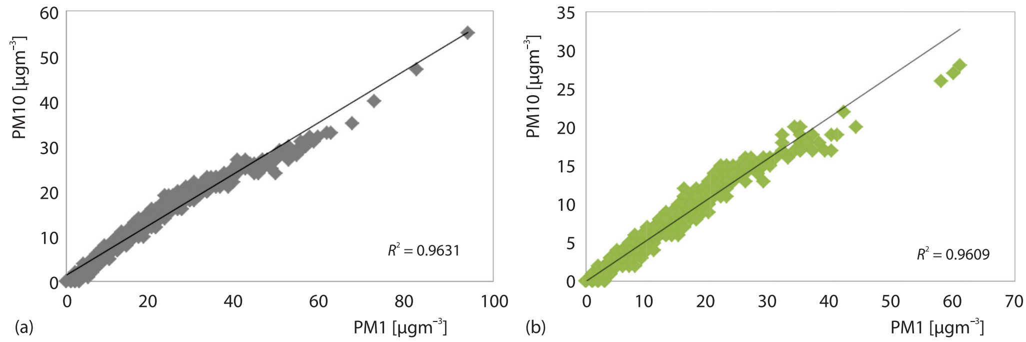


Figure 6. The ratio of PM1/PM10 mass concentration above; (a) reference roof and (b) green roof

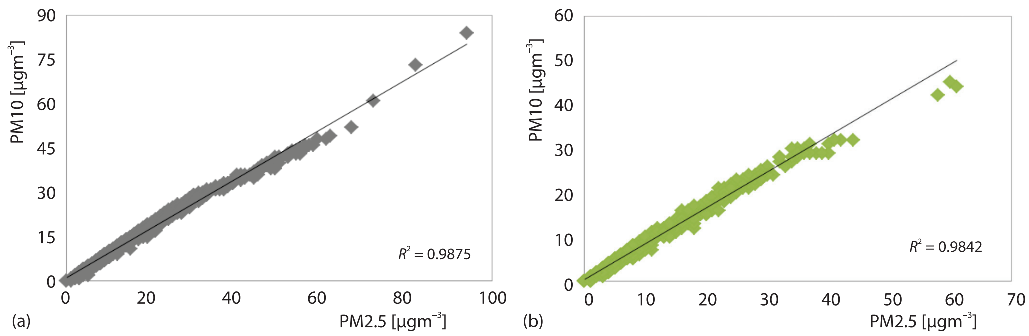


Figure 7. The ratio of PM2.5/PM10 mass concentration above; (a) reference roof and (b) green roof

The mean daily concentrations of PM1, PM2.5, and PM10 above the green roof and the reference roof are shown in fig. 8. The mean daily PM1 concentrations above the reference roof were from 6-17 μg/m^3, while above the green roof, the values were from 2-8 μg/m^3. The mean daily concentrations of PM2.5 above the reference roof were from 8-24 μg/m^3, while above the green roof, the values were from 3-13 μg/m^3. The mean daily concentrations of PM10 above the reference roof were from 9-27 μg/m^3, while above the green roof, the values were from 4-16 μg/m^3. According to the new WHO air quality guidelines [31], the 24 hours mean values for PM2.5 and PM10 concentration should not exceed 15 μg/m^3 and 45 μg/m^3 more than 3-4 days per year, respectively. Only 24 hours mean values of PM2.5 concentrations above the reference roof exceed the WHO guideline value during four days.

The percentage reference-green roof differences in mean daily PM concentrations are shown in fig. 9. The minimal differences in daily mean ambient PM1, PM2.5, and PM10 concentrations were, respectively 49%, 45%, and 42%. The maximum differences in daily mean

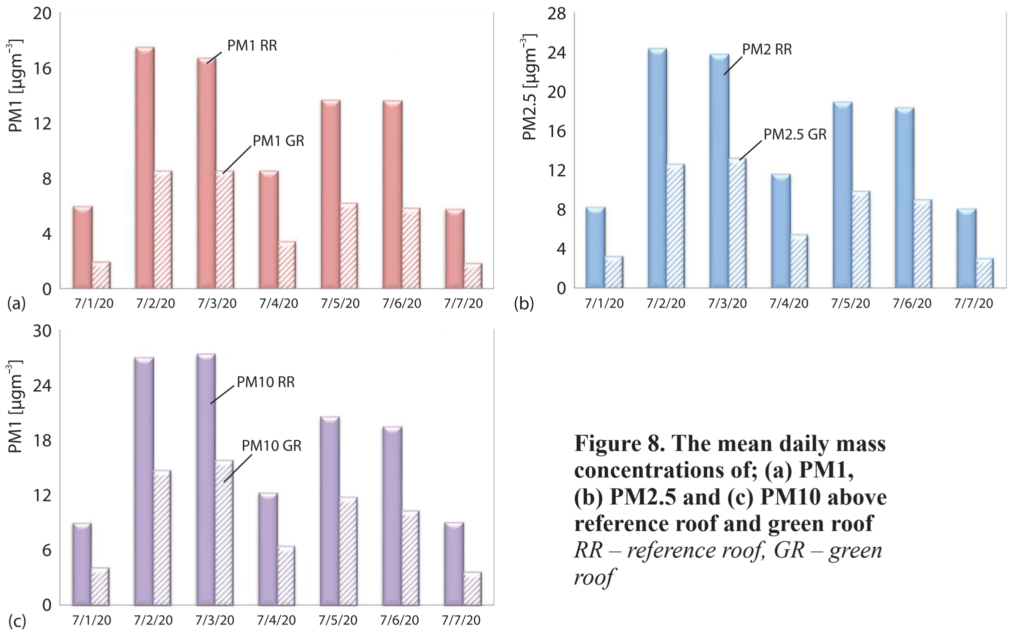


Figure 8. The mean daily mass concentrations of; (a) PM1, (b) PM2.5 and (c) PM10 above reference roof and green roof
RR – reference roof, GR – green roof

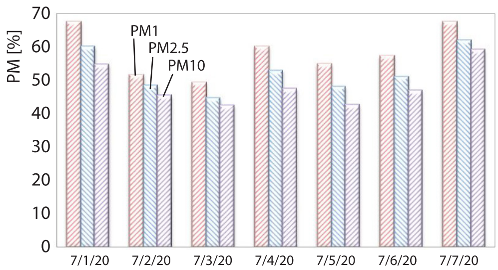


Figure 9. Difference of mean daily PM concentrations above reference roof and green roof

ambient PM1, PM2.5, and PM10 concentrations were, respectively 67%, 62%, and 59%. The reduction effect of green roof on particles with smaller aerodynamic diameters that are the most harmful to human health was more pronounced. The observed summer period in July corresponds to the growth season of green roof vegetation (large leaf area), thus the reduction in PM was significantly effective during this time. The minimal percentage reduction in PM concentration was recorded during the second and third days of the measurements campaign when the concentration of PM fractions was highest. These could indicate that in conditions of high PM concentration levels, the plant leaves reach saturation of the storage capacity and no longer adsorb particles.

The order of significance in reductions for PM followed a trend of PM1 > PM2.5 > PM10 as reported earlier in [17, 32]. The results of this study reveal that the vegetation on the roof reduces ambient particulate concentration. This is in accordance with a previous study which stated that urban roof top vegetable farm reduced PM2.5 concentration by up to 33% [33]. Research performed in the semiarid climates of Chile showed that *Sedum Album* vegetation on green roofs can reduce the concentrations of PM2.5 up to 45.3% [34]. Similar results were found for PM10. However, in Singapore, the green roof increased PM2.5 and PM10 concentrations by 16% and 42%, respectively [13]. In Australia, green roof had no significant influence on PM2.5 concentration. The influence of green roof vegetation on particulate pollution needs to be further investigated.

The study from the same authors [35] presented mean monthly PM concentrations measured above the same green roof and reference roof during the heating season (from September 2019 to January 2020). According to that study, the mean monthly PM1, PM2.5, and PM10 concentrations above the green roof were reduced by up to 31.8%, 28%, and 22.5%, respectively. During the heating season, the mean monthly PM concentrations were from 9.98-125.52 μg/m$^{3.}$ A higher reduction of PM concentrations above the green roof was observed during the summer compared to winter. The reason for this could be: the highest particulate concentrations in winter compared to summer, and a larger amount of precipitation during the winter period which reduced the PM through the washout as shown in [36].

Analyzing the experimental data, the daily sub-AQI was calculated using the AQI Calculator-US EPA Scale converter [37] for seven days (1 to 7 July 2020) and the results are given in tab. 3. The AQI (PM2.5) above the reference roof is between 33-76, while between 13-52 above the green roof. The AQI (PM10) is between 8-25 above the reference roof, while between 4 and 15 above the green roof. The air above both roofs was good (green color) in terms of PM10 concentrations, while the air was from good (green color) to moderate (yellow color) in terms of PM2.5 concentrations. In case of moderate levels of health concern, the advice is to reduce outdoor strenuous activities. The mean value AQI (PM2.5) above the reference roof and green roof was 57 and 33, respectively. Above the reference roof and green roof, the mean value AQI (PM10) was 16 and 9, respectively. PM2.5 was the main pollutant during the observed period. When it comes to PM2.5 concentrations, a higher number of days with good air are observed above the green roof compared to the reference roof. The green roof not only reduced PM2.5 concentrations but also improved the sub-AQI.

Table 3. Air Quality Index values for PM2.5 andPM10 above reference roof and green roof

Date	Reference roof		Green roof	
	PM2.5	PM10	PM2.5	PM10
7/1/20	33	8	13	4
7/2/20	76	25	52	14
3/7/20	76	25	52	15
4/7/20	50	11	21	5
5/7/20	65	18	42	11
6/7/20	63	17	38	9
7/7/20	33	8	13	4
Mean value	57	16	33	9

Conclusions

During the last few years, particle matter concentrations have exceeded the guidelines in the majority of Serbian cities. The measurement of PM concentrations in ambient air was performed during the summer period, to assess the impact of extensive lightweight green roof on outdoor particulate pollution and AQI. The measurements of PM1, PM2.5, and PM10 concentrations were performed from 1 to 7 July 2020 above the green roof and reference roof of a school building located in Belgrade, Serbia. The ratio of PM2.5 to PM10 mass concentrations was determined to access the underlying atmospheric and anthropogenic sources of PM concentrations. A backward trajectory analysis was conducted to estimate the air mass direction linked to PM sources using the HYSPLIT model. The results of experimental research reveal that the lightweight extensive green roof with mineral wool growing substrate and sedum plants acts as a biological filter of PM.

The 24 hours mean PM2.5 concentrations above the reference roof exceed the WHO air guideline value for four days. The mean daily PM concentrations roof during the summer days were reduced above the green roof from 42% to 67% compared to the reference roof. The green roof has a larger impact on finer particles, which are the most dangerous for human health. When it comes to the AQI, PM2.5 was the main pollutant. The air above both roofs was good in terms of PM10 concentrations, while in the case of PM2.5 concentrations, the air was moderate for four days above the reference roof and two days above the green roof. Above the green roof and reference roof, the correlation coefficient between PM10 and PM1 concentrations was 0.96, while 0.98 was between PM10 and PM2.5 concentrations, indicating fine particulate dominance and that all PM fractions came from similar emission sources. Backward air mass trajectories revealed that the particles at site location had originated from the region of the North Atlantic Ocean.

Increasing the green roof areas in urban areas can contribute to air quality improvement. The findings of this experimental research help identify plant species suitable for urban greening that can effectively remove suspended particles. The findings of this research can be used to develop more effective air pollution control measures. This paper can support the development of policies and incentives that can foster green roof installation in Serbia to mitigate particulate pollution. Improving the quality of the environment through the increase of green areas is important for cities in Serbia to become sustainable and adapted to climate change. The short term measurement period is the limitation of this study. Future research needs to investigate the long-term impact of green roofs on different air pollutants.

Acknowledgment

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Nomenclature

BP_{Hi} – concentration breakpoint that is greater than or equal to C_p, [μgm^{-3}]
BO_{Lo} – concentration breakpoint that is less than or equal to C_p, [μgm^{-3}]
C_p – truncated concentration of pollutant p, [μgm^{-3}]
I_{Hi} – AQI value corresponding to BP_{Hi}
I_{Lo} – AQI value corresponding to BP_{Lo}
I_p – index of pollutant
PM1 – particulate matter with diameter ≤ 1 μm, [μgm^{-3}]
PM2.5 – particulate matter with diameter ≤ 2.5 μm, [μgm^{-3}]
PM10 – particulate matter with diameter ≤ 10 μm, [μgm^{-3}]

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