



Breath of change: a meteorological and green infrastructure perspective on air quality in skopje, north macedonia

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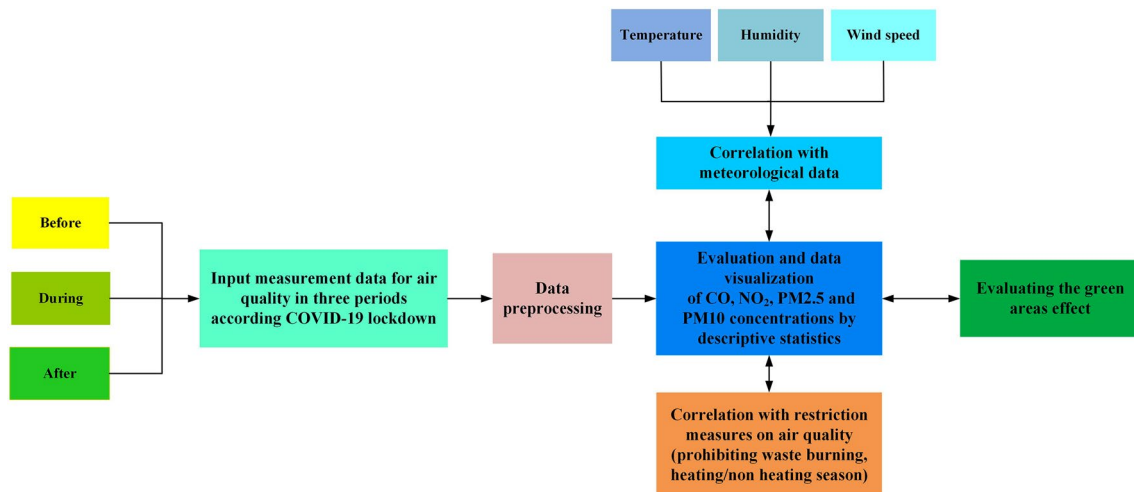
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Abstract

In urban settings, a significant issue revolves around poor air quality, characterized by elevated levels of particulate matter (PM) and diverse pollutants (CO and NO₂) detrimental to both human health and the global environment. Consequently, there exists an immediate imperative to mitigate air pollution through the adoption of a spectrum of short and long-term strategies. This study examines different factors that influence air quality in Skopje, North Macedonia, focusing on the impact of meteorological parameters, the implementation of policy measures as waste burning ban, the impact of green infrastructure as well as the effects of measures against COVID-19 spread. To analyze the impact of these factors, the data analysis spans various periods: pre-COVID-19 lockdown restrictions (with emphasis on 2018), the lockdown period (2020), and subsequent years (2021 and 2022) as life gradually returns to normal. Additionally, it evaluates the effects of meteorological parameters such as wind speed, relative humidity, and temperature on air quality and their impact on particulate matter reduction. Furthermore, the paper establishes a significant correlation between the most common types of particulate matter, namely those with diameters of 10 µm or less (PM₁₀) and 2.5 µm or less (PM_{2.5}). Our statistical analyses unveil significant correlations between the collected data, confirming a negative correlation between PM and higher air temperatures/wind speed. Furthermore, the investigation highlights elevated pollutant concentrations during nighttime hours. Notably, the study identifies positive outcomes associated with reduced traffic and decreased use of fossil fuels for heating during winter months, as evidenced by the acquired data.

Graphical abstract



Keywords Air pollution reduction · Particulate matter · Meteorological parameters · COVID-19 pandemic

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Introduction

Air pollution poses one of the most significant environmental risks to human health, comprising a complex mixture of hazardous substances such as gases, particulates, and biological molecules. According to the World Health Organization (WHO 1999) in 1999, over one million people worldwide succumb to the effects of polluted air annually. As reported by the United States Environmental Protection Agency (USEPA 2020) in 2020, ground-level ozone (O₃), carbon monoxide (CO), and nitrogen oxide (NO) are identified as the gases with the most detrimental health impacts. Additionally, particulate matter (PM), composed of nitrates, sulfides, black carbons, and organic matter, is recognized by the Agency as another pollutant negatively affecting human health. Particulate matter with a diameter of 10 µm or less (PM₁₀) is typically emitted from various heating sources and power plants, whereas particulate matter with a diameter of 2.5 µm or less (PM_{2.5}) is primarily sourced from exhaust emissions from vehicles, as well as the combustion of wood, plastic, and waste materials

Urban areas are characterized by high population densities, extensive industrial activities, and heavy vehicular traffic, all of which contribute to elevated levels of air pollution, (Seinfeld 2016). The resulting urban air quality degradation poses significant challenges to public health and environmental sustainability (HEI 2019). According to a report by the European Environment Agency (EEA 2019), air pollution is one of the leading causes of death in many European countries, causing more than 400,000 premature deaths. In addition to its effects on human health, these pollutants can also be a serious hazard to monuments and artwork, particularly those located in city centers (Samet, 2000). PM, SO₂, CO, O₃, nitrogen oxides (NO_x), and volatile organic compounds (VOCs) are the major air pollutants in cities (Mayer 1999). Various factors influence air quality in big cities, including meteorological conditions, topography, urban morphology, and socioeconomic factors, (Liang, 2020). For instance, atmospheric inversions and stagnant weather conditions can exacerbate the accumulation of pollutants, leading to episodes of poor air quality, (Tobías, 2020). Additionally, the spatial distribution of pollution sources and land use patterns within cities can influence the dispersion of pollutants and contribute to localized air quality hotspots, (Li, 2021).

Motivation

The issue of global air pollution has emerged as a serious concern for the residents of Skopje. Particularly during winter months, data collected from various measurement sites across the city consistently reveal elevated levels of

particulate matter (PM) (Srbinovska 2021). Both governmental authorities and non-governmental organizations have investigated the causes behind these alarming PM levels (Jovanovski 2020). However, a definitive list of entities responsible for the situation has yet to be compiled. A major contributing factor is the incomplete expansion of the district heating network to all areas of the city, leading to widespread use of wood stoves and similarly inefficient heating equipment in households, which significantly contributes to PM emissions during winter. Additionally, the presence of small-scale industrial facilities operating with equipment below European Union (EU) environmental standards, along with unauthorized landfills situated on the outskirts of certain municipalities, further exacerbates PM pollution, not only during the heating season but also in the summer months. As public awareness and pressure to address the issue have escalated in recent years, some measures have been initiated to mitigate air pollution in Skopje and other major cities across the country. The motivation behind the research presented in this paper is closely linked to addressing the air quality challenges facing the city of Skopje. The overarching aim of the project leading to the findings presented in this paper is to contribute to the public discourse on air quality by utilizing pertinent measured data and increasing awareness among governmental bodies tasked with addressing this issue.

Background research

This subsection provides an overview of the various influencing factors on air pollution, including the impact of meteorological parameters, the implementation of green infrastructure as well as the effects of measures against COVID-19 spread. The findings of the referenced papers are related to the research presented in the paper.

The efforts to mitigate the negative effects of air pollutants have increased over the past decade, focusing both on local and global solutions. Global measures include decarbonization of energy, transport and other sectors. Local solutions include increasing the green surfaces and wide scale deployment of green infrastructures, implementation of measures to reduce fossil fuels use on local level and incentives for using environmentally friendly transport. Green infrastructure, such as green walls and roofs, has gained prominence. Green walls consist of vertical surfaces with vegetation, employing various techniques to attach plants, thereby creating favorable conditions for the growth of dense and diverse vegetation (Bolton 2014). These plants serve as natural filters, effectively removing pollutants like nitrogen dioxide (NO₂) and fine dust from the air. Similarly, green roofs are vegetated systems installed on rooftops, featuring waterproof membranes and additional irrigation and drainage systems to support plant growth. Green infrastructure

studies assess the impact of air pollution on land use and the environment by studying the effects of air pollution on vegetation, soil, and water resources, (Alberto 2017). Implementation of green walls, green infrastructures and green buildings has numerous benefits, including improved thermal characteristics of objects, reduced noise levels and lower energy requirements for facilities (Radić 2019). The impact of vegetation on building thermal environments has been investigated in (Lin, 2019), with additional aspects on indoor cooling and ventilation (Chen 2017). Huang (2009) quantified that the average ambient temperature can be lowered by 0.3 °C when green roofs are used in Tokyo, while according to (Chen H. O., 2009), the temperature can be 0.1 °C lower. Also, the influence of garden roof on air temperature mitigation was explored in (Liu, 2020).

The impact of meteorological parameters on air quality has been examined in the papers discussed in this subsection. They indicate that variables such as humidity, wind speed, wind direction, and temperature exert certain influences on air quality. However, there is a lack of universal quantitative rules establishing the relationship between these factors and air quality (Latini 2002). (Gaffin 2010) observed that humidity has the greatest impact on PM10 removal, followed by wind speed and temperature. Conversely, (Xu 2018) concluded, based on specific locations, that humidity combined with low wind speed adversely affects PM2.5. Additionally, rough terrain, as discussed by Hewson (2012), deflects pollutant gases and particles, altering the influence of wind speed and direction. Seo, (2018) confirmed, over a 15-year period, that increasing wind speed at a specific location positively affects PM10 mitigation. They also noted that stagnant, high-pressure conditions lead to increased PM10 concentrations in short-term analyses. The significance of wind speed, wind direction, and mixing of layer heights on contaminant concentrations is discussed by Schäfer (2014) who also analyzes the chemical composition of pollutants.

According to Baklanov (2016) PM concentrations are directly affected by meteorological parameters such as temperature, wind, and precipitation. Same conclusions are derived by Tian (2022). (Hosker 1982) explains that winds reduce the concentration of particulates like PM2.5 and PM10. Also, our past conducted research (Srbínovska 2021) showed that green areas on average mitigate PM2.5 and PM10 by 25% and 37%, respectively, compared to non-green areas. Additionally, the combination of low temperatures, high humidity, and low or no wind speed has been found to lead to high PM concentrations Andonovic (2020). The research presented in this paper demonstrates the correlation between weather parameters such as wind, temperature, and humidity with air pollution, suggesting that machine learning air pollution models can be developed using weather information and historical measurement data on pollution.

The COVID-19 outbreak, originating in Wuhan, China, rapidly spread globally, including to Malaysia, prompting the implementation of the 2020 Malaysia Movement Control Order (MCO) to contain it. During the MCO, significant reductions in air pollutants, particularly PM2.5, were observed, suggesting the need for further investigation into the contributing factors beyond just the MCO's effects. During the MCO, PM2.5 concentrations saw a significant decrease in up to 58.4%, with some red zone areas experiencing reductions of up to 28.3%, (Abdullah 2020). However, the reduction wasn't solely attributable to the MCO, prompting researchers to recommend further investigation on other influencing factors for future adherence. Similarly, Authors in (Dantas 2020) examined that the partial lockdown in Rio de Janeiro significantly impacted air quality, with reductions in CO and NO₂ levels but an increase in ozone concentrations due to decreased road traffic and economic activity. Similar trends were observed during a 2018 truck driver strike. Given Rio's concerns with particulate matter and ozone, assessing air quality policies necessitates considering industrial air masses, VOC speciation, and NMHC/NO_x ratios' impact on ozone levels, particularly considering favorable ozone formation conditions. They concluded that meteorological conditions should also be examined in future analyses. The COVID-19 lock down measures served as a real-life example of how some of these measures can impact the environment and decrease air pollution. The implementation of lockdown measures in response to the coronavirus disease 2019 (COVID-19) pandemic has resulted in a decrease of global economic and transportation activity. The findings from the studies that have been conducted, however, suggest that limiting unnecessary outdoor mobility will be beneficial to air quality in the post-pandemic world (Andova 2023).

During the COVID-19 lockdown in Almaty, Kazakhstan, from March 19 to April 14, 2020 (Kerimray 2020) there were observable improvements in air quality, albeit with variations in areas characterized by significant nontraffic-related pollution sources. PM2.5 concentrations decreased by 21%, yet still exceeded WHO limits on 18 days. CO and NO₂ saw reductions of 49% and 35%, respectively, while O₃ increased by 15%. Despite favorable meteorological conditions, spatial variations highlight the lockdown's impact on pollution levels, emphasizing the diverse contributors to Almaty's air pollution, including coal-fired plants, household heating, and other irregular sources. Similarly, the air quality in Wuhan, Jingmen, and Enshi, Hubei Province, China, was analyzed from January to March 2017–2020 in the study (Xu 2020) to assess the impact of epidemic prevention measures. Significant reductions in atmospheric pollutants during February 2020 compared to previous years were observed, with PM2.5, PM10, SO₂, CO, and NO₂ decreasing by 30.1%, 40.5%, 33.4%, 27.9%, and 61.4%, respectively.

However, O_3 concentrations did not decrease significantly due to constraints on the $NO + O_3$ reaction. Insights for establishing effective air pollution control strategies are suggested in the study. The lockdown's impact on air quality in Iran is assessed in the study (Broomandi 2020), focusing on changes in six criteria pollutants from March 21 to April 21 in 2019 and 2020. Data from 12 air quality stations were analyzed, supplemented with satellite data due to limited ground-level measurements, especially in Tehran. Concentrations of primary pollutants in Tehran decreased (SO_2 5–28%, NO_2 1–33%, CO 5–41%, PM_{10} 1.4–30%), although WHO daily limit levels were still exceeded for several days. Conversely, O_3 and $PM_{2.5}$ increased by 0.5–103% and 2–50%, respectively. Decreases in SO_2 and NO_2 levels were observed nationally, but aerosol optical depth (AOD) increased during the lockdown, with unfavorable meteorological conditions impeding pollutant dispersion. Despite challenges, the reduction in primary pollutant levels suggests potential improvements in Iran's air quality. On the other hand, another paper investigates the impact of restricted human activities on urban air quality in Ecuador, where strict quarantine measures were implemented from March 17, 2020, (Zalakeviciute 2020). Significant reductions in NO_2 (–68%), SO_2 (–48%), CO (–38%), and $PM_{2.5}$ (–29%) concentrations were observed in Quito during the first month of quarantine, confirming the human activities impact on urban air quality. However, Guayaquil experienced slower improvement due to delayed quarantine measures, potentially impacting mortality rates. Overall, the data illustrates the rapid improvement in air quality when emissions are reduced.

The work examining the worldwide atmospheric consequences of residential fuel combustion revealed that emissions, including fine PM with an aerodynamic diameter $< 2.5 \mu m$ ($PM_{2.5}$), organic compounds, and black carbon, are primarily influenced by transportation in North America, open burning in Africa, and the use of residential solid fuels in Asia (Bond 2004). Another study, presented in the paper (Srbinovska 2023) indicates that the highest concentration of PM occurs during the winter months, with peak levels observed during nighttime hours (around 2–3 am). This is likely attributed to the usage of fossil fuel heating systems in the Skopje area.

Chen (2022) employs a system dynamics approach to tackle urban pollution arising from vehicle exhaust, emphasizing the worsening issues of traffic congestion and emissions due to urbanization. The research findings highlight that while various restriction policies can mitigate traffic congestion in the short term, a combination of public-transport development and driving restrictions proves to be the most effective and sustainable approach, significantly reducing congestion, air pollution, and enhancing environmental

carrying capacity. This combined strategy demonstrates its potential benefits for society, health, and the environment.

Initiating measurements marks the phase in assessing the efficacy of implemented measures against air pollution. Conventional monitoring systems gauge various pollutant concentrations using distinct analyzers, necessitating regular calibration and maintenance. However, advancements in integrated on-chip technologies have paved the way for redefining the conventional approach to pollutant measurement. A new breed of sensor systems, characterized by compact dimensions and mobility, has emerged as a viable solution (Latini 2002) typically organized as wireless sensor networks (WSNs), these systems find extensive application across diverse domains, as evidenced by a survey outlined in (Rashid 2016).

Sensor networks comprise nodes capable of data exchange via wireless networks. Each node typically encompasses a battery-powered unit, one or more sensors, a microprocessor, and a transceiver. While the sensor measures specific physical quantities (such as light, temperature, humidity, pressure, or acceleration), the processor acquires and processes the measured data, with the transceiver facilitating data transmission through WSNs. These networks are predominantly designed for autonomous and independent operation, particularly in scenarios with underdeveloped infrastructure (Srbinovska 2015) or specialized applications like cow dairy farms, as detailed in (Benaissa 2016).

The purpose of this paper is to investigate the relations between various factors and their on air quality, and thus contribute to the global efforts to develop measures for air pollution mitigation. It is noteworthy to mention that while some of the studies discussed above examine similar factors, the influence of local geo-spatial conditions, economic activities and level of development of infrastructure differ in various regions and they too, impact the relations between meteorological parameters and air pollution. Therefore, the research presented in this paper offers a valuable contribution in revealing the influence of various factors on air pollution and serves as solid basis for developing effective measures to reduce it. The factors analyzed in this paper include prohibition of waste burning, taking into account the limiting factors imposed by meteorological conditions and COVID-19 pandemic. Furthermore, the influence of green areas on air quality was investigated, as well as the impact of heating versus no heating season, daytime versus nighttime. The measurement data are analyzed in the period before the COVID-19 lockdown restrictions (with a focus on 2018), during the COVID-19 lockdown (2020), and 2021 and 2022, when life returns to normal. Due to technical difficulties and insufficient data in 2019, the measurement results are not included in this paper.

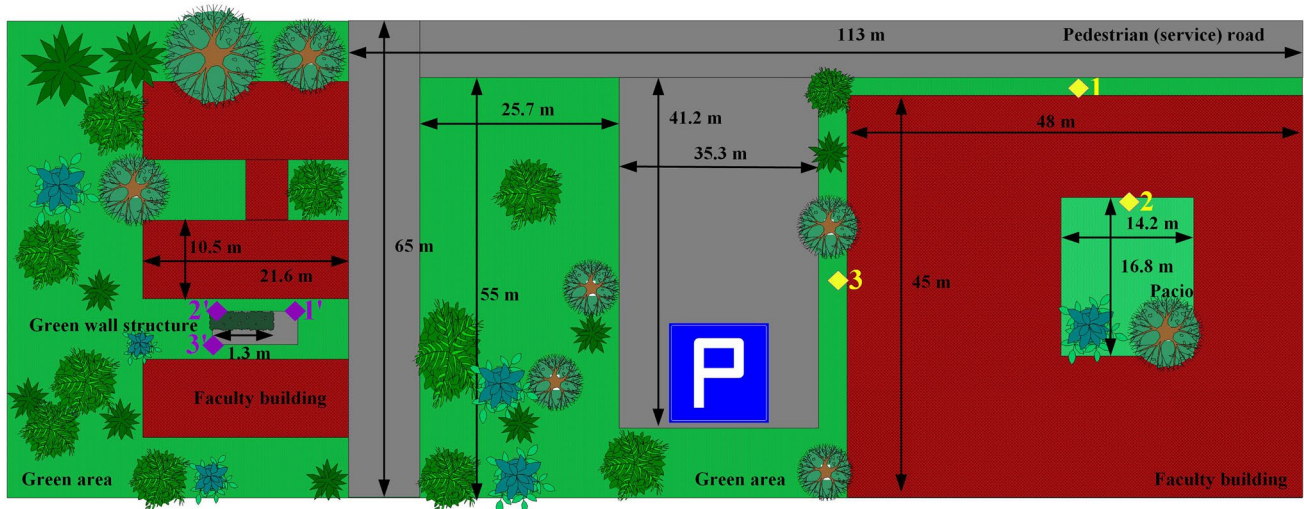


Fig. 1 Overview of the location and distribution of sensor nodes

Table 1 Summaries of average PM concentrations, RH and temperature (\pm standard deviation)

Dry period				Wet period			
PM sensor ($\mu\text{g}/\text{m}^3$)	PM reference instrument ($\mu\text{g}/\text{m}^3$)	Temperature ($^{\circ}\text{C}$)	RH (%)	PM sensor ($\mu\text{g}/\text{m}^3$)	PM reference instrument ($\mu\text{g}/\text{m}^3$)	Temperature ($^{\circ}\text{C}$)	RH (%)
8.9 ± 2.3	11.2 ± 2.5	23.7 ± 5.9	50 ± 10.7	16.1 ± 5.5	18.9 ± 4.5	20.2 ± 1.9	69.4 ± 9.5

Materials and methods

To determine the effect of green areas, traffic and movement of people, different positions for the sensor nodes were determined. In 2018, the nodes were located around the Faculty of Electrical Engineering and Information Technologies building (as seen in Fig. 1—the sensor nodes are depicted in magenta). A green wall structure was installed beforehand, consisting of two rows of heder helix plants that were planted in the spring. The sensor nodes were mounted on a platform, with two photovoltaic panels already set up. Sensor node 3' was situated closest to the secluded green area, while sensor node 2' was located near the green wall structure, and sensor node 1' was close to a road with many people and vehicles passing through. The results of the impact of the green wall structure on air quality improvement have been reported in (Srbínovska 2021). In 2019, the positions of the nodes were changed (as depicted in Fig. 1—the sensor nodes depicted in yellow). Sensor node 1 was close to the pedestrian pavement, and sensor node 2 was near a small green area (part of the building patio).

Measurement system description

The measurement monitoring system, which was initially developed using wireless sensor network technology, consists of several sensor nodes, each integrating four sensors and a Wi-Fi module on a single board controller. These sensors measure parameters such as PM_{2.5}, PM₁₀, CO, and NO₂. The SDS011 device is equipped with PM_{2.5} and PM₁₀ sensors, which detect particles of size 0.3 μm to 10 μm . The maximum relative error is $\pm 15\%$ and $\pm 10 \mu\text{g}/\text{m}^3$ for temperature 25 $^{\circ}\text{C}$ and RH = 50%. The MiCS-4514 unit, is fitted with two sensors for CO and NO₂ measurements. The sensor nodes which are integrated with Wi-Fi modules, transmit data to the closest routers located in the Faculty building. The obtained data from the routers is uploaded to an open platform (Internet of Things open platform 2020) and can be observed online or downloaded for further analysis. The hardware details and the main characteristics of this setup are discussed in (Velkovski 2019). Additional information regarding the hardware specifications of the sensor nodes can also be found in Srbínovska (2017). The supplementary material includes the technical characteristics and detailed specifications of both the sensing units and the microcontroller.

The sensor nodes were calibrated utilizing the MicroDust Pro Aerosol Monitoring system, boasting an accuracy of 2%. This measurement instrument employs an infrared source with a wavelength of 880 nm and achieves a resolution of 0.001 mg/m³.

The averaged PM concentrations from the sensor nodes and the reference instrument, at the location near the sensor 1 during one week are listed in Table 1. In general, the ambient conditions at all three locations were quite similar. Hourly PM concentration from sensor nodes during the measurement period was maximum 53 µg/m³. The PM concentrations and characteristics could be different from season to season.

Measurement errors are greater when measuring smaller values of PM concentrations compared to higher concentrations of PM. Higher values of PM concentrations are recorded for wet period, while measurement errors are more pronounced during the dry season than during the wet period.

Data acquisition

The dataset for this study is drawn from two main sources: a sensor data and publicly accessible weather information. For the entire study period, the data was extracted in CSV format, then organized and prepared for further analysis. Python, a versatile and powerful programming language, was used to process and analyze the data. Sensor data was initially collected every 30 s. To make the data more manageable and meaningful, frequent readings were converted into hourly averages, calculated by finding the mean of the readings taken during each hour. Several datasets were combined, including data from three different sensors and weather information, into a single, comprehensive dataset. To ensure consistency and comparability across the data, sensor readings were converted from ohms (Ω) to micrograms per cubic meter (µg/m³). Further details regarding the conversion from ohms to micrograms per cubic meter (µg/m³) are provided in the annex materials.

Specific weather variables (temperature, humidity and wind speed) were selected from the weather dataset. These variables helped convert the sensor data into a format more conducive to the study. This careful and methodical process of data collection and preparation has laid a strong foundation for the further analysis and interpretations in the study.

Statistical tools

To analyze the collected data standard statistical tools (Field 2013) such as descriptive statistics, correlation, and hypothesis testing are used, while for data visualization histograms

and violin plots are used. Violin plots are a type of data visualization tool that displays the distribution of data. They are similar to box plots in that they show the median, quartiles, and range of the data, but they also show the shape of the distribution therefore are preferred over box-plot for data without normal distribution.

Different hypothesis tests (Field 2013) are also applied. The significance level is set to be $\alpha = 0.05$. When the assumptions of parametric tests, such as normality or equal variance, are not met nonparametric test (Conover 1999, 3rd ed.) are used. In the group of nonparametric test we distinguish independent tests: Wilcoxon rank-sum test, also known as Mann–Whitney U test (Wilcoxon 1945), (Mann 1947) and Kruskal–Wallis test (1952) used to compare the medians of two or more independent groups of data, respectively. Paired tests: Wilcoxon signed-rank test (Wilcoxon 1945) and Friedman test (1937) used to compare the medians of two or more related (paired) samples, respectively.

When three or more groups are compared (for Kruskal–Wallis and Friedman test), and the test rejects the Null hypothesis, then appropriate post hoc tests are performed to locate the difference. When the Null Hypothesis is rejected, i.e., the results confirm that there is a difference in the conditions, one can evaluate the effect. The effect size r is calculated with:

$$r = \frac{Z}{\sqrt{N}}$$

where Z is the Z score of the test, and N is the size of the sample. Alternatively, with the same parameters one can calculate η^2 as

$$\eta^2 = \frac{Z^2}{N - 1}$$

The η^2 evaluates the percentage of variabilities that is encounter by the conditions.

Results and discussion

In this section, the results of our study on the impact of air pollution in North Macedonia, from different perspectives are presented. The effect of the meteorological parameters and the influence of the green infrastructure, as well as the effect of the COVID-19 restrictions, and the waste burning effect on PM_{2.5}, PM₁₀, NO₂, and CO are investigated. The analyzed data are collected over the years 2018, 2020, 2021, and 2022

Figure 2 shows an accumulation of air pollutants (PM_{2.5}, PM₁₀, CO, and NO₂) over the years 2018–2022. As presented in Fig. 2, the collected data does not follow a normal

Fig. 2 Aggregated distribution of PM2.5, PM10, NO₂, and CO pollutants over the years 2018–2022

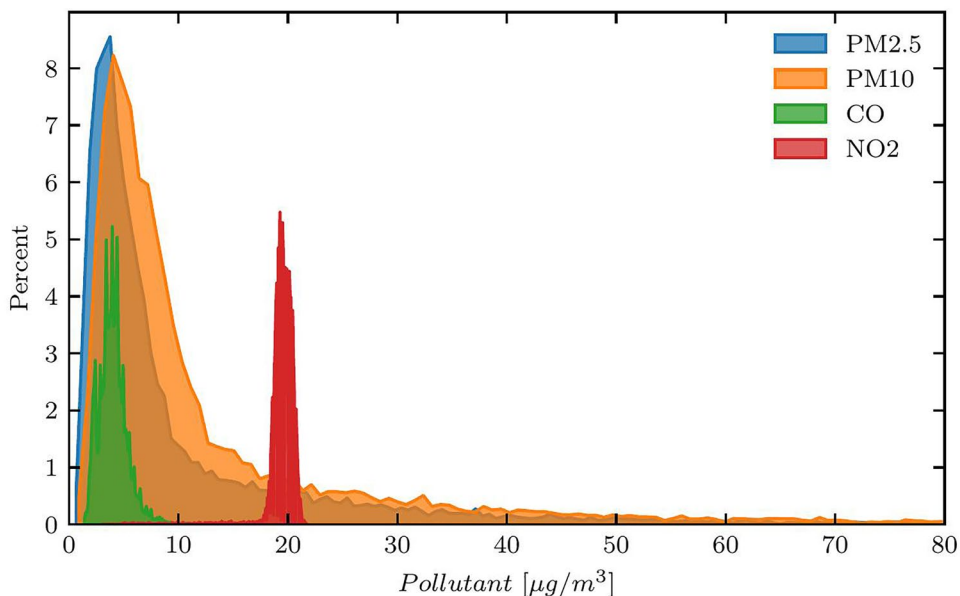
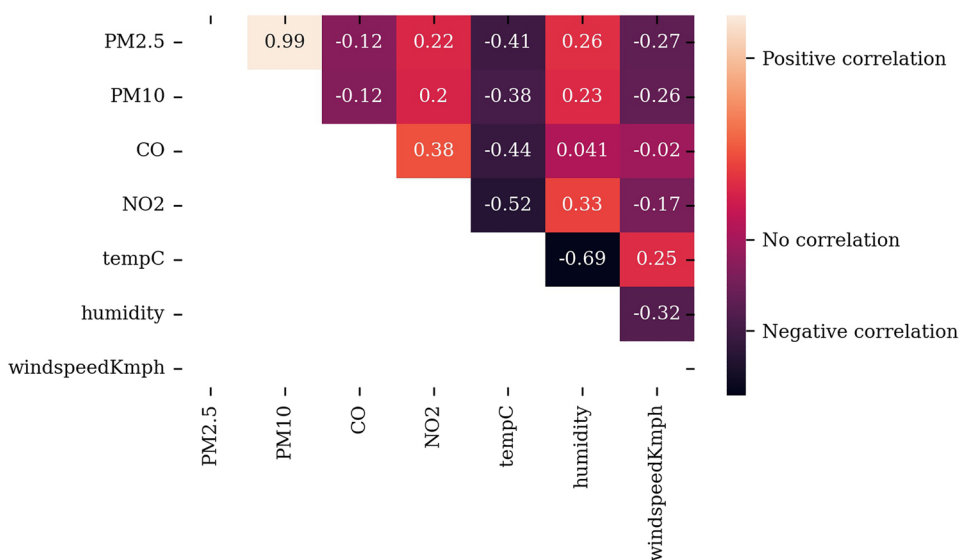


Fig. 3 Heatmap of correlation between the concentration of PM2.5, PM10, NO₂, and CO pollutants and meteorological parameters



distribution, thus requiring the implementation of nonparametric tests during the analyses. The implementation of these tools and the related results are presented further in this text.

Meteorological parameters and air pollutants correlation

In this subsection, the relationship between air pollutants and meteorological parameters such as temperature, wind speed and humidity are examined. Analyses showed that the values for the meteorological parameters over all the years

considered in the study form relatively similar distributions. This suggests that meteorological conditions have remained relatively stable over the years, which is important when assessing the impact of air pollution.

Figure 3 shows a heatmap of correlation between the pollutants and meteorological parameters. The figure reveals that there is a negative correlation between the pollutants and temperature, as well as the pollutants and wind speed. This suggests that high temperatures (the correlation coefficients between the temperature and the concentration of PM2.5, PM10, CO, and NO₂ are -0.41, -0.38, -0.44, and -0.52, respectively) and strong winds (the correlation coefficients between the

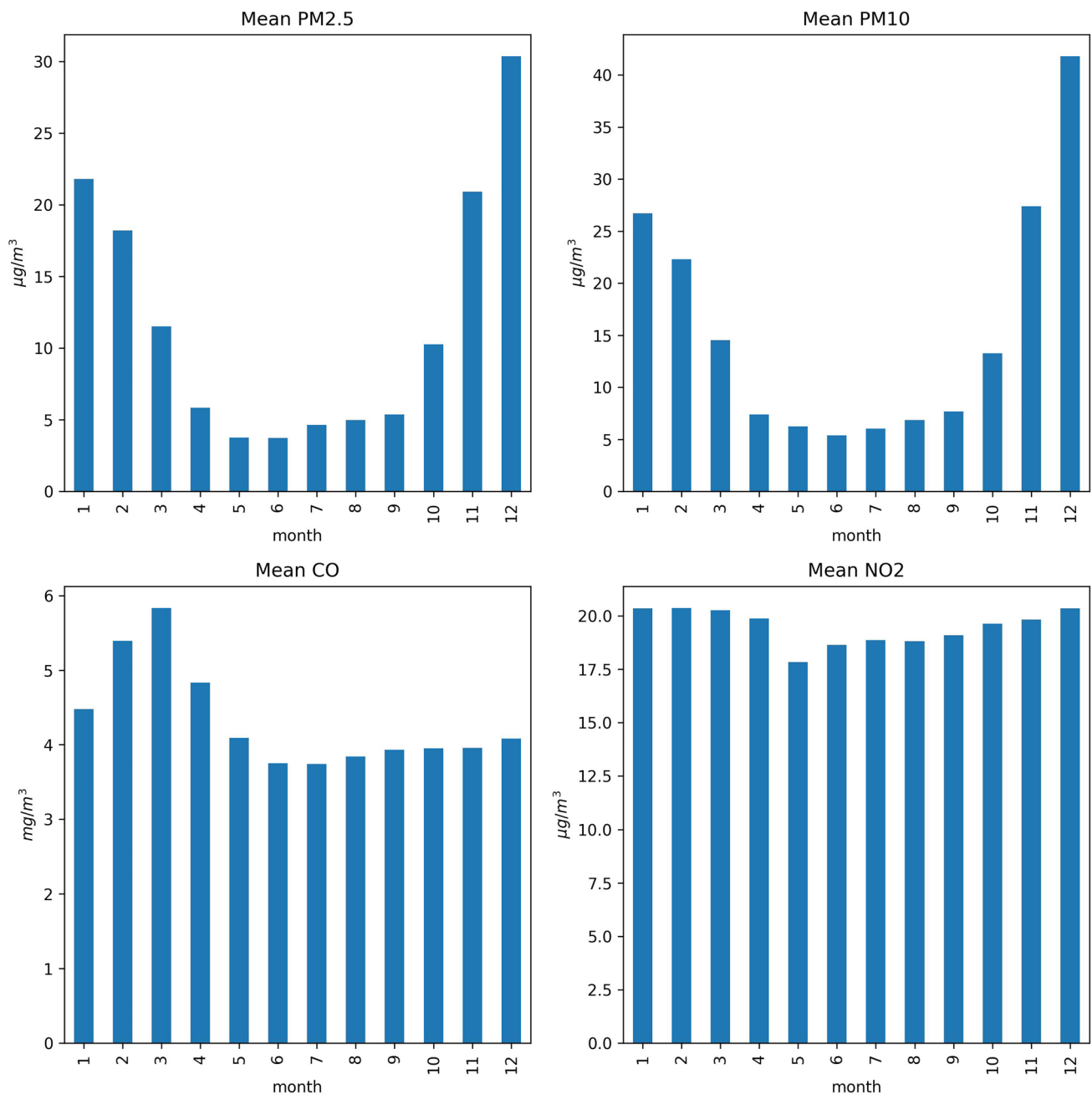


Fig. 4 Average concentration of a) PM2.5, PM10, and b) NO₂, and CO pollutants by months over the years 2018, 2020, 2021, and 2022

wind speed and the concentration of PM2.5, PM10, and NO₂, are -0.27 , -0.26 , and -0.17 , respectively) can help disperse pollutants, reducing their concentration in the air.

From Fig. 3, it could be noticed that there is no correlation between the wind speed and the concentration of CO. The results also suggest that meteorological parameters should be taken into account when designing appropriate measures to reduce air pollution. Although lesser, there

is a positive correlation between these pollutants and the humidity, which indicates higher pollution during humid and cold weather. Typically, under such conditions the pollution in Skopje, North Macedonia, is the highest (Jovanovski 2020).

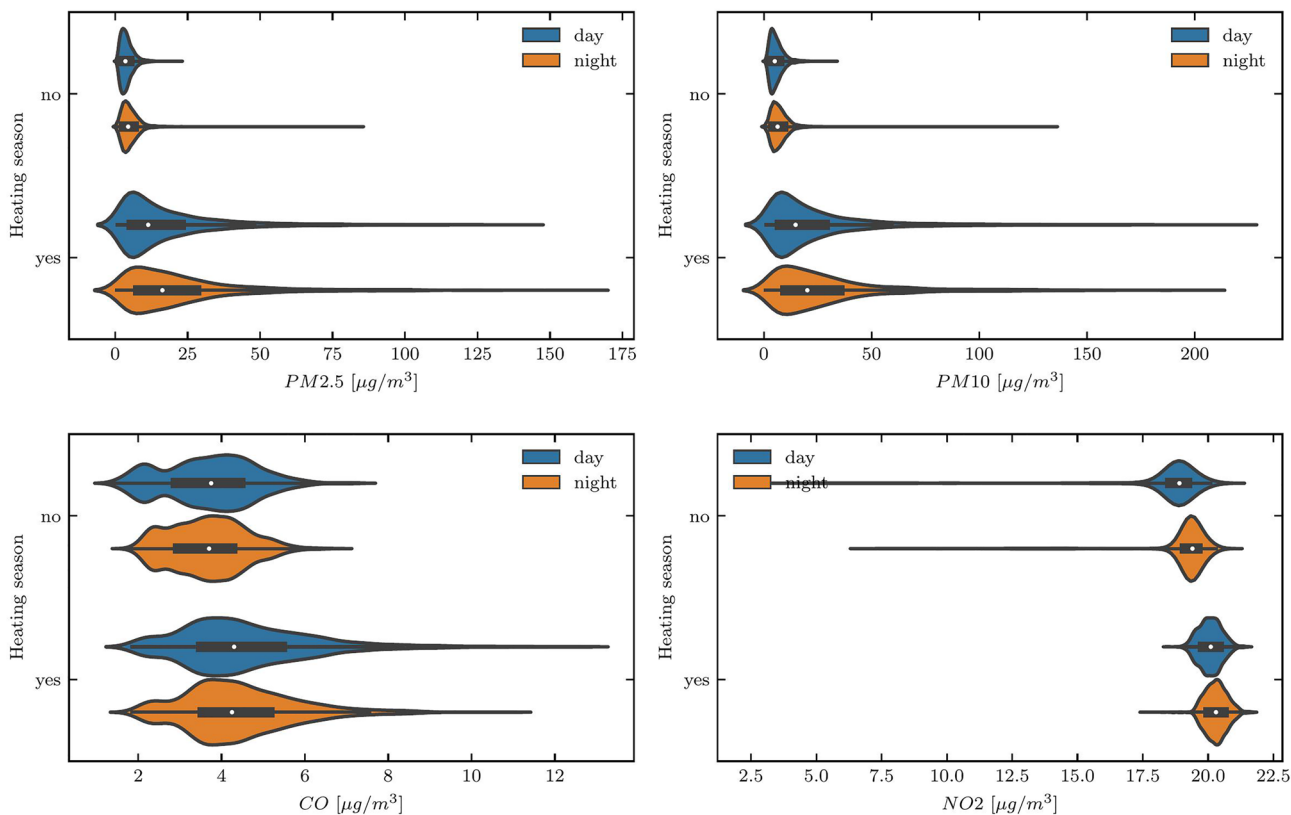


Fig. 5 Violin plots showing the distribution of PM2.5, PM10, CO, and NO₂ pollutants during heating and non-heating seasons, as well as during day and night

Air pollution analysis by months over the observed period

Figure 4a presents the average concentration of PM2.5 and PM10 and Fig. 4b presents the average concentration of CO and NO₂, for each month over the years 2018, 2020, 2021, and 2022.

The figure clearly shows that the concentration of PM is highest in December and then followed by January and November. The lowest concentration of PM is reported during the summer months: May, June, and July. Figure 4 also presents the average concentrations of CO and NO₂. The results report that there is no difference in the concentration of NO₂ during the year, while higher concentrations of CO are reported in February, March, and April. Their results are later confirmed by hypothesis tests.

Over the years it has been reported that the concentration of pollutants in Skopje (Srbínovska 2021) is much higher during nighttime (for 8:00 P.M. till 8:00 A.M.) than during daytime (from 8:00A.M. till 8:00P.M.), as well as that the air is more polluted during colder months. Similarly, the average concentrations of these pollutants are examined across

heating¹ and non-heating seasons, as well as during daytime and nighttime. The findings are illustrated in Fig. 5, featuring 2 × 2 subplots of violin plots for each pollutant (PM2.5, PM10, CO, and NO₂), indicating distinctions between the heating season (designated with “yes” for heating season and with “no” for the rest of the year) and time of day (daytime and nighttime). Violin plots visually represent data distribution, with plot width reflecting the frequency of data points in specific ranges. Figure 5 highlights that pollutant concentrations escalate during the heating season, particularly

Table 2 Statistics tests for significant difference – the effect of heating and non-heating season on air pollution level

	Test statistic	<i>p</i> -value	Effect size	η^2
PM2.5	63,526,562.0	0.0	0.604	0.365
PM10	62,004,730.0	0.0	0.569	0.324
CO	49,254,960.5	0.0	0.276	0.076
NO ₂	70,526,787.5	0.0	0.764	0.585

¹ The heating season is delineated as the duration when city heating is utilized, spanning from October 15 to April 15.

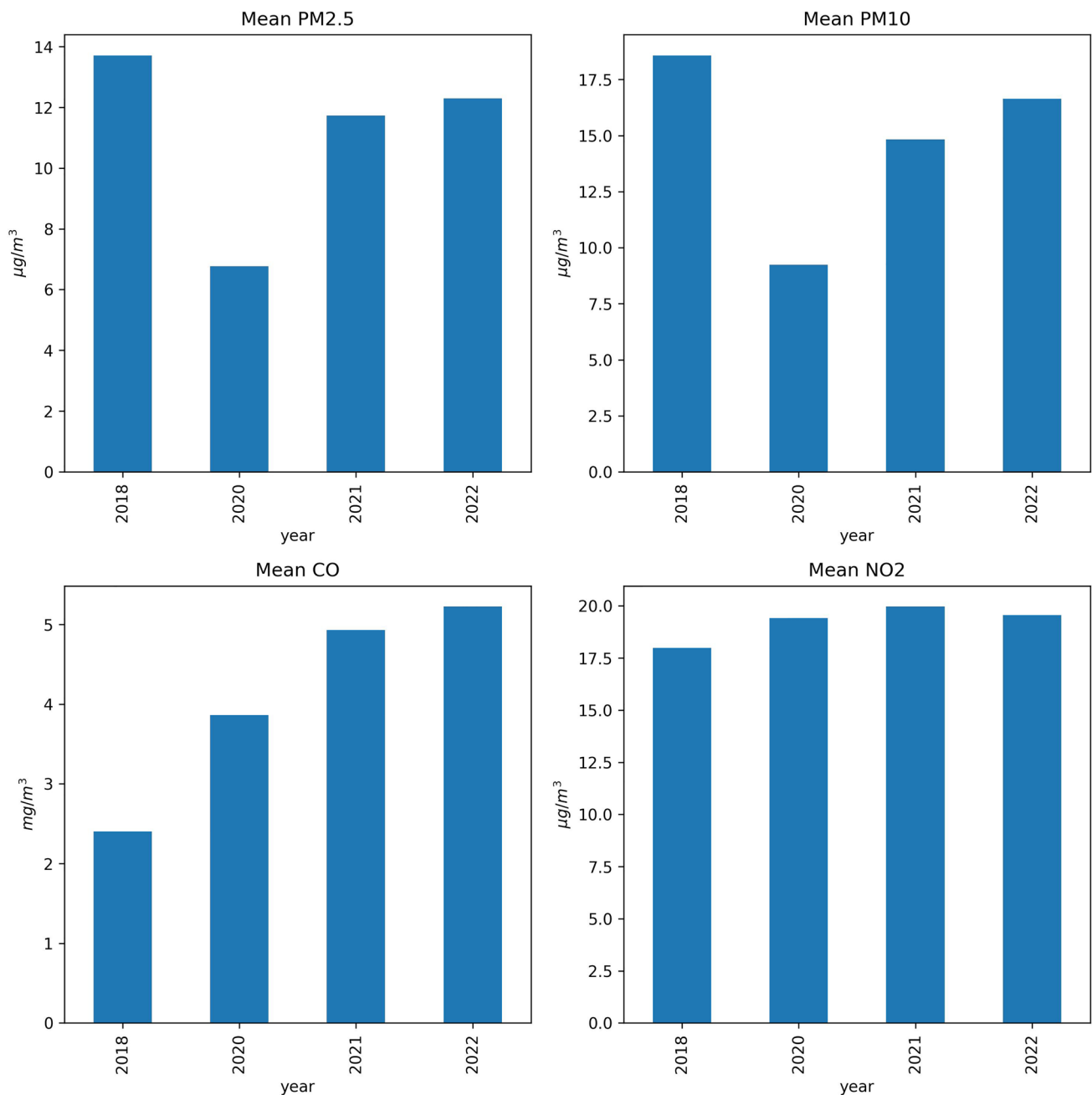


Fig. 6 Average concentration of PM2.5, PM10, CO, and NO₂ pollutants by year

at night, possibly attributable to heightened usage of fossil fuel-based heating systems in winter, leading to increased emissions. These outcomes underscore the need for measures to mitigate emissions from such systems or advocate for cleaner energy heating solutions to address air pollution concerns.

In order to confirm these assumptions, Mann–Whitney test was further performed to test the Null H_0

There is no significant difference in the air pollution level for the heating and non-heating season. The results are provided in Table 2.

Based on the Mann–Whitney test results for air pollution during heating and non-heating seasons, it can be concluded that there is a significant difference in air pollution levels between these two seasons. The p-values are all below 0.05, indicating that the results are statistically significant. Furthermore, the effect sizes, as measured by η^2 shown in Table 2 indicates that the difference in air pollution levels

Table 3 Average concentration of the pollutants before and after the prohibition of waste burn

	Before	After
PM2.5 ($\mu\text{g}/\text{m}^3$)	13.7	10.1
PM10 ($\mu\text{g}/\text{m}^3$)	18.57	13.4
CO ($\mu\text{g}/\text{m}^3$)	4.9	4.6
NO ₂ ($\mu\text{g}/\text{m}^3$)	19	19.6

can vary significantly between the two seasons depending on the type of pollutant. As expected, the heating and the winter weather conditions have a notable effect on the concentration of PM2.5, PM10, and NO₂ (the effect is above 0.569) and medium effect on the concentration of CO.

The effect of COVID-19 on air pollution

In March 2020 a global pandemic COVID-19, and some, at times rigorous, measures were introduced, such as lockdowns, curfews, and moving restrictions. With the occurrence of the first cases of COVID-19 in North Macedonia, all pre-university education facilities and universities were closed at the same time, as well as industry facilities, public and other companies, and stores. These restrictions resulted in reduced movement of people and goods. This section examines the effect of this policy on air quality.

Figure 6 shows the average concentration of the pollutants PM2.5, PM10, CO, and NO₂ per year. The results show the lowest concentration of PM2.5 and PM10 in 2020 which coincides with the COVID-19 pandemic, therefore with the restrictions.

It can also be observed that the concentration of PM is gradually increasing since 2020. As the restriction measures in Skopje started at the end of March 2020, and in some form lasted till the end of the summer 2020, we compared the air quality in Skopje pre-COVID-19 (April 2018–September 2018), during COVID-19 (April 2020–September 2020), and post COVID-19 (April 2021–September 2021, and April 2022–September 2022). The statistical analyses of the collected data shows difference in the concentration of PM2.5, PM10, CO, and NO₂ pre-, during, and post COVID-19. The p-values for all tests were very small (approx. 0.0), indicating that the observed differences between the two groups are unlikely to be due to chance. The effect sizes were negative in all cases, indicating that the median levels of pollutants were higher during the non-COVID-19 period. These findings suggest that the COVID-19 pandemic may have had a positive impact on air quality, and could inform future public health and environmental policy decisions.

Waste burning effect on air pollution

The prohibition of waste burning can have a significant impact on air pollution, especially in densely populated

areas. Burning waste releases large amounts of pollutants into the air, including CO₂, NO₂, and volatile organic compounds. By preventing the burning of waste, air quality can be improved, leading to cleaner air for everyone. In North Macedonia, the prohibition of waste burn was introduced on February 10, 2020. The prohibition of waste burning was enforced, prompting analyses to be conducted both before and after its implementation. However, as the period following the prohibition coincides with the COVID-19 era, distinguishing whether lower PM concentrations are attributed to the prohibition or the pandemic becomes challenging. Table 3 shows the mean values of the air pollutants (PM2.5, PM10, CO, and NO₂) before and after the period of the prohibition of waste burn. It can be concluded that it has a positive impact on PM2.5, PM10 and CO air pollution improvement except for the NO₂ values.

The results of the Mann–Whitney test show that for each pollutant, the test statistic is significant with very low p-values, indicating that the differences between the air pollution levels before and after the ban are highly unlikely to be due to chance. Moreover, the effect sizes suggest that the ban led to a reduction in air pollution levels. Even more, it suggests that the waste burning ban has the highest impact on the concentration of CO ($r=0.63$, $\eta^2=40.4\%$), then on the concentration of NO₂ ($r=0.23$, $\eta^2=5.4\%$). The findings suggest that the ban on waste burning is an effective measure to improve air quality.

Green area influence on air pollution

At the first part of the studied period (2018 and 2019) the sensor nodes 1', 2', and 3' were positioned as shown in Fig. 1. On this micro location it is evident that Node 1 is farthest from the green area, Node 2' is closer to the small green wall, and Node 3 is closest to the green area. The findings presented in the previous work (Srbínovska 2021) demonstrate that green areas mitigate PM2.5 by an average of 25% and PM10 by an average of 37% compared to adjacent non-green areas. In this work, it can be concluded that high PM concentrations are associated with a combination of low temperatures, high humidity, and minimal or no wind speed.

Figure 7 shows the distributions of all four pollutants in three considered locations with respect to the green area. On this figure the concentration of PM concentrations is lowest at Node 3. This suggests that the presence of green infrastructure can help reduce air pollution by providing a natural filter for pollutants. The results highlight the importance of incorporating green infrastructure into urban planning and design. While the lowest PM concentration is observed at Node 3 nearest to the green area, the same trend is not evident for the other two air pollutants, CO and NO₂. NO₂ values across all three sensor nodes are notably similar, whereas CO values peak at node 2.

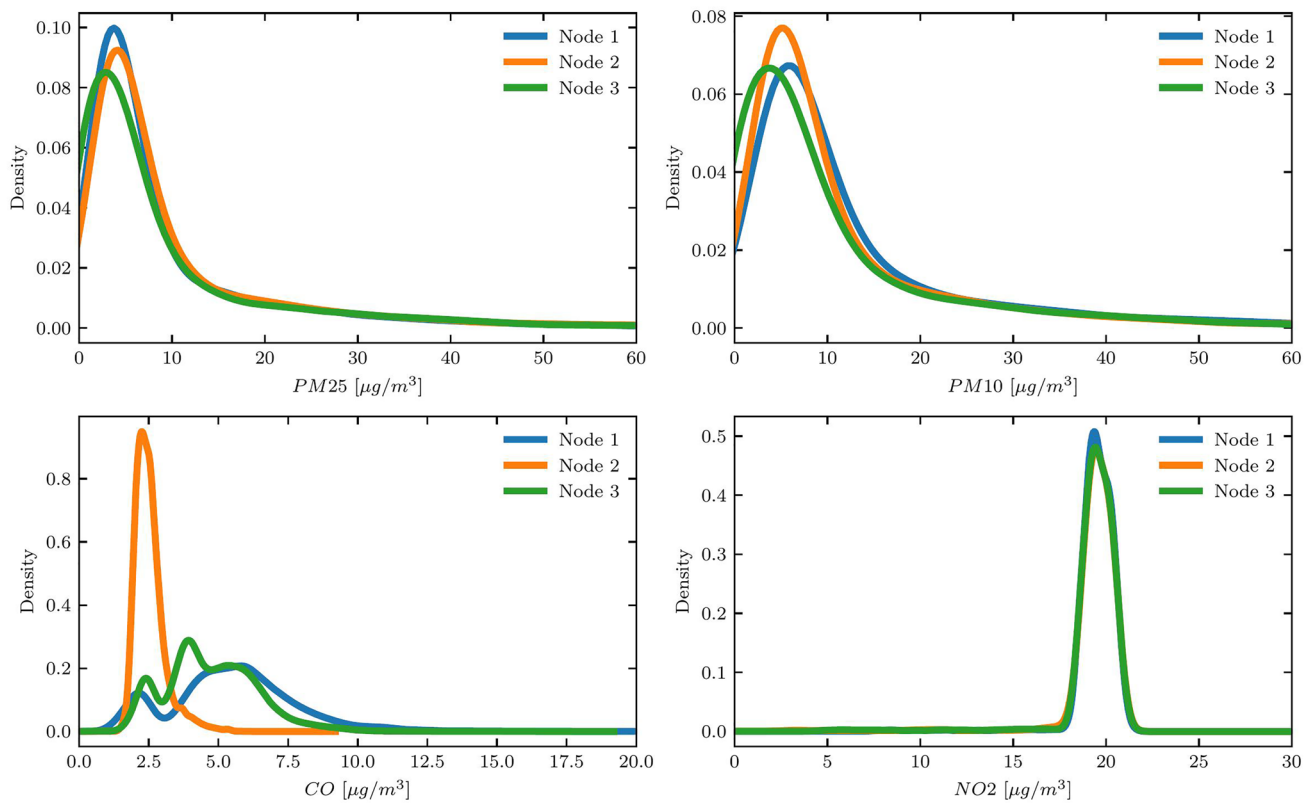


Fig. 7 Distributions of PM_{2.5}, PM₁₀, CO, and NO₂ pollutants at three different locations with respect to green areas

The findings highlight the need for continued efforts to address air pollution, including reducing emissions from heating systems and energy consumption, and also incorporating green infrastructure into urban planning when designing measures to reduce air pollution.

Wilcoxon signed-rank test was used to compare if there is a statistically significant difference in air pollution levels in places with and without a green area as it is shown in. Therefore, the test was applied on the data from Node 1' and Node 3'. The p-value for all the tests is approximately 0.0, which indicates statistically significant difference between the two locations in favor of the location that is closer to the green area (Node 3'). The effect of the green area is estimated to be small to medium for all studied pollutants. Overall, the results suggest that having green areas may help to reduce air pollution, although other factors may also influence this relationship.

Conclusion

The paper provides an overview of the current situation in Skopje, North Macedonia in terms of air pollution and its effects on the environment. The analyses include

identification of relations between meteorological parameters and air pollutant concentrations. As the collected data encompasses several years, it is also used to assess the influence of specific events and changes of policies on air pollution. Namely, the paper considers the influence of the COVID-19 pandemic as well as the introduction of legislative changes—waste burning ban. The performed analyses are the basis for discussing potential strategies and measures to improve air quality in the country.

Considering the correlation between the pollutants and meteorological parameters the results indicate a negative correlation between the pollutants and temperature, as well as the pollutants and wind speed. There is a relatively strong negative correlation between the pollutants (PM_{2.5}, PM₁₀, CO, NO₂) and temperature (between -0.38 and -0.52) and slightly lesser between particulate matter (PM_{2.5} and PM₁₀) and wind speed. This implies that high temperatures and strong winds contribute to dispersing pollutants and decreasing their concentration in the air. The meteorological parameters show certain consistency throughout the observed period, which is also important to consider when designing appropriate measures to mitigate air pollution. The analyzed data shows that the concentration of air pollutants rises during the winter season, particularly at night. This is likely due to the increased utilization of heating systems based on

fossil fuels. The positive correlation between pollutant concentrations and humidity, especially during colder months, should be also considered among the factors that influence the observed high air pollution in Skopje.

As mentioned above, legislative changes, especially targeting the energy and environment sectors, have certain impact on air pollution. Waste management is among the measures to reduce air and soil pollution. In this context, the waste burn ban is an important measure in dealing with air pollution, which is confirmed by the analyses of the collected data. The average PM concentration is reduced by 26–27% due to the introduction of the ban. Therefore, our findings suggest that strategies to reduce energy consumption increase the use of clean energies and introduce effective waste treatment could contribute to air pollution mitigation in North Macedonia.

As presented in the introductory section, the implementation of restrictive measures during the COVID-19 pandemic has had a global effect on air pollution mitigation. In this regard, Skopje is not an exception. The results for 2020 show the lowest concentration of PM_{2.5} and PM₁₀, which coincides with the COVID-19 pandemic and the restrictions it imposed. Additionally, the concentration of these pollutants has been gradually increasing since 2020; however, the difference in the concentration of PM_{2.5} and PM₁₀ between 2018 and 2020, as well as between 2018 and 2021, and 2018 and 2022 is still statistically significant, with a medium effect for 2020 and a small effect for 2022. The implementation of the specific Mann–Whitney test further confirms the positive effects of COVID-19 measures on reducing PM and other pollutant concentrations.

For future work, it is important to conduct on-site observations to assess how the green wall structure interacts with the wind. Factors such as airflow patterns should be taken into consideration, and an analysis should be made on how they might affect the distribution of pollutants or heat around the green wall. Additionally, it is recommended to utilize computational models or simulations to predict the potential impact of different wind conditions on the performance of the green wall. This could involve modeling airflow patterns and simulating the dispersion of pollutants or heat in varying wind scenarios.

Finally, it is important to stress that continuous measurement campaigns enable assessment of the impact of various factors on air quality. The collected data from such campaigns and their statistical analyses should be the basis for the development of effective air pollution mitigation measures. Considering that air pollution mitigation measures encompass both general and location specific measures, data collected during a longer time period are essential for the development of location specific measures.

Appendix

The main features of the sensing units are presented in Table 4.

The fundamental characteristics of the controller are listed in Table 5.

To ensure consistency and comparability across the data, sensor readings were converted from ohms (Ω) to micrograms per cubic meter ($\mu\text{g}/\text{m}^3$) (Table 5).

To convert from CO values in ohms to ppm following relations are used:

$$\text{CO (ppm)} = (\text{CO (ohms)} - R_{\text{zero}}) / (\text{Sensitivity} * \text{Gain}) \quad (1)$$

where: CO (ohms) is the CO value displayed in ohms, R_{zero} is the resistance of the sensor in clean air (usually provided by the manufacturer). Sensitivity is the sensitivity of the sensor in ppm per ohm (usually provided by the manufacturer). Gain is the gain of the amplifier circuit used to amplify the sensor output (usually provided by the manufacturer).

Concentration ($\mu\text{g}/\text{m}^3$) = molecular weight x concentration (ppb) \div 24.45. The number 24.45 in the equation is the volume (liters) of a mole (gram molecular weight) of a gas when the temperature is at 25 °C and the pressure is at 1 atmosphere (1 atm = 1.01325 bar).

Table 4 Main features of the sensing units

	SDS011	MiCS-4514
Measurement parameters	<i>PM2.5, PM10</i>	<i>CO, NO2</i>
Supply voltage	5 V	4.9 V-5.1 V
Operating temperature range	-20 to 50°C	-30 to 85 °C
Range	0.0–999.9 $\mu\text{g}/\text{m}^3$	/
CO detection range	/	1–1000 ppm
Sensing resistance in air	/	100–1500 k Ω
Maximum working current		220 mA

Table 5 Main characteristics of the controller

Controller	
Measurement parameters	<i>EPS32</i>
Supply voltage	2.7–3.6 V
Operating temperature range	-40 to 85 °C
Module interface	SD Card, UART, SPI, I2C, Motor PWM
Wi-Fi frequency range	2.4–2.5 GHz

ppb = 1.15 µg/m³ for CO, 1 ppb = 1.23 µg/m³ for NO₂ (2)

The induced uncertainty depends on the measurement uncertainties of the sensitivity factor and gain factor.

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Author contributions M.S contributed to conceptualization, methodology, writing—draft version preparation; V. Andova done statistical analysis, math analysis and discussion; A.K.M helped in writing, reviewing and editing; M.C.K done experimental analysis, visualization and technical editing, prepared figure 1; V. Andonovic done statistical analysis and prepared figures 2-5; M.K. done math analysis and prepared figures 6,7; M.M done statistical analysis and prepared figures 6,7. All authors reviewed the manuscript.

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