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Impact of Air Pollution on Human Health: A Comprehensive Analysis in the Case of Pristina City, Kosovo

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ABSTRACT

Air pollution in Pristina presents a significant environmental and health concern, directly affecting the quality of life of its citizens. The high concentrations of pollutants such as PM10, PM2.5, and NO2 indicate the impact of traffic, fuel combustion, and industrial activities, which constitute the main sources of pollution in this area. This study is based on air quality monitoring data provided by the Hydrometeorological Institute of Kosovo for the period 2020–2023. The concentrations of key pollutants (PM10, PM2.5, NO_2, O_3, SO_2, CO) were analyzed in two different locations: Pristina (a high-pollution area) and Brezovica (a clean-air area). The findings show that Pristina consistently records higher pollutant concentrations, particularly during the winter months, as a result of fossil fuel combustion and emissions from traffic. The highest levels of fine particulate matter (PM10 and PM2.5) were observed in cold months, while ozone (O3) reached peak values during summer due to photochemical reactions. In contrast, Brezovica maintained relatively low pollution levels, but its cleaner atmosphere favored the formation of secondary pollutants such as ozone. The comparative analysis over the years suggests a persistent pollution problem in Pristina, necessitating immediate intervention. The results highlight the urgent need for effective pollution control measures by local authorities. Strategies such as traffic management, the establishment of low-emission zones, and the promotion of sustainable transportation, including electric buses and bicycles, could significantly improve air quality. Continuous air quality monitoring is essential for real-time assessment and policy effectiveness. Only through a collective and science-based approach can air quality improvement and public health protection be achieved.

INTRODUCTION

Air pollution poses a significant threat to human health and is considered the largest environmental issue worldwide. Additionally, it is a preventable factor leading to death and disease. In the WHO report (2021), air pollution is responsible for 7 million premature deaths every year, making it one of the leading factors of global mortality. Specifically, approximately 4.2 million individuals worldwide experience premature mortality due to ambient air pollution, primarily linked to heart disease, stroke, chronic obstructive pulmonary disease, lung cancer, and acute respiratory infections in children. Furthermore, developing nations face a disproportionate burden, particularly affecting women, children, and the elderly, who frequently encounter both ambient and indoor air pollution (Borrego et al., 2009). Air pollution typically arises due to gaseous pollutants, such as ozone, nitrogen dioxide, sulfur dioxide, carbon monoxide, and others. Additionally, particulate matter, particularly particles with a diameter less than 2.5 (PM2.5), also contributes to air pollution. Over the past few decades, the global mortality rate associated with air pollution has demonstrated a declining pattern, primarily attributed to the reduction in indoor air pollution. Conversely, outdoor particulate matter and ozone pollution have experienced minimal changes.

By region, Africa shows the highest deaths per 100,000 people (180.9 deaths per year), followed by Southeast Asia with 165.8 deaths. Europe and America experience far fewer deaths from air pollution with 29.7 and 36.3 deaths per 100,000 people respectively. The level of air pollution is significantly higher for individuals residing in Asia and Africa in comparison to those living in America and Europe. For example, the annual average PM2.5 exposure in the regions of East Asia and the Pacific is 43 g/m^3, whereas in Sub-Saharan Africa it is 67 g/m^3. Conversely, in North America, the annual average PM2.5 exposure is 9 g/m^3, and in the European Union it is 14 g/m^3. Consequently, the exposure level for the population in Africa can be 7 orders of magnitude greater than that of individuals in North America. In the latest report of the World Health Organization (WHO, 2021) on global air quality guidelines for 2021, it is recommended that the annual level of PM2.5 should be 5 $\mu g/m^3$, reduced from the previous recommendation of 10 $\mu g/m^3$. According to these guidelines, 95% of the global population is currently exposed to PM2.5 levels higher than 5 $\mu g/m^3$, highlighting the need to improve air quality to protect public health. This statistic encompasses not only individuals in Asia and Africa but also those in Europe and South America (WHO, 2021). Air pollutants can be broadly categorized into two groups based on their origin: primary air pollutants and secondary air pollutants. Primary air pollutants refer to those that are directly released from various sources such as factories and cars. Examples of primary air pollutants include carbon monoxide (CO), carbon dioxide (CO_2), methane (CH_4), volatile organic compounds (VOCs), ammonia (NH_3), sulfur dioxide (SO_2), and nitric oxide (NO). On the other hand, secondary air pollutants are formed in the atmosphere as a result of chemical reactions. These include particulate matter (PM), ozone (O_3), nitric acid (HNO_3), sulfate (SO_4), and sulfuric acid (H_2SO_4). Notably, certain pollutants such as PM and nitrogen dioxide (NO_2) can be classified as both primary and secondary pollutants (WHO, 2021).

Carbon monoxide (CO) is a flammable, colorless, odorless, poisonous gas that reacts slowly with other chemical compounds in the ambient air and remains in the atmosphere for a considerable time, ranging from 0.1 to 5 years. The main sources of carbon monoxide in the city of Pristina include incomplete combustion, such as biomass burning and vehicle exhaust resulting from fuel combustion. The impact of Carbon Monoxide on health is profound. When this gas enters the bloodstream, it displaces oxygen from the red cells, resulting in a reduced supply of oxygen to vital organs such as the heart and brain. Consequently, severe tissue damage, dizziness, confusion, chest pain, and blurred vision can occur. Exposure to high levels of Carbon Monoxide can even lead to loss of consciousness and death. Prolonged exposure to low concentrations of Carbon Monoxide in the ambient air can also result in neurological damage. Individuals with underlying health complications may experience angina, characterized by chest pain due to reduced oxygen levels in the blood, following short-term exposure to Carbon Monoxide (CDCP, 2024).

Ozone is an important component of smog, along with PM. Ozone has a relatively long shelf life, lasting several weeks, allowing it to be transported over long distances. O_3 at ground level is considered a secondary air pollutant, formed through a complex photochemical reaction involving CO, NMVOC, NO_X, CH_4, and sunlight. Inhalation of O_3 leads to contraction of airway muscles, resulting in immediate difficulty breathing and coughing. Individuals with pre-existing lung disease are particularly susceptible to worsening of their conditions, including asthma and chronic obstructive pulmonary disease (COPD), which may require hospitalization. Duration of exposure to O_3, extending beyond eight hours, has different health consequences in different age groups (Chen et al., 2007).

Nitrogen oxides (NOx) include a group of compounds characterized by their toxic, irritating, and highly reactive nature with atmospheric molecules. NOx emissions are mainly derived from anthropogenic activities, especially high-temperature combustion processes such as fuel combustion (eg gas, oil, coal). In urban environments, the transport sector remains the main contributor to NOx emissions. Nitrogen dioxide (NO_2) mainly poses a significant risk to respiratory health. After inhalation, NO_2 can cause inflammation in the lungs and compromise the immune response, thus triggering symptoms such as bronchitis, cough, flu, and cold. Prolonged exposure to NO_2 also increases the risk of developing asthma, especially in children, who exhibit a higher respiratory rate relative to body weight compared to adults. Additionally, research suggests that prolonged exposure to NO_2 during infancy and childhood may impair lung development, resulting in lower lung capacity at maturity compared to those with minimal NO_2 exposure (Jonson et al., 2017).

Particulate matter (PM10 and PM2.5) poses significant health risks by causing damage to the respiratory tract. After inhalation, PM particles are deposited in the pulmonary alveoli and penetrate lung cells, causing oxidative stress that can damage or kill cells, leading to airway inflammation and decreased lung function. Chronic exposure to PM2.5 exacerbates oxidative stress in lung cells, increasing susceptibility to lung infections and the development of respiratory conditions such as asthma, chronic bronchitis, and chronic obstructive pulmonary disease (COPD). In addition, PM2.5 can induce oxidative stress in the central nervous system, particularly affecting the hypothalamus, which can disrupt the cardiac autonomic nervous system and lead to abnormal heart rate variability, thereby increasing the risk of cardiovascular disease. Evidence suggests that exposure to PM2.5 is particularly harmful to infants, contributing to premature births and lower birth weight (Feng et al., 2016).

Sulfur oxides (SOx) are a group of compounds that contain sulfur and oxygen. SO_2 emissions derive from the burning of fossil fuels, particularly in stationary sources such as coal-fired power plants, which account for the majority of SO_2 emissions. The SO_2 emission rate from fuel combustion varies according to the sulfur content of the fuel. Brief exposure (eg, 10 minutes) to elevated levels of sulfur dioxide (SO_2) can irritate the eyes, nose, throat, and respiratory tract, leading to symptoms such as coughing. Individuals with asthma may experience intensified asthma attacks in response to SO_2 exposure. Furthermore, SOx compounds can undergo atmospheric chemical reactions to form sulfate particles, which become important components of PM2.5.

Air pollution in Pristina is a major issue that directly affects the health of its residents. The capital of Kosovo faces high levels of fine particulate matter (PM2.5 and PM10), primarily originating from heavy traffic, the use of fossil fuels for heating, as well as industrial and energy-related activities. The concentrations of these particulates often exceed the limits recommended by the WHO (WHO, 2021), making Pristina one of the most polluted cities in Europe. Prolonged exposure to these pollutants is associated with an increased incidence of respiratory diseases, including chronic bronchitis, asthma, and cardiovascular conditions.

This study aims to analyze and assess the impact of key air pollutants including PM10, PM2.5, NO_2, O_3, SO_2, and CO on the health of Pristina's population. The primary objective is to identify pollution trends, understand its main sources, and examine its direct effects on public health. Through pollutant monitoring and epidemiological data analysis, this research seeks to provide evidence based recommendations for more effective air quality management policies. The study will contribute to raising awareness among the public and responsible institutions about the importance of reducing pollution and improving environmental conditions in Pristina.

MATERIALS AND METHODS

The data used in this analysis were obtained from the Hydrometeorological Institute of Kosovo (IHMK - Air Quality Management Institution). The data assess the changes in air quality in the city of Pristina and the locality of Brezovica during the years 2020-2023. In this study, two contrasting locations in Kosovo have been selected to analyze the impact of air pollution on environmental quality and public health. Pristina has been chosen as a high-air-pollution area, while Brezovica serves as a reference for a clean-air environment. Pristina is the capital and the largest urban and industrial center of Kosovo, where air pollution is one of the major environmental issues. The selection of Pristina as a study area is based on the following factors: The presence of power plants (Kosovo A and B), heavy urban traffic, construction activities, and the burning of various materials contribute to high levels of PM10, PM2.5, and PM1. Pristina has a high population density, making exposure to pollutants more harmful to public health. Reports from the Hydrometeorological Institute of Kosovo and the European Environment Agency have identified Pristina as one of the most polluted cities in the Balkans. Cases of respiratory and cardiovascular diseases are more frequent in Pristina due to prolonged exposure to air pollutants.

Fig 1. Air Pollution in Pristina

Fig. 2. Clean Air in Brezovica

Brezovica is one of the cleanest mountainous areas in Kosovo and serves as a reference point for understanding the impact of pollution on the human body compared to a pristine environment. The selection of this location is based on distance from pollution sources. Brezovica is a protected area, far from industrial centers and high-traffic roads. The mountainous climate, dense forests, and the absence of industrial pollutants ensure high air quality. Past measurements indicate that Brezovica (fig. 2) has very low levels of PM10, PM2.5, making it an ideal area for comparison with Pristina (fig. 1). In this study, data provided by the Institute of Hydrometeorology of Kosovo (IHMK, 2024) were used to analyze the levels of major air pollutants in Pristina. Air quality monitoring was carried out using equipment certified according to European standards (EN), ensuring accurate and reliable measurements of pollutant concentrations. Carbon monoxide (CO) was measured according to standard EN 14626, using non-dispersive infrared (NDIR) spectroscopy. This method allows precise detection of CO concentrations in the air, assessing its impact on air quality and public health. Nitrogen dioxide (NO_2) and nitrogen oxides (NOx) were measured according to EN 14211, using chemiluminescence, a sensitive and specific method for analyzing these pollutants, which mainly originate from the combustion of fossil fuels. Sulfur dioxide (SO_2) was analyzed according to EN 14212, using ultraviolet fluorescence, which provides accurate measurement of SO_2 concentrations in the atmosphere, especially in areas near industrial sources. Ozone (O_3) was measured according to EN 14625, using ultraviolet photometry, a standard technique for monitoring ozone levels in the air, which can have harmful effects on human health and the environment. Fine particulate matter (PM10 and PM2.5) was monitored according to EN 12341, using two main methods: Beta attenuation (Sharp)**,** a technique that ensures continuous and accurate measurement of fine particles in the air, and Optical measurements (Grimm M180)**,** a method that allows the determination of the size and concentration of suspended particles in the atmosphere. PM10 particles were also analyzed using the gravimetric method, which provides an accurate assessment of particle mass based on weighing filters after exposure to the air. For this study, the data were statistically analyzed using GraphPad Prism – version 7.05. Pearson correlation coefficients were calculated to assess the relationship between air pollutant levels (PM10, PM2.5, NO_2, O_3, SO_2, CO). The level of significance was set at $p < 0.05$ to ensure the statistical validity of the results.

On February 7, 2024, the US Environmental Protection Agency (EPA, 2024) announced the new rule to strengthen national ambient air quality standards for fine particulate matter (PM2.5) or soot. EPA is setting the annual primary (health-based) PM2.5 standard level at 9.0 micrograms per cubic meter ($\mu g/m^3$) to provide greater protection of public health.

Table 1: Air Quality Index (AQI) for fine Particulate Matter (PM2.5)

AQI Category and Index Value	Previous AQI Category Breakpoints	Updated AQI Category Breakpoints	What changed?
Good (0 – 50)	0.0 to 12.0	0.0 to 9.0	EPA updated the breakpoint between Good and Moderate to reflect the updated annual standard of 9 micrograms per cubic meter
Moderate (51 – 100)	12.1 to 35.4	9.1 to 35.4	
Unhealthy for Sensitive Groups (101 – 150)	35.5 to 55.4	35.5 to 55.4	No change, because EPA retained the 24-hour fine PM standard of 35 micrograms per cubic meter.
Unhealthy (151 – 200)	55.5 to 150.4	55.5 to 125.4	EPA updated the breakpoints at the upper end of the unhealthy, very unhealthy, and hazardous categories based on scientific evidence about particle pollution and health. The Agency also combined two sets of breakpoints for the Hazardous category into one.
Very Unhealthy (201 – 300)	150.5 to 250.4	125.5 to 225.4	
Hazardous (301+)	250.5 to 350.4 and 350.5 to 500	225.5+	

Source: US, EPA 2024.

RESULTS AND DISCUSSION

The data on air pollution exposure in the city of Pristina and the locality of Brezovica as a point of comparison were obtained from IHMK and presented in tables 2, 3, 4, and 5 according to the years 2020-2023. The same results are expressed through figures 3.

The table 2 presents the annual average concentrations and the number of exceedances of permitted limits for key air pollutants (PM10, PM2.5, NO_2, SO_2, O_3, and CO) in two locations, Pristina and Brezovica, for the year 2020. In Pristina, the concentrations of PM10 and PM2.5 are significantly higher than in Brezovica, with PM10 reaching an annual average of 37.4 µg/m³ and PM2.5 at 24.0 µg/m³, whereas in Brezovica, these values are much lower, at 7.6 µg/m³ and 5.7 µg/m³, respectively. The number of exceedances of the 24-hour (a year) limit for PM10 in Pristina is 78, while in Brezovica, it is only 1, reflecting high urban pollution in the capital due to traffic, fuel combustion, and industrial activities, whereas the air in Brezovica is cleaner due to reduced anthropogenic influence. For NO_2, Pristina has an average of 26.0 µg/m³ with one exceedance per hour, whereas in Brezovica, the concentration is much lower, at 1.5 µg/m³, indicating the impact of dense traffic and other combustion sources in urban areas. For SO_2, the values are lower in both locations, with an average of 11.0 µg/m³ in Pristina and 3.8 µg/m³ in Brezovica, suggesting a relatively limited impact from fossil fuel combustion sources. For O_3, Pristina has an average of 46.3 µg/m³ with three cases of exceedances of the 24-hour limit, whereas Brezovica has a higher concentration of 92.4 µg/m³ with 18 exceedances, indicating a greater formation of tropospheric ozone in cleaner areas due to photochemical reactions in the presence of solar radiation and a reduction of primary pollutants that contribute to its breakdown in urban areas. For carbon monoxide (CO), the concentration in Pristina is 1.5 mg/m³, while in Brezovica, it is significantly lower at 0.3 mg/m³, reflecting the impact of traffic and combustion processes in the urban area. These data indicate much higher air pollution in Pristina for pollutants associated with human activity, while Brezovica has better air quality, except for ozone, which is higher due to atmospheric conditions and the reduction of pollutants that contribute to its breakdown.

Table 2. Air Pollutants in Pristina and Brezovica for the Year 2020

Parameter	Locality	Average annual concentration	Exceedances 24 h	Exceedances 8 h	Exceedances 1 h
PM10	Pristina	37.4 µg/m^3	78		
PM2.5		24.0 µg/m^3			
NO_2		26.0 µg/m^3			1
SO_2		*11.0 µg/*m^3			
O_3		*46.3 µg/*m^3		3	
CO		*1.5 mg/*m^3			
PM10	Brezovica	7.6 µg/m^3	1		
PM2.5		5.7 µg/m^3			
NO_2		1.5 µg/m^3			
SO_2		*3.8 µg/*m^3			
O_3		*92.4 µg/*m^3		18	
CO		*0.3 mg/*m^3			

In the following years, according to data from tables 3, 4, and 5, there is a gradual decrease in pollution for some parameters, though not for all pollutants. In the subsequent year, the PM10 concentration in Pristina drops to 33.8 µg/m^3, and the number of exceedances falls to 62, reflecting a slight improvement possibly due to environmental measures or climatic factors. The PM2.5 concentration also decreases to 21.1 µg/m^3, though this change is not very significant. In the next year, PM10 further declines to 32.6 µg/m^3, with 61 instances of 24-hour exceedances, while PM2.5 remains stable at 21.2 µg/m^3, indicating a stabilization in pollution levels that still exceed recommended norms.

For NO_2, the concentration in Pristina was 26.0 µg/m^3 in 2020, but in the following years, it shows a significant decrease, reaching 16.8 µg/m^3 in the last two years, suggesting a reduction in the impact from traffic and other urban sources. SO_2 shows a slight decrease in the first year after 2020, dropping from 11.0 to 7.6 µg/m^3, but then rises again to 9.9 µg/m^3, suggesting variability influenced by industrial combustion sources or meteorological conditions.
Ozone in Pristina exhibits a consistent trend, with concentrations fluctuating between 46.3 and 47.6 µg/m^3 and a constant number of exceedances (around 2), whereas in Brezovica, ozone remains consistently higher, reaching up to 81.7 µg/m^3 with exceedances ranging from 6 to 12, as a result of reduced primary pollutants that normally contribute to its breakdown in cleaner areas due to photochemical processes.
For carbon monoxide (CO), the concentration in Pristina was 1.5 mg/m^3 in 2020, increased to 2.4 mg/m^3 in the following year, and then decreased to 1.1 mg/m^3 in the later years, while in Brezovica, it has consistently remained at very low levels, from 0.3 to 0.7 mg/m^3. These data show that overall air pollution in Pristina has experienced a moderate decline for some pollutants such as PM10, PM2.5, and NO_2, while other pollutants like SO_2 and CO have fluctuated due to various influencing factors. In Brezovica, pollutant values remain lower for all substances except ozone, which continues to be higher because of the atmospheric characteristics of the mountainous area. However, despite the declining trend in some pollutants, the values remain above permissible limits in Pristina, posing a risk to public health. Therefore, local authorities must take further measures to improve air quality and reduce pollution in urban areas.

The assessment of PM10 and PM2.5 concentrations by air quality standards is based on annual values, therefore, in the analysis of dust pollution, the standard values have been exceeded, where the allowed rate is 25 µg/m^3 during the year, with the excess months biggest: January, February, March, April, October, November and December. The urban areas of the city should be declared as areas with a special protection environment because the discharges of risk into the environment are several times above the approved standards. In Pristina, in addition to PM10 and PM2.5, there are other air pollutants such as CO, NOx, Pb, Zn, Cr, and CO_2.

Table 3. Air Pollutants in Pristina and Brezovica for the Year 2021

Parameter	Locality	Average annual concentration	Exceedances 24 h	Exceedances 8 h	Exceedances 1 h
PM10	Pristina	33.8 μg/m^3	62		
PM2.5		21.1 μg/m^3			
NO_2		26.3 μg/m^3			
SO_2		*7.6 μg/m^3*			
O_3		*47.6 μg/m^3*		2	
CO		*2.4 mg/m^3*		29	
PM10	Brezovica	11.7 μg/m^3	6		
PM2.5		7.9 μg/m^3			
NO_2		3.5 μg/m^3			
SO_2		*2.3 μg/m^3*			
O_3		*81.2 μg/m^3*		6	
CO		*0.7 mg/m^3*			

Table 4. Air Pollutants in Pristina and Brezovica for the Year 2022

Parameter	Locality	Average annual concentration	Exceedances 24 h	Exceedances 8 h	Exceedances 1 h
PM10	Pristina	32.6 μg/m^3	61		
PM2.5		21.2 μg/m^3			
NO_2		16.8 μg/m^3			
SO_2		*9.9 μg/m^3*			
O_3		*45.9 μg/m^3*		2	
CO		*1.1 mg/m^3*		13	
PM10	Brezovica	10.4 μg/m^3	2		
PM2.5		7.3 μg/m^3			
NO_2		1.5 μg/m^3			
SO_2		*5.2 μg/m^3*			
O_3		*81.7 μg/m^3*		12	
CO		*0.6 mg/m^3*			

Table 5. Air Pollutants in Pristina and Brezovica for the Year 2023

Parameter	Locality	Average annual concentration	Exceedances 24 h	Exceedances 8 h	Exceedances 1 h
PM10	Pristina	26.0 μg/m^3	13		
PM2.5		17.0 μg/m^3			
NO_2		6.5 μg/m^3			
SO_2		*6.4 μg/m^3*			
O_3		*46.8 μg/m^3*		1	
CO		*0.4 mg/m^3*			
PM10	Brezovica	10.5 μg/m^3	1		
PM2.5		8.0 μg/m^3			
NO_2		1.3 μg/m^3			
SO_2		*4.5 μg/m^3*			
O_3		*85.3 μg/m^3*		6	
CO		*0.8 mg/m^3*			

Figure 3 (charts 1-4) presents the monthly concentrations of key air pollutants (PM10, PM2.5, NO_2, O_3, SO_2, and CO) in two locations, Pristina and Brezovica, during the period 2020 - 2023. Pristina exhibits higher concentrations of fine particulate matter (PM10, PM2.5) and gaseous pollutants (NO_2, SO_2, CO), particularly during the winter months, reflecting the impact of fossil fuel combustion for heating and heavy traffic. In the summer months, ozone (O_3) reaches its highest levels as a result of photochemical reactions influenced by solar radiation.

In contrast, Brezovica shows significantly lower pollutant concentrations, highlighting the influence of natural factors and the absence of major anthropogenic pollution sources. The year-to-year comparison suggests variations in pollution trends, influenced by climatic factors and regulatory measures for air quality.

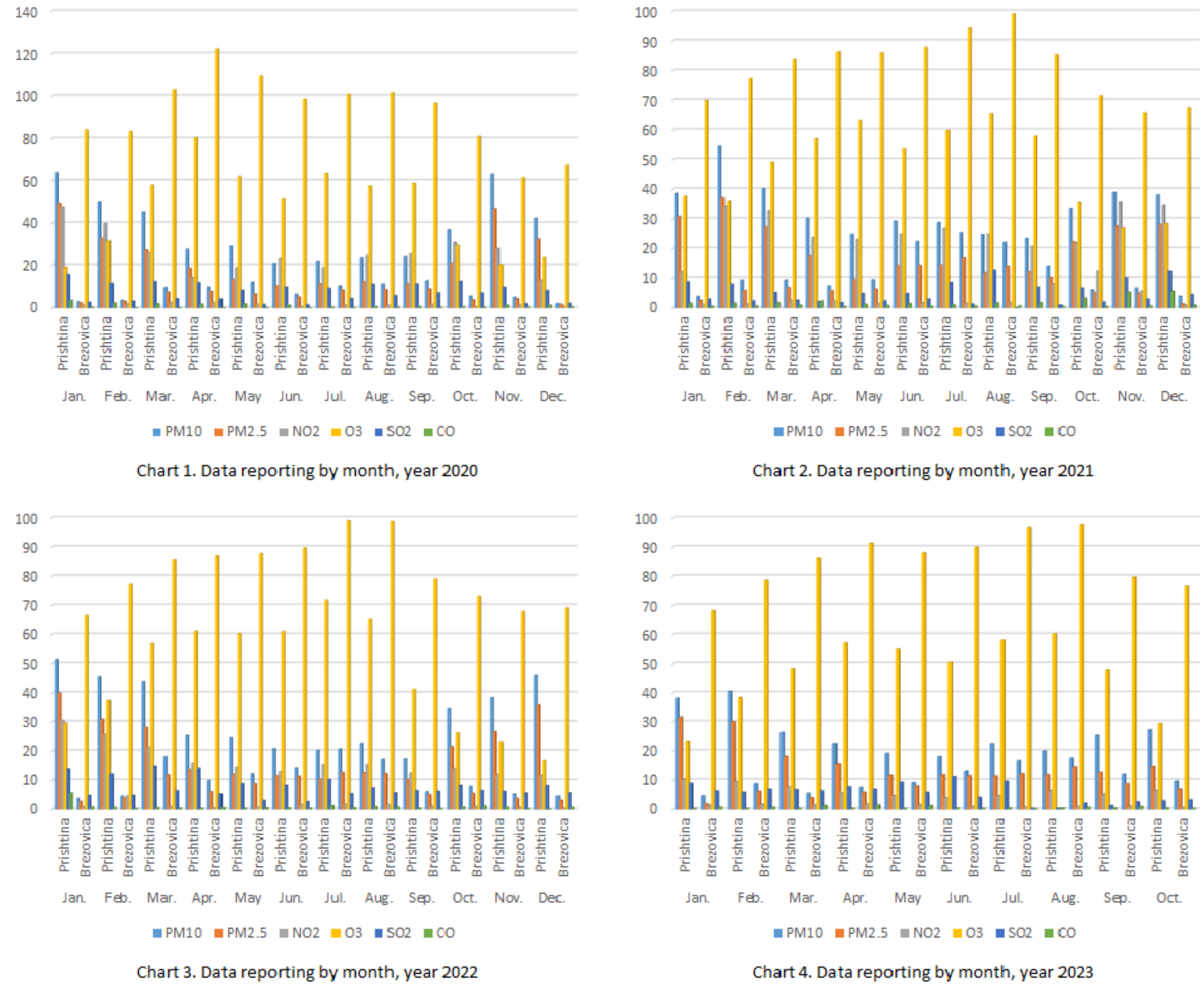

Fig. 3**.** Monthly concentrations of key air pollutants in Pristina and Brezovica (2020-2023)

The analysis of the correlation between the main air pollutants in Pristina and Brezovica reveals significant differences in air quality between these two locations. Pristina, as an urban area with high pollution, is characterized by intensive sources of pollution, such as traffic, industry, and construction, while Brezovica, a mountainous area with clean air, is minimally affected by these factors. The correlation between pollutant concentrations in these two areas helps to understand how pollution is dispersed and influenced by environmental factors. The correlation coefficients for PM10 ($r = -0.42$) and PM2.5 ($r = -0.38$) indicate a weak and negative relationship between these two locations. This suggests that the concentrations of fine particles in Pristina are primarily associated with local factors, such as traffic and construction, while Brezovica remains a clean area due to the lack of pollution sources. The lack of a strong correlation between these two locations indicates that fine particle pollution is mainly a localized phenomenon and does not have a wide distribution over large distances. The correlation coefficient for NO_2 ($r = 0.68$) shows a moderate positive relationship between the two locations. NO_2 is a gaseous pollutant that can be transported by winds, and meteorological conditions can influence its distribution over long distances. This indicates that some of the pollution from Pristina may partially affect the air quality in Brezovica, although concentrations in this mountainous area remain much lower. The correlation value for ozone is nearly zero (r = -0.05), indicating the lack of a relationship between the concentrations of this pollutant in Pristina and Brezovica. O3 is not a primary pollutant but is created through atmospheric reactions related to the presence of NO2 and sunlight. This means that the formation of ozone is not directly affected by local pollution sources but depends more on meteorological conditions and the presence of precursor gases. The correlation coefficient for SO2 is negative and relatively strong (r = -0.56), indicating a clear distinction between high pollution in Pristina and very low concentrations in Brezovica. SO2 is a pollutant primarily associated with the burning of fossil fuels, particularly in power plants and industries of the city. The presence of this pollutant in Pristina is high, while Brezovica, as a mountainous area without large industrial sources, has minimal or negligible concentrations. The correlation coefficient for CO (r = -0.63) is also negative and strong, indicating that carbon monoxide pollution is a specific issue for Pristina and does not affect Brezovica. CO is a pollutant primarily produced by the burning of fossil fuels, especially from road traffic. The absence of a strong correlation between these two locations suggests that CO emissions remain concentrated primarily in urban areas and do not spread widely over large distances. The results of the correlation analysis confirm the expectations that Pristina and Brezovica have different levels of air pollution, influenced by local factors and meteorological conditions.

There is a link between the incidence of lung cancer and air pollution with PM2.5 (Čabanová et al., 2019). According to the new WHO recommendations, exposure to PM2.5 fine particle concentrations should be less than 5 $\mu g/m^3$ as an annual average and less than 15 $\mu g/m^3$ as a 24-hour average. When we breathe in polluted air, many particles enter our respiratory system. However, the deposition of particles in different regions of our pulmonary system depends on the particles. Figure ss shows the deposition fractions of particles in the pulmonary system in the interior of the particles. In each part of the respiratory tract, different amounts of a particulate matter (nanoparticles and microparticles) are deposited. Air pollutants, after entering and passing through the pulmonary system, will become a danger to human health. Those particles are able to diffuse through the lung and lung barriers into the blood and affect the normal functions of the human body. For example, the blockage of blood vessels can lead to complications in the brain (Xu et al., 2017).

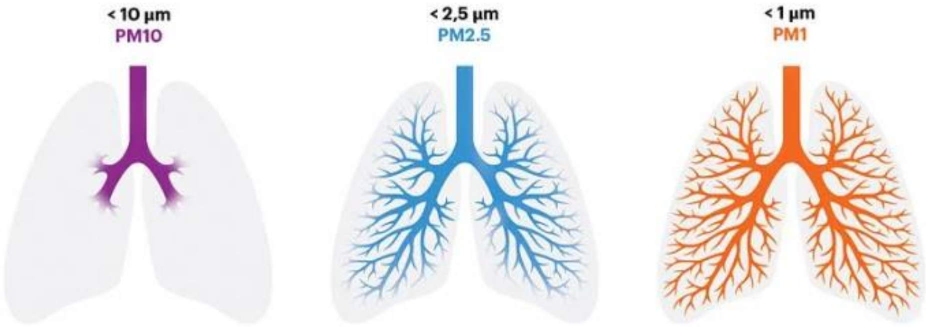

Fig. 4. Smaller particles can penetrate deeper into the lungs

Fig. 4 illustrates the penetration of particulate matter (PM) pollutants into the respiratory system based on their size. PM10 (< 10 µm, purple color), these particles are relatively large and are mostly trapped in the nose and upper respiratory tract (trachea and main bronchi). They can cause inflammation of the nasal and throat mucosa, coughing, increased mucus production, and eye irritation. PM2.5 (< 2.5 µm, blue color), these finer particles can penetrate deeper into the lungs, reaching the terminal bronchioles and pulmonary alveoli. They can cause significant inflammation, increased oxidative stress, and negative effects on lung function. Studies show that long-term exposure to PM2.5 is linked to chronic lung diseases such as chronic bronchitis and chronic obstructive pulmonary disease (COPD), as well as an increased risk of cardiovascular diseases. PM1 (< 1 µm, orange color), The smallest and most dangerous particles, as they can pass through the alveolar barrier and enter the bloodstream. They directly affect the cardiovascular system by causing systemic inflammation, atherosclerosis, and an increased risk of heart attacks and strokes. Due to their small size, PM1 can carry toxic chemicals and heavy metals into the body, increasing oxidative stress and carcinogenic potential. The smaller the particles, the deeper they penetrate into the respiratory system and the greater their impact on health. Long-term exposure to PM2.5 and PM1 is associated with chronic lung and heart diseases, as well as an increased risk of cancer and systemic damage (Pope et. al., 2006; Brook et al., 2010).

Air pollution is an important public health issue, and numerous studies have revealed a clear link between air pollution and many health problems in the general population. The effects of air pollution often occur in varying degrees, from subclinical effects to increased risk of premature death. Some of these effects are: An increase in respiratory diseases, including bronchiolitis, rhinopharyngitis, and bronchial hypersecretions, which affect the quality of breathing and the overall health of the airways. The degraded function of the respiratory system, including low breathing capacity, increased incidence of asthma, and persistent coughing. Irritation of the eyes and other mucous membranes of the respiratory tract can cause severe discomfort and discomfort. Increased cardiovascular disease, including the risk of heart disease and hypertension, which are closely related to the quality of the air we breathe. Negative impact on the immune system, making the organism more vulnerable to infections and other diseases. Increased short-term mortality due to respiratory and cardiovascular diseases, creates a huge burden on health services and the families of the sick. Impact on long-term mortality, which is related to the carcinogenic effect of some air pollutants (Danna, et al., 2022).

In recent years, air pollution has become an important issue on the global environmental agenda, causing major concerns for public health and the environment in general. With a continued increase in economic activity and energy demand, it is clear that global emissions of air pollutants will increase significantly in the coming decades. The projections of the Organization for Economic Development and Cooperation (OECD, 2016) based on environmental-economic models predict a doubling of emissions of some pollutants by 2060. This scenario causes serious concerns for public health and for the health of the environment, since the pollution of air is closely related to many health problems. On a practical level, it is important for each country to monitor and limit emissions of common air pollutants such as: PM10, PM2.5, carbon monoxide, nitric oxides (NOx), sulfur dioxide (SO_2). The half-life of PM10 and PM2.5 particles in the atmosphere is quite long, they can be transferred and spread over long distances where people can be exposed (Wilson et al., 1997). These fine particles are the main cause of the formation of "fog" in different cities.

Numerous studies show that about 8% of global deaths were directly related to ambient air pollution (Wan-Hsiang Hsu et al., 2017; Andrea et al., 2023). The main urban air pollution in the city of Pristina comes from the burning of fossil fuels, which contain particles such as PM10 and PM2.5, which not only causes breathing problems but also pose health risks related to neurodegenerative diseases such as Alzheimer's and Parkinson's (Eduarda et al., 2023).

Human exposure to PM10 and PM2.5 particles is associated with increased formation of reactive oxygen species (ROS), leading to oxidative stress, fig. 5 (Deng et al., 2013). Authors Fang and Lakey (Fang et al., 2019; Lakey et al., 2016) have emphasized the role of organic and inorganic compounds of PM2.5 in promoting the production of ROS, which then results in biomolecular injuries. This oxidative stress arises from an imbalance between the production of ROS species and the body's antioxidant defense mechanisms. The human body creates antioxidant defenses, both enzymatic and non-enzymatic, which play a crucial role in mitigating the harmful effects of ROS. Zeng (Zeng et al., 2018) emphasize the importance of these defenses in neutralizing the action of ROS and preserving the cellular environment. However, prolonged exposure to these particulate matter can overwhelm these defenses, leading to compromised antioxidant capacity and exacerbating damage associated with oxidative stress. Exposure to PM2.5 and PM10 has been shown to damage antioxidant defense mechanisms in many internal organs such as the heart, kidneys, liver, and lungs (de Paula et al., 2019).

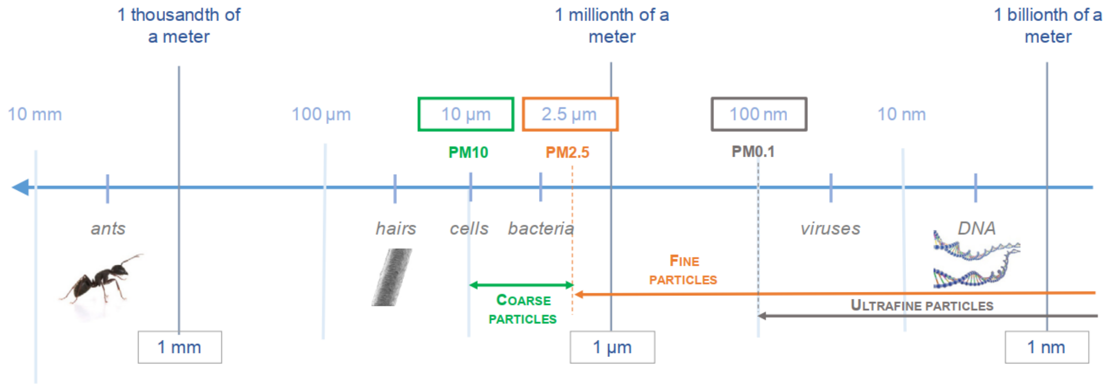

Fig. 5. Relative size of particles PM10, PM2.5

The results of air contamination in Pristina align with findings from similar studies, such as the one conducted in Chiangmai, Thailand (Piyavadee et al. 2024), where temperature and rainfall were found to significantly influence air pollutant concentrations. In Pristina, high levels of PM10 and NO_2 have been recorded, particularly during colder months when temperature inversions trap pollutants near the surface, exacerbating air quality issues. Similar to the Chiangmai study, where increased temperatures were associated with higher concentrations of PM10 and O_3, Pristina also experiences worsening air pollution during dry and stagnant atmospheric conditions. However, rainfall plays a crucial role in reducing pollutant concentrations through wet deposition, effectively washing particulate matter and gaseous pollutants from the atmosphere, mirroring the beneficial effects observed in Chiangmai.

The study in Cape Town (Ndletyana et al., 2023) found that heavy traffic and industrial activities were the main contributors to air pollution, a trend that is also evident in Pristina, where vehicle emissions and coal-based energy production are major sources of pollution. Furthermore, the findings from Cape Town highlighted the impact of seasonal variations, with pollution levels peaking during winter due to stable atmospheric conditions that prevent pollutant dispersion. This pattern aligns with air quality trends in Pristina, where cold weather conditions exacerbate pollution episodes, further increasing health risks. Due to this harmful impact, it is essential to implement measures to reduce emissions, including improving public transportation, promoting alternative energy sources, and strengthening air quality monitoring to minimize the negative effects on public health and the environment.

Nitric oxides include nitric oxide (NO) and nitrogen dioxide (NO_2), created as a result of the oxidation of nitric oxide by ozone. Nitrogen dioxide is a by-product of combustion reactions and is usually produced during the burning of fossil fuels in power plants. In Kosovo and especially in Pristina, NO_2 comes precisely from the work of thermal power plants, and a large part also comes from the discharge of gases from motor vehicles. Nitric oxide in low levels is an important molecule in human cells, but it has a high toxicity when its concentrations increase in the atmosphere. Prolonged exposure to nitrogen dioxide can cause breathing problems in the elderly and pregnant women (WHO, 2021). Nitric oxide (NO) is a gas that can irritate the respiratory system. It can enter the lungs and cause breathing difficulties, coughing, dyspnea, bronchospasm, pulmonary edema etc. In cases where NO concentrations are higher than 2.0 ppm, it can also affect the immune system by attacking T lymphocytes, particularly CD8+ cells, and natural killer (NK) cells (Chen at al. 2007).

Ozone is known as the Earth's protective layer at high altitudes, which protects the atmosphere against harmful ultraviolet radiation emitted by the sun. Ozone values in our research areas are within normal values. These values in most cases result from reactions between nitric oxide and volatile organic compounds (such as hydrocarbons present in gasoline). Ozone causes problems in the upper layers of the skin. A study conducted on mice exposed to high levels of ozone showed that after a while malondialdehyde formation was stimulated in the upper part of the skin (epidermis) but a decrease in vitamins C and E was also recorded (Thiele et al. 1997).

The values of sulfur dioxide (SO_2) recorded in the locality of Pristina have in many cases exceeded the normal values. SO_2 is a gas produced by burning sulfur-containing fuel, such as coal and diesel. It can also be discharged into the atmosphere through natural processes, such as organic decomposition or volcanic eruptions, but our study area is not characterized by this phenomenon. High values of sulfur dioxide irritate the skin and mucous membranes (eyes, nose, throat and lungs) and also have a negative impact on the respiratory system (WHO, 2021). High values of SO_2 emissions in urban areas irritate the respiratory tract and cause bronchitis, mucus production in the respiratory tract, and bronchospasm. SO_2 is a sensory irritant, it penetrates deep into the lungs is converted into bisulfite, and interacts with sensory receptors causing bronchoconstriction (US EPA, 2024).

Carbon monoxide has a much greater affinity for hemoglobin than oxygen. Based on this, carbon monoxide poisoning causes serious harm to people exposed to high levels of carbon monoxide. Taking carbon monoxide for a long period of time can cause problems with hypoxia, ischemia, and cardiovascular disease. Acute symptoms of carbon monoxide poisoning include headache, dizziness, weakness, nausea, vomiting and, finally, loss of consciousness (Shazia et al., 2024).

In comparison to the guidelines of the European Union (EU) and the World Health Organization (WHO), air pollution in Pristina during the period from 2020 to 2023 has shown alarming levels, often exceeding the recommended limits. According to data collected by the Institute of Hydrometeorology of Kosovo (IHMK), the concentrations of fine particulate matter (PM10 and PM2.5), as well as other pollutants such as CO, NO2, and SO2, have frequently surpassed the safety thresholds set by WHO and the EU. For example, the levels of PM10 and PM2.5 have been much higher than WHO recommendations, which set a limit of 40 $\mu g/m^3$ for the annual average of PM10 and 25 $\mu g/m^3$ for PM2.5. In Pristina, these levels have often exceeded these limits, posing a risk to the health of residents, especially those suffering from respiratory and cardiovascular diseases. Additionally, the concentrations of NO2 and CO have often surpassed the recommended limits for health protection, which are set to reduce the risk of lung and heart diseases. This has been the result of multiple sources of pollution, including heavy traffic, the use of fossil fuels for heating, and industrial activities. A comparison of data for the years 2020-2023 shows a continuity of high pollution levels, highlighting the urgent need to improve policies and measures for air quality management, including reducing the use of fossil fuels and improving infrastructure for clean and sustainable transport.

CONCLUSIONS

This study highlights the serious issue of air pollution in Pristina, emphasizing its environmental and public health implications. The comparative analysis between Pristina and Brezovica over the period 2020–2023 confirms that Pristina consistently experiences significantly higher concentrations of air pollutants, particularly PM10, PM2.5, and NO2. These pollutants are primarily linked to traffic emissions, fuel combustion, and industrial activities, with their impact being more severe during the winter months. In contrast, Brezovica, with its lower pollution levels, serves as a valuable reference for a cleaner atmosphere, although secondary pollutants such as ozone (O3) tend to form more readily due to photochemical reactions. The findings suggest an ongoing and persistent air pollution problem in Pristina, which requires immediate and effective intervention. Measures such as stricter traffic regulations, the implementation of low-emission zones, and the promotion of sustainable urban mobility solutions such as electric public transportation and cycling are crucial for improving air quality. Furthermore, continuous air quality monitoring remains essential to assess pollution trends, evaluate the effectiveness of implemented policies, and guide future strategies. Overall, addressing air pollution in Pristina necessitates a coordinated and science-based approach involving policymakers, environmental agencies, and the public. Only through such collective efforts can significant improvements be achieved, leading to a healthier and more sustainable urban environment.

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