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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. High concentrations of pollutants such as PM10, PM2.5, and NO_2 indicate the impact of traffic, fuel combustion, and industrial activities, which are 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 of 2020–2023. The concentrations of key pollutants (PM10, PM2.5, NO_2, O_3, SO_2, and CO) were analyzed at 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 winter, owing to fossil fuel combustion and traffic emissions. The highest levels of fine particulate matter (PM10 and PM2.5) were observed in the cold months, whereas ozone (O_3) reached peak values during summer owing 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 interventions. These results highlight the urgent need for effective pollution control measures by local authorities. Strategies such as traffic management, establishment of low-emission zones, and promotion of sustainable transportation, including electric buses and bicycles, could significantly improve air quality. Continuous air quality monitoring is essential for real-time assessments and policy effectiveness. Only through a collective and science-based approach can air quality improvement and public health protection be achieved in China.

INTRODUCTION

Air pollution poses a significant threat to human health and is considered the largest environmental issue globally. Additionally, it is a preventable factor leading to death and disease development. According to a WHO report (2021), air pollution is responsible for 7 million premature deaths annually, 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 ambient and indoor air pollution (Borrego et al. 2009). Air pollution typically arises from gaseous pollutants such as ozone, nitrogen dioxide, sulfur dioxide, and carbon monoxide. Additionally, particulate matter, particularly particles with a diameter of 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 levels. Conversely, outdoor particulate matter and ozone pollution experienced minimal changes.

By region, Africa showed the highest number of deaths per 100,000 people (180.9 deaths per year), followed by Southeast Asia (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 than for 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 seven 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 in these regions. This statistic encompasses individuals in Asia, Africa, Europe, and South America (WHO 2021). Air pollutants can be broadly categorized into two groups based on their origin: primary and secondary. Primary air pollutants 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). In contrast, 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, and poisonous gas that reacts slowly with other chemical compounds in 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 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 red blood 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 may 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 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, which allows 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 the airway muscles, resulting in immediate difficulty in breathing and coughing. Individuals with pre-existing lung diseases, such as asthma and chronic obstructive pulmonary disease (COPD), are particularly susceptible to worsening of their conditions, which may require hospitalization. Exposure to O_3, extending beyond eight hours, has different health consequences in different age groups (Chen et al. 2007).

Nitrogen oxides (NOx) are 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 (e.g., gas, oil, and coal). In urban environments, the transportation sector remains the main contributor to NOx emissions. Nitrogen dioxide (NO_2) 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 than adults. Additionally, research suggests that prolonged exposure to NO_2 during infancy and childhood may impair lung development, resulting in a lower lung capacity at maturity than those with minimal NO_2 exposure (Jonson et al. 2017).

Particulate matter (PM10 and PM2.5) poses significant health risks by damaging 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 birth and lower birth weight (Feng et al. 2016, Wang-Hsiang et al. 2017).

Sulfur oxides (SOx) are compounds that contain sulfur and oxygen. SO_2 emissions are derived 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 (e.g., 10 min) 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 are important components of PM2.5.

Air pollution in Pristina is a major issue that directly affects residents' health. The capital of Kosovo faces high levels of fine particulate matter (PM2.5 and PM10), primarily originating from heavy traffic, fossil fuel use for heating, and 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 disease.

This study aimed 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 was to identify pollution trends, understand their main sources, and examine their direct effects on public health. Through pollutant monitoring and epidemiological data analysis, this study seeks to provide evidence-based recommendations for more effective air quality management policies. This study will contribute to raising awareness among the public and responsible institutions about the importance of reducing pollution and improving environmental conditions in Pristina.

Fig. 1: Air Pollution in Pristina.

Fig. 2: Clean Air in Brezovica.

MATERIALS AND METHODS

The data used in this analysis were obtained from the Hydrometeorological Institute of Kosovo (IHMK-Air Quality Management Institution). The data assessed 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 were selected to analyze the impact of air pollution on environmental quality and public health. Pristina was chosen as a high-air-pollution area, whereas Brezovica served as a reference for a clean-air environment. Pristina is the capital and largest urban and industrial center of Kosovo, where air pollution is a major environmental issue. Pristina was selected as the study area 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, which 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. Respiratory and cardiovascular diseases are more frequent in Pristina due to prolonged exposure to air pollutants.

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 in comparison to a pristine environment. The selection of this location was based on its distance from pollution sources. Brezovica is a protected area far from industrial centers and high-traffic roads. The mountainous climate, dense forests, and absence of industrial pollutants ensure high air quality. Past measurements indicate that Pristina (Fig. 1) has high levels of PM10 and PM2.5, while Brezovica (Fig. 2) shows very low levels, making it an ideal area for comparison. In this study, data provided by the Institute of Hydrometeorology of Kosovo (IHMK 2024) were used to analyze the levels of the major air pollutants in Pristina. Air quality monitoring was performed using equipment certified according to European standards (EN), ensuring accurate and reliable measurements of pollutant concentrations. The carbon monoxide (CO) concentration was measured according to standard EN 14626 using non-dispersive infrared (NDIR) spectroscopy. This method allows for the precise detection of CO concentrations in the air and assessment of 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 fossil fuel combustion. Sulfur dioxide (SO_2) was analyzed according to EN 14212, using ultraviolet fluorescence, which provides an 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 the particle mass based on weighing filters after exposure to air. The data was statistically analyzed using GraphPad Prism version 7.05. Pearson's correlation coefficients were calculated to assess the relationships between air pollutant levels (PM10, PM2.5, NO_2, O_3, SO_2, and CO). The level of significance was set at $p < 0.05$ to ensure the statistical validity of the results.

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 the 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).

On February 7, 2024, the US Environmental Protection Agency (EPA, 2024) announced a new rule to strengthen national ambient air quality standards for fine particulate matter (PM2.5) or soot. EPA has set 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.

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 are presented in Tables 2, 3, 4, and 5 according to the years 2020-2023. The same results are expressed in Fig. 3.

Table 2 presents the annual average concentrations and the number of exceedances of the permitted limits for key air pollutants (PM10, PM2.5, NO_2, SO_2, O_3, and CO) in two locations, Pristina and Brezovica, for 2020. In Pristina, the concentrations of PM10 and PM2.5 were significantly higher than those in Brezovica, with PM10 reaching an annual average of 37.4 $\mu g.m^{-3}$ and PM2.5 at 24.0 $\mu g.m^{-3}$, whereas in Brezovica, these values were much lower, at 7.6 $\mu g.m^{-3}$ and 5.7 $\mu g.m^{-3}$, respectively. The number of exceedances of the -24h (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 the reduced anthropogenic influence. For NO_2, Pristina has an average of 26.0 $\mu g.m^{-3}$ with one exceedance per hour, whereas in Brezovica, the concentration is much lower at 1.5 $\mu g.m^{-3}$, indicating the impact of dense traffic and other combustion sources in urban areas. For SO_2, the values were lower at both locations, with an average of 11.0 $\mu g.m^{-3}$ in Pristina and 3.8 $\mu g.m^{-3}$ in Brezovica, suggesting a relatively limited impact from fossil fuel combustion sources. For O_3, Pristina has an average of 46.3 $\mu g.m^{-3}$ with three cases of exceedances of the -24hour limit, whereas Brezovica has a higher concentration of 92.4 $\mu g.m^{-3}$ 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 in primary pollutants that contribute to its breakdown in urban areas. For carbon monoxide (CO), the concentration in Pristina is 1.5 $mg.m^{-3}$, while in Brezovica, it is significantly lower at 0.3 $mg.m^{-3}$, reflecting the impact of traffic and combustion processes in urban areas. 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 degradation.

In the following years, according to the data in Tables 3, 4, and 5, there was a gradual decrease in pollution for some parameters, although not for all pollutants. In the subsequent year, the PM10 concentration in Pristina dropped to 33.8 $\mu g.m^{-3}$, and the number of exceedances fell to 62, reflecting a slight improvement, possibly due to environmental measures or climatic factors. The PM2.5 concentration also decreased to 21.1 $\mu g.m^{-3}$, although this change was not significant. In the next year, PM10 further declined to 32.6 $\mu g.m^{-3}$, with 61 instances of 24-h exceedances, while PM2.5 remained stable at 21.2 $\mu g.m^{-3}$, indicating a stabilization in pollution levels that still exceeded recommended norms.

For NO_2, the concentration in Pristina was 26.0 $\mu g.m^{-3}$ in 2020, but in the following years, it showed a significant decrease, reaching 16.8 $\mu g.m^{-3}$ in the last two years, suggesting a reduction in the impact of traffic and other urban sources. SO_2 showed a slight decrease in the first year after 2020, dropping from 11.0 to 7.6 $\mu g.m^{-3}$, but then rose again

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

Parameter	Locality	Average annual concentration	Exceedances 24 h	Exceedances 8 h	Exceedances1 h
PM10	Pristina	37.4 $\mu g.m^{-3}$	78		
PM2.5		24.0 $\mu g.m^{-3}$			
NO_2		26.0 $\mu g.m^{-3}$			1
SO_2		*11.0* $\mu g.m^{-3}$			
O_3		*46.3* $\mu g.m^{-3}$		3	
CO		*1.5 mg*.m-^{3}			
PM10	Brezovica	7.6 $\mu g.m^{-3}$	1		
PM2.5		5.7 $\mu g.m^{-3}$			
NO_2		1.5 $\mu g.m^{-3}$			
SO_2		*3.8* $\mu g.m^{-3}$			
O_3		*92.4* $\mu g.m^{-3}$		18	
CO		*0.3 mg*.m^{-3}			

to 9.9 μg.m^{-3}, suggesting variability influenced by industrial combustion sources or meteorological conditions.

Ozone in Pristina exhibited a consistent trend, with concentrations fluctuating between 46.3 and 47.6 μg.m^{-3} and a constant number of exceedances (approximately two). In Brezovica, ozone remained 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 owing 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 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, such as SO_2 and CO, have fluctuated owing to various influencing factors. In Brezovica, pollutant values remained lower for all substances except ozone, which continued to be higher because of the atmospheric characteristics of the mountainous area. However, despite the declining trend in some pollutants, the values remain above the permissible limits in Pristina, posing a risk to public health. Therefore, local authorities must implement 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 months being January, February, March, April, October, November, and December. The urban areas of the city should be declared as areas with a special

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 m*g.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}			

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

protected environment because the discharges of risk into the environment are several times higher than 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.

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

In contrast, Brezovica showed 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.

The analysis of the correlation between the main air pollutants in Pristina and Brezovica revealed significant differences in air quality between the two locations. Pristina, an urban area with high pollution, is characterized by intensive sources of pollution, such as traffic, industry, and construction, whereas Brezovica, a mountainous area with clean air, is minimally affected by these factors. The correlation between pollutant concentrations in these two areas helps us 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 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, whereas Brezovica remains a clean area owing 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) showed a moderate positive relationship between the two locations. NO_2 is a gaseous pollutant that can be transported by wind, and meteorological conditions can influence its distribution over long distances. This indicates that some pollution from Pristina may partially affect the air quality in Brezovica, although the concentrations in this mountainous area remain much lower. The correlation value for ozone was nearly zero (r = -0.05), indicating the lack of a relationship between the concentrations of this pollutant in Pristina and Brezovica. O_3 is not a primary pollutant but is created through atmospheric reactions related to the presence of NO_2 and sunlight. This indicates 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 SO_2 was negative and relatively strong (r = -0.56), indicating a clear distinction between high pollution in Pristina and very low concentrations in Brezovica. SO_2 is a pollutant primarily associated with the burning of fossil fuels, particularly in power plants and industries. The presence of this pollutant in Pristina is high, whereas Brezovica, a mountainous area without large industrial sources, has minimal or negligible concentrations. The correlation coefficient for CO (r = -0.63) was 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 combustion of fossil fuels, particularly in 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 from the urban areas. The results of the correlation analysis confirmed 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-h average. When we breathe polluted air, many particles enter the respiratory system. However, the deposition of particles in different regions of the pulmonary system depends on the particles. Fig. 4 shows the deposition fractions of particles in the pulmonary system and the interior of the particles. Different amounts of particulate matter (nanoparticles and microparticles) are deposited in each part of the respiratory tract. Air pollutants become a danger to human health after entering and passing through the pulmonary system. These particles can diffuse through the lung and lung barriers into the blood and affect the normal functions of the human body. For example, blood vessel blockage can lead to complications in the brain (Xu et al. 2017).

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

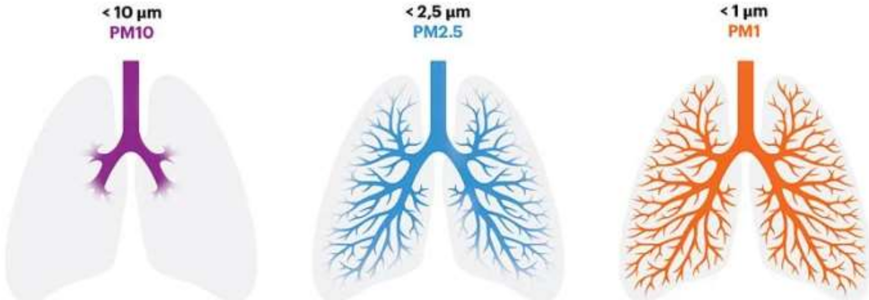

Fig. 4. Smaller particles can penetrate deeper into the lungs.

the lungs, reaching the terminal bronchioles and pulmonary alveoli. They can cause significant inflammation, increase oxidative stress, and have negative effects on lung function. Studies have shown 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) is the smallest and most dangerous particle, as it can pass through the alveolar barrier and enter the bloodstream. They directly affect the cardiovascular system by causing systemic inflammation and atherosclerosis and increasing the 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 the carcinogenic potential. The smaller the particles, the deeper they penetrate 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 & Dockery 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 several health problems in the general population. The effects of air pollution often occur in varying degrees, from subclinical effects to an increased risk of premature death. Some of these effects include an increase in respiratory diseases, including bronchiolitis, rhinopharyngitis, and bronchial hypersecretion, which affect the quality of breathing and overall health of the airways. Degraded respiratory function includes 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. Increased cardiovascular disease, including the risk of heart disease and hypertension, is closely related to the quality of the air we breathe. It has a 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. The impact on long-term mortality 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 regarding public health and the environment in general. With a continued increase in economic activity and energy demand, 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 raises serious concerns for public health and environmental health, as air pollution is closely related to many health problems. On a practical level, it is important for each country to monitor and limit the emissions of common air pollutants, such as PM10, PM2.5, carbon monoxide, nitric oxides (NOx), and sulfur dioxide (SO_2). The half-lives of PM10 and PM2.5 particles in the atmosphere are quite long, and they can be transferred and spread over long distances, where people can be exposed (Wilson & Suh 1997). These fine particles are the main cause of the formation of "fog" in different cities.

Numerous studies have shown that approximately 8% of global deaths are directly related to ambient air pollution (Hsu et al. 2017, Pozzer 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 cause 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). Fang and Lakey (Fang et al. 2019, Lakey et al. 2016) emphasized the role of organic and inorganic compounds of PM2.5 in promoting the production of ROS, which then results in biomolecular injuries. Oxidative stress

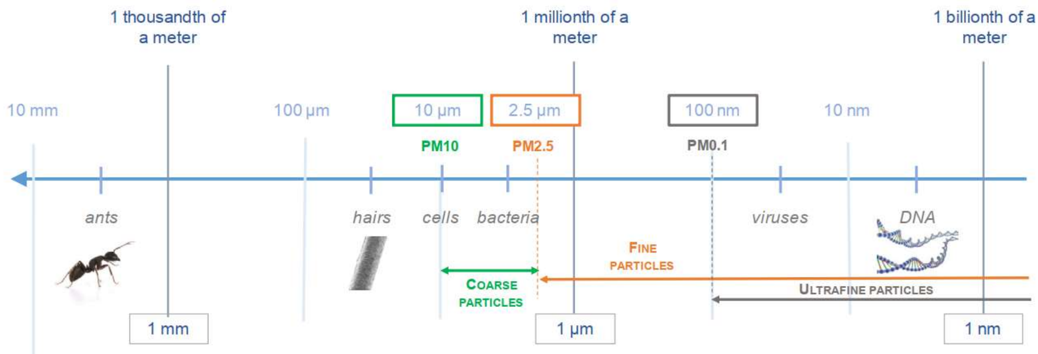

Fig. 5: Relative size of particles PM10, PM2.5.

arises from an imbalance between the production of ROS and the body's antioxidant defense mechanisms. The human body creates both enzymatic and non-enzymatic antioxidant defenses, which play a crucial role in mitigating the harmful effects of ROS. Zeng et al. (2018) emphasized the importance of these defenses in neutralizing ROS and preserving the cellular environment. However, prolonged exposure to these particulate matters 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).

The results of air contamination in Pristina align with those of similar studies, such as that conducted in Chiangmai, Thailand (Piyavadee et al. 2024), where temperature and rainfall significantly influenced air pollutant concentrations. In Pristina, high levels of PM10 and NO_2 have been recorded, particularly during the 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 under 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 Chiang Mai.

A 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 the major sources of pollution. Furthermore, the findings from Cape Town highlighted the impact of seasonal variations, with pollution levels peaking during winter owing to stable atmospheric conditions that prevent pollutant dispersion. This pattern aligns with the 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), which are created as a result of the oxidation of nitric oxide by ozone. Nitrogen dioxide is a byproduct of combustion reactions and is usually produced during the burning of fossil fuels in power plants. In Kosovo, especially in Pristina, NO_2 comes from the operation of thermal power plants, and a large part also comes from the discharge of gases from motor vehicles. Nitric oxide at low levels is an important molecule in human cells, but it is highly toxic when its concentrations increase in the atmosphere. Prolonged exposure to nitrogen dioxide can cause breathing problems in older adults and pregnant women (WHO 2021). Nitric oxide (NO) is a gaseous irritant of the respiratory system. It can enter the lungs and cause breathing difficulties, coughing, dyspnea, bronchospasm, and pulmonary edema. In cases where NO concentrations are higher than 2.0 ppm, it can also affect the immune system by attacking T lymphocytes, particularly CD8+ and natural killer (NK) cells (Chen et 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. The ozone values in our research areas were within the normal range. In most cases, these values result from reactions between nitric oxide and volatile organic compounds (such as hydrocarbons present in gasoline). Ozone causes problems in the upper skin layers. A study conducted on mice exposed to high levels of ozone showed that malondialdehyde formation was stimulated in the upper part of the skin (epidermis);

however, a decrease in vitamins C and E was also recorded (Thiele et al. 1997).

The values of sulfur dioxide (SO_2) recorded in Pristina have, in many cases, exceeded the normal values. SO_2 is a gas produced by burning sulfur-containing fuels such as coal and diesel. It can also be discharged into the atmosphere through natural processes, such as organic decomposition or volcanic eruptions; however, 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 harm the respiratory system (WHO 2021). High 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 that 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 individuals exposed to high levels of carbon monoxide. Long-term exposure to carbon monoxide for a long period of time can cause hypoxia, ischemia, and cardiovascular disease. Acute symptoms of carbon monoxide poisoning include headache, dizziness, weakness, nausea, vomiting, and 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 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) and other pollutants such as CO, NO_2, and SO_2 have frequently surpassed the safety thresholds set by the 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 often exceed these limits, posing a risk to the health of residents, especially those suffering from respiratory and cardiovascular diseases. Additionally, the concentrations of NO_2 and CO often surpassed the recommended limits for health protection, which are set to reduce the risk of lung and heart diseases. This is 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 for the future. The comparative analysis between Pristina and Brezovica over the period 2020–2023 confirmed that Pristina consistently experiences significantly higher concentrations of air pollutants, particularly PM10, PM2.5, and NO_2. These pollutants are primarily linked to traffic emissions, fuel combustion, and industrial activities, and their impact is more severe during 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 (O_3), tend to form more readily owing to photochemical reactions. The findings suggest an ongoing and persistent air pollution problem in Pristina that 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 is essential for assessing pollution trends, evaluating the effectiveness of implemented policies, and guiding future strategies. Overall, addressing air pollution in Pristina necessitates a coordinated, science-based approach involving policymakers, environmental agencies, and the public. Only through such collective efforts can significant improvements be achieved, leading to healthier and more sustainable urban environments.

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