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Influence of meteorological parameters on particulate matter ($PM_{2.5}$ and PM_{10}) concentrations in Prishtina, Kosovo

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ABSTRACT

Air pollution remains one of the most pressing environmental challenges in rapidly urbanizing cities of the western Balkans, where meteorological variability strongly modulates pollutant dispersion. This study investigates the relationship between particulate matter ($PM_{2.5}$ and PM_{10}) and key meteorological parameters in Prishtina, Kosovo's capital, during 2023 providing the first comprehensive year-long analysis that integrates multivariate and principal component approaches for this region. Using daily data on temperature, relative humidity, wind speed, and air pressure, correlation analyses and principal component analysis (PCA) were applied to identify dominant atmospheric controls on particulate concentrations. The findings revealed that higher temperatures and stronger winds reduce $PM_{2.5}$ and PM_{10} levels, while cold and stagnant winter conditions coincide with substantial increases in pollution, largely driven by lignite-based power generation, domestic heating and vehicle emissions. The results validate the critical influence of meteorological dynamics on air quality in Prishtina and underscore the need for targeted emission reduction strategies and adaptive environmental policies aimed at mitigating seasonal air pollution episodes.

Keywords: air quality dynamics; atmospheric dispersion; correlation analysis; principal component analysis; urban pollution assessment; western Balkans.

INTRODUCTION

Air quality in urban environments is an increasingly concerning issue, influenced by socioeconomic activities, industrial development, and meteorological conditions. Natural factors such as topography and climatic variability affect both the concentration and dispersion of pollutants. Air pollution has become a global challenge, contributing to both short-term and long-term environmental and health impacts (Nakyai et al., 2024). Over the past two decades, this problem has intensified due to accelerated urbanization, population growth, and energy demand, particularly in developing and transition economies.

Early research identified industrial activities, vehicular emissions, and agricultural practices as primary sources of pollution (Holman, 1999). Since then, numerous studies have demonstrated that meteorological parameters play a crucial role in determining outdoor air quality (Manju et al., 2018; Dung et al., 2019; Fang et al., 2024). Among these parameters, air temperature, humidity, and wind speed are especially influential, with their effects most pronounced during winter months (Zender-Świercz et al., 2024, Arslan & Toltar, 2023). Studies conducted in Asia and Europe (Fang et al., 2024; Zender-Świercz et al., 2024; Yang et al., 2017) demonstrate that thermal conditions and humidity govern the seasonal variability of particulate concentrations.

According to the World Health Organization (WHO), about 4.2 million premature deaths occur annually worldwide due to outdoor air pollution

(Barnett-Itzhaki & Levi, 2021). Similarly, the European Environment Agency (EEA) reports that nearly 96% of the EU's urban population is exposed to unsafe concentrations of fine particulate matter ($PM_{2.5}$) (Targa et al., 2024). The World Bank report estimates that around 760 people in Kosovo die prematurely each year due to air pollution (AAP), with about 11% of the burden in Prishtina. In winter, air pollution contributes not only to long-term mortality but also to acute health impacts, including more cardiovascular and respiratory hospitalizations and increased lost workdays. These short-term effects cannot be estimated due to insufficient baseline morbidity data (World Bank, 2019). This persistent exposure highlights the need to understand how meteorological variability interacts with pollutant concentrations to support evidence-based environmental policies.

At the regional scale, air pollution remains a critical environmental and public health issue across the Balkans. Variations in pollutant concentrations are influenced by both seasonal changes and meteorological conditions. In many Balkan cities, urban construction, heavy vehicular traffic, and solid fuel combustion contribute significantly to elevated pollution levels. Such conditions reflect the combined impact of anthropogenic sources and adverse meteorological phenomena, including temperature inversions and stagnant air masses typical of continental basins.

High pollution episodes are generally associated with densely populated urban centers that experience limited atmospheric dispersion (Neubauer et al., 2020). Several studies have demonstrated strong relationships between particulate matter (PM_{10} and $PM_{2.5}$) and meteorological parameters in Southeastern Europe, for example, in Albania (Hysenaj & Duraj, 2021; Baraj et al., 2025), North Macedonia (Manevska et al., 2025), Montenegro (Zaric et al., 2021), Greece (Maraziotis et al., 2013) etc. These studies show that temperature, wind speed, and humidity act as dominant modulators of PM variability. However, despite the growing number of investigations across Europe, comprehensive analyses integrating meteorological factors with $PM_{2.5}$ and PM_{10} dynamics are still scarce in Kosovo.

Prishtina, Kosovo's capital and largest city, represents a particularly critical case due to its geographical position, dense traffic, and reliance on lignite-fired thermal power plants located nearby. About 97% of the country's electricity is generated from lignite combustion, while most households still depend on wood or coal for heating (Kabashi et al., 2011; Bajçinovci, 2019). It is estimated that the city experienced around 130,000 vehicle movements per day in 2023, contributing substantially to atmospheric particulate emissions. These anthropogenic pressures, combined with Prishtina's basin-like morphology, create conditions favorable to pollutant accumulation, particularly during winter inversion events.

Although air quality monitoring in Prishtina began in 2009 and has expanded in recent years, previous studies have primarily presented descriptive results without quantifying meteorological influence (Hajrizi et al., 2023). Unlike those works, the present study applies a correlation-based and multivariate analytical framework, including Principal Component Analysis (PCA), to evaluate the role of meteorological factors in particulate matter dynamics. This approach provides the first year-long, data-driven assessment of $PM_{2.5}$ and PM_{10} relationships with atmospheric variables in Prishtina, offering new insights into the meteorological mechanisms governing air pollution in Kosovo's urban environments.

MATERIALS AND METHODS

Study area

Prishtina, the focus of this study, is located in the eastern sector of the Kosovo Plain (Figure 1). Given its geographic setting, population density, and industrial activity, the city provides a representative case for analyzing the interaction between meteorological conditions and air quality in the Western Balkans.

The "Rilindja" air quality monitoring station, used in this study, is situated in the city center at coordinates 42°39′35″ N and 21°09′24″ E, with an elevation of 583 m a.s.l. (Figure 1). From a geomorphological perspective, Prishtina lies along the tectonic and morphographic boundary between the mountainous terrain to the east and the flat plains to the west. This topographic contrast influences local airflow patterns and temperature distribution, both of which affect pollutant dispersion.

The city's topography is intersected by small valleys and low ridges extending mainly in a

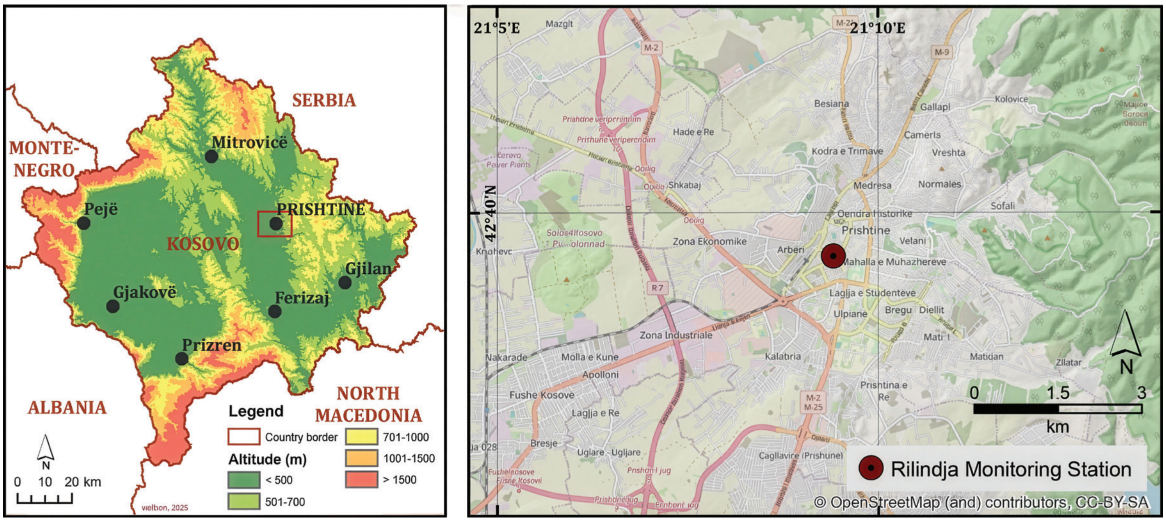

Figure 1. Location of Prishtina

west–east orientation. Such morphological features, combined with frequent winter temperature inversions, often lead to limited atmospheric mixing and pollutant accumulation. Cold and humid winters remain a major meteorological challenge, while summers are typically hot and dry.

According to the 2024 census, Prishtina had 145,149 permanent residents, making it the largest and most rapidly expanding urban area in Kosovo. As the national capital, it hosts the central government institutions, universities, hospitals, and major service sectors. Over the past two decades, the city has experienced intense construction and rapid population growth, resulting in increased vehicular emissions and pressure on urban infrastructure. Land-use transformation is characterized by a notable increase in artificial surfaces (Bytyqi et al., 2024), while its eastern part remains covered by the deciduous forests of Gërmia, a designated protected nature park (Berisha et al., 2025).

The city's climate is classified as humid continental, characterized by distinct seasonal contrasts with cold winters and warm summers. The average annual air temperature during the 2014–2023 period was 11.9°C, while in 2023 it rose to 12.6°C, indicating a gradual warming trend consistent with broader regional climate observations. Mean annual precipitation over the same decade was 726 mm, with a total of 856.7 mm recorded in 2023. These climatic characteristics, together with the city's enclosed valley location, make Prishtina particularly sensitive to air stagnation and pollutant buildup during winter months, especially during air inversion.

Data

This study employed daily datasets on particulate matter concentrations ($PM_{2.5}$ and PM_{10}) and key meteorological variables for the year 2023. Air quality data were obtained from the official e-Kosova portal (airqualitykosova.rks-gov.net), which provides continuous monitoring information from the "Rilindja" urban monitoring station located in the city center of Prishtina. The database contains hourly, daily, and monthly values of $PM_{2.5}$ and PM_{10} concentrations recorded throughout the year.

To ensure data completeness and accuracy, short missing intervals (up to seven consecutive days) were interpolated using linear and moving average techniques. All records were verified for consistency, screened for outliers, and compiled into daily mean values.

Meteorological data for the same period were obtained from the Hydrometeorological Institute of Kosovo (HMIK, 2023), as published in the Hydrometeorological Yearbook 2023. The parameters analyzed include daily mean air temperature (°C), relative humidity (%), precipitation (mm), maximum wind speed (m s^{-1}), and air pressure (mb), all measured on a daily basis (Table 1).

All datasets were organized and processed using Microsoft Excel 2021 and Analyse-it. Descriptive statistical analyses, including the calculation of mean, median, standard deviation, range, maximum, and minimum values, were performed to summarize the temporal variability of both particulate concentrations and meteorological parameters before proceeding to correlation and multivariate analyses.

Descriptive statistics of particulate matter and meteorological parameters for 2023 are summarized in Table 1, providing an overview of the data distribution used in the subsequent correlation and multivariate analyses.

Correlation analysis

To assess the statistical relationships between variables, three correlation techniques were applied: Pearson's correlation coefficient (r) to measure linear relationships, Spearman's rank correlation (ρ) for monotonic associations, and Kendall's tau (τ) for ordinal correlations. These coefficients quantify the direction and strength of associations between $PM_{2.5}$, PM_{10}, and the selected meteorological variables air temperature, relative humidity, wind speed, and air pressure. The interpretation of correlation strength followed standard thresholds: $|r| \geq 0.7$ indicates a strong correlation, 0.4–0.69 a moderate correlation, 0.2–0.39 a weak correlation, and <0.2 a negligible relationship. Negative values signify inverse associations, where an increase in one parameter corresponds to a decrease in the other.

Correlation matrices and scatterplot diagrams were generated to visualize the interactions between particulate matter concentrations and meteorological variables, enabling both quantitative and graphical interpretation of results.

Multivariate and principal component analysis

To identify the dominant factors influencing particulate matter concentrations, principal component analysis (PCA) was performed. PCA is a statistical method that transforms correlated variables into a smaller set of uncorrelated components (principal components), thus reducing data dimensionality while retaining most of the original variance.

Before applying PCA, all variables were standardized to Z-scores to ensure comparability by removing scale differences among units. Components with eigenvalues greater than 1 were retained, and their cumulative variance contribution was evaluated. The first two principal components (PC_1 and PC_2), explaining the largest proportion of total variance, were used for interpretation. A biplot was constructed to visualize the correlations between particulate matter and meteorological parameters. The length and orientation of vectors in the biplot represent the strength and direction of relationships among variables.

This combined approach, integrating correlation analysis with PCA, allowed for both pairwise and multivariate assessment of how temperature, humidity, wind speed, and air pressure influence $PM_{2.5}$ and PM_{10} dynamics in Prishtina.

Statistical and air quality classification procedures

In addition to correlation and PCA, several complementary statistical procedures were conducted to strengthen data interpretation and ensure analytical consistency.

A multivariate regression analysis was applied to assess the combined effects of meteorological parameters on $PM_{2.5}$ and PM_{10} concentrations, allowing the identification of key predictors contributing to particulate variability. A scatterplot matrix was generated to visualize the pairwise relationships among variables and to examine the distribution patterns and potential collinearity within the dataset.

Prior to the correlation and regression analyses, descriptive statistics were calculated, including the mean, median, standard deviation, range, minimum, and maximum values for each parameter, to summarize the general characteristics of the data.

Furthermore, the European Environment Agency (EEA) air quality classification was

Table 1. Descriptive statistics of analysed parameters for the year 2023

Parameter	PM_{10} (μg m⁻³)	$PM_{2.5}$ (μg m⁻³)	Daily mean temp. (°C)	Relative humidity (%)	Rainfall (mm)	Max. wind speed (m s⁻¹)	Air pressure (mb)
Mean	41.4	27.6	12.6	77.1	2.3	3.2	1014.6
Median	30.3	17.9	13.3	78.0	0.0	2.9	1014.4
Stand. dev.	35.3	27.4	8.0	11.4	6.3	2.3	7.2
Maximum	218.2	171.1	28.4	100.0	62.4	12.9	1043.9
Minimum	6.8	4.7	-6.0	46.0	0.0	0.0	996.4
Rang	211.4	166.4	34.4	54.0	62.4	12.9	47.4

applied to categorize daily $PM_{2.5}$ and PM_{10} concentrations into six classes: good, fair, moderate, poor, very poor, and extremely poor. This classification provided a standardized framework for evaluating daily and seasonal air quality fluctuations in relation to meteorological conditions.

RESULTS

Meteorological parameters and their correlation

Prishtina has a continental climate, characterised by cold winters and hot summers. The 10-year average air temperature in the city was 11.9 °C, while 2023 was notably warmer, with an annual mean temperature of 12.6 °C. The mean annual relative humidity was 77%. In 2023, the lowest daily mean air temperature recorded in Prishtina was –6.0 °C (on 5 February 2023), and the highest daily mean temperature was 28.4 °C (on 25 July 2023). In absolute terms, the minimum temperature was –11.5 °C (11 February 2023), and the maximum temperature was 37.4 °C (25 July 2023). Meteorologically, temperature distribution throughout the year showed considerable variability. These data confirm the city's distinctly continental climate regime, with pronounced seasonal contrasts. The relatively high number of days within the 15–25 °C range indicates prolonged warm periods, while the presence of low winter temperatures highlights conditions favourable to thermal inversion events factors that significantly influence air pollutant dispersion and accumulation in Prishtina.

Relative humidity in 2023 averaged 77% with a standard deviation of 11.4%, showing moderate temporal variability. Monthly mean values were highest in winter (up to ~90% in January) and lowest in mid-summer (~69% in July–August). High-humidity days (>80%) were concentrated mainly in the colder months, coinciding with temperature inversions and limited atmospheric mixing (Figure 2). These findings confirm that

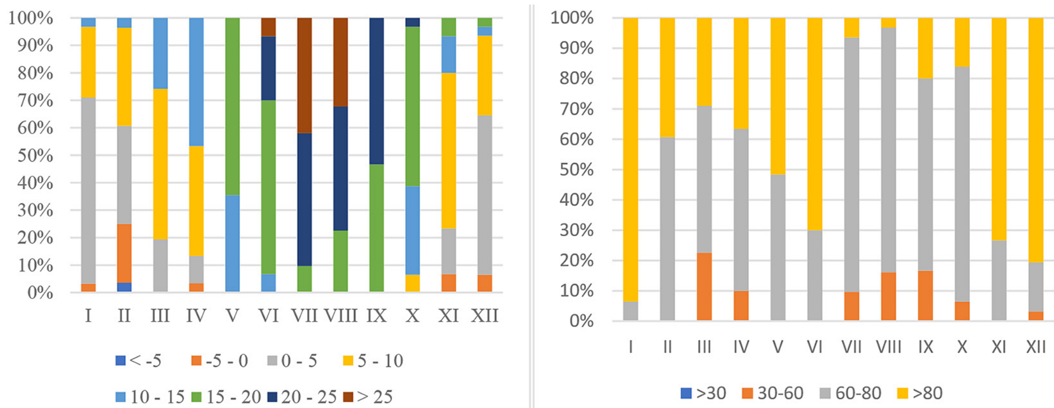

Figure 2. Frequency distribution of mean air temperature and relative humidity during 2023

Table 2. Correlation matrix between meteorological parameters

Parameter	Relative humidity	Daily average temp.	Air pressure	Max. wind speed	
Relative humidity	-	-0.485	0.096	-0.130	Pearson's r
	-	-0.498	0.073	-0.107	Spearman's rs
	-	-0.350	0.049	-0.072	Kendall's tau
Daily average temp.	-0.485	-	-0.382	0.011	
	-0.498	-	-0.332	0.043	
	-0.350	-	-0.225	0.024	
Air pressure	0.096	-0.382	-	-0.241	
	0.073	-0.332	-	-0.242	
	0.049	-0.225	-	-0.167	
Max. wind speed	-0.130	0.011	-0.241	-	
	-0.107	0.043	-0.242	-	
	-0.072	0.024	-0.167	-	

Prishtina's winter climate conditions cold and humid with calm winds create an atmospheric environment that favors pollutant accumulation.

Correlations among meteorological parameters were analysed to describe the interactions between key atmospheric variables in Prishtina during 2023, including daily mean air temperature (°C), relative humidity (%), air pressure (mb), and maximum wind speed (m s^{-1}). The results (Figure 2; Table 2) reveal that temperature and humidity are moderately inversely related ($r = -0.485$), whereas air pressure and relative humidity show a weak positive association ($r = 0.096$). Wind speed is weakly and inversely related to both humidity and pressure, indicating that calmer conditions generally coincide with higher humidity. These interactions among meteorological parameters illustrate the atmospheric setting that governs pollutant dispersion in Prishtina.

Correlation of $PM_{2.5}$ values with meteorological parameters

$PM_{2.5}$ concentrations throughout 2023 showed clear temporal variability, with elevated levels during the colder months and lower concentrations during the warmer period. The annual mean $PM_{2.5}$ concentration was 27.6 µg m^{-3}, with a standard deviation of 27.4, reflecting pronounced inter-daily and seasonal fluctuations. Meteorological parameters were identified as significant modulators of $PM_{2.5}$ variability, with daily mean air temperature and relative humidity exerting the most substantial influence on air quality dynamics in Prishtina.

$PM_{2.5}$ levels displayed distinct seasonal variability, peaking during winter and reaching minimum values in summer. Frequency analysis indicated that most daily concentrations fell within

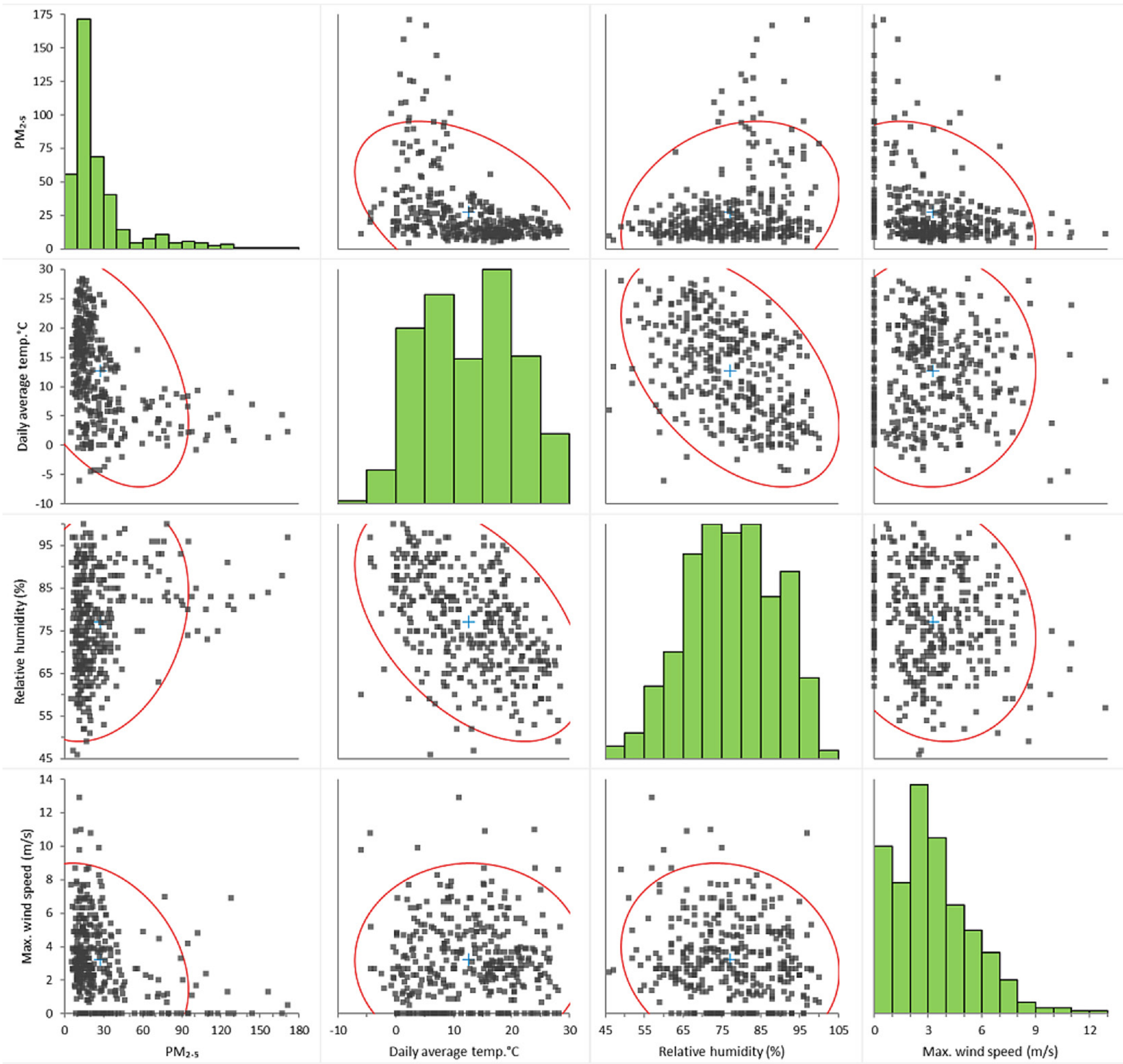

Figure 3. Correlation of $PM_{2.5}$ values with meteorological parameters

the 10–20 μg m^{-3} range, consistent with the predominance of "fair" to "moderate" air quality conditions during the warmer months. In contrast, high pollution episodes were concentrated during November–January, when low temperatures and high relative humidity prevailed (Figure 3). These results confirm that cold, stagnant atmospheric conditions favor the accumulation of fine particulates in the city.

The correlation analysis (r = –0.444) confirmed a moderate inverse relationship between daily mean temperature and $PM_{2.5}$ concentrations (Table 3; Figure 3). This indicates that as air temperature increases, $PM_{2.5}$ concentrations tend to decrease. Monthly trends showed that elevated $PM_{2.5}$ levels coincided with lower temperatures, particularly during winter months (November–January), whereas higher temperatures during summer corresponded to improved air quality conditions. These patterns reflect the strong seasonal dependence of particulate accumulation in Prishtina's atmosphere.

$PM_{2.5}$ concentrations displayed a clear seasonal pattern at the "Rilindja" monitoring station in Prishtina. Monthly averages decreased from January (31.6 μg m^{-3}) to July (11.4 μg m^{-3}) and increased again toward December, reaching a maximum of 90.8 μg m^{-3}. Low concentrations (≤20 μg m^{-3}) corresponding to "good" or "fair" air quality dominated the warm months, while "poor" to "extremely poor" categories prevailed in winter, particularly in December and November (Figure 4). These findings confirm a pronounced inverse seasonal pattern in particulate levels, with cleaner summer conditions and severely degraded air quality during winter.

The maximum daily $PM_{2.5}$ concentration reached 171 μg m^{-3} on 31 December 2023,

Table 3. Correlation matrix between $PM_{2.5}$ and PM_{10} concentrations with meteorological parameters

Parameter	PM_{10}	$PM_{2.5}$	Daily average temp.	Relative humidity	Max. wind speed	Correlation
PM_{10}	-	0.955	-0.327	0.130	-0.295	Pearson's r
	-	0.906	-0.259	0.007	-0.275	Spearman's rs
	-	0.751	-0.171	0.008	-0.184	Kendall's tau
$PM_{2.5}$	0.955	-	-0.444	0.252	-0.317	
	0.906	-	-0.481	0.196	-0.308	
	0.751	-	-0.318	0.135	-0.211	
Daily average temp.	-0.327	-0.444	-	-0.485	0.011	
	-0.259	-0.481	-	-0.498	0.043	
	-0.171	-0.318	-	-0.350	0.024	
Relative humidity	0.130	0.252	-0.485	-	-0.130	
	0.007	0.196	-0.498	-	-0.107	
	0.008	0.135	-0.350	-	-0.072	
Max. wind speed	-0.295	-0.317	0.011	-0.130	-	
	-0.275	-0.308	0.043	-0.107	-	
	-0.184	-0.211	0.024	-0.072	-	

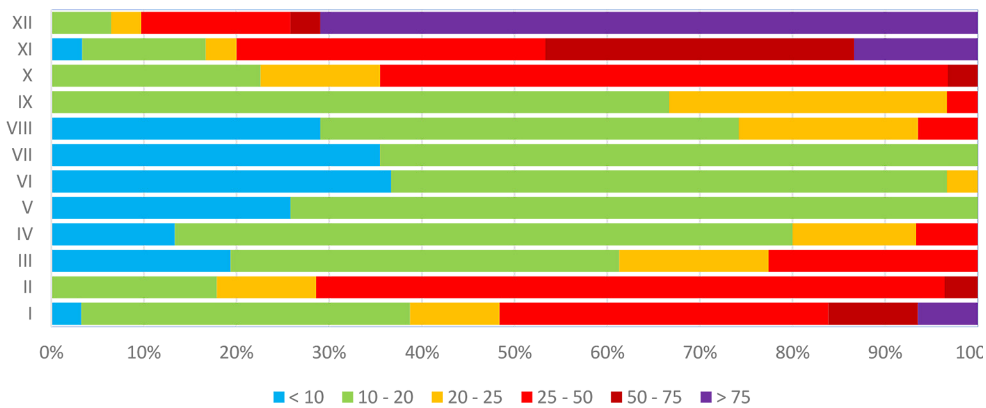

Figure 4. Frequency of days with $PM_{2.5}$ categories during 2023

classified as "extremely poor" under the AQI. This episode coincided with calm, cold, and humid meteorological conditions (mean temperature 2.3°C, relative humidity 97%, maximum wind speed 0.5m s^{-1}, and atmospheric pressure 1022.9 mb). Elevated PM_{10} concentrations were also recorded on the same day (212.2 μg m^{-3}), confirming severe air pollution across particulate fractions.

Time-series analysis revealed that poor-to-extremely-poor air quality episodes occurred predominantly in winter, lasting several hours to multiple days. The longest continuous event persisted for about 90 hours in December, followed by 86 hours in January and 43 hours in February. These multi-day episodes typically developed under nocturnal inversion conditions with low wind speeds and high humidity, highlighting the persistence of stagnant winter atmospheres over Prishtina.

Correlation of PM_{10} values with meteorological parameters

PM_{10} concentrations exhibited substantial seasonal and daily variability. Annual mean levels reached 41.3 μg m^{-3} (median 30.3 μg m^{-3}), exceeding WHO guidelines. The minimum concentration (6.8 μg m^{-3}) occurred on 28 March 2023, while the maximum (218.2 μg m^{-3}) was observed on 5 December 2023 under cold, humid, and calm meteorological conditions (mean temperature 1.4°C, relative humidity 84 %, maximum wind speed 1.3 m s^{-1}, and pressure 1014.4 mb). Seasonal analysis showed that winter months recorded the highest mean concentrations (up to 123 μg m^{-3} in December), whereas summer levels remained low and stable (minimum 18.1 μg m^{-3} in June).

Based on the Air Quality Index (AQI), 242 days (≈ 66% of the year) were classified as

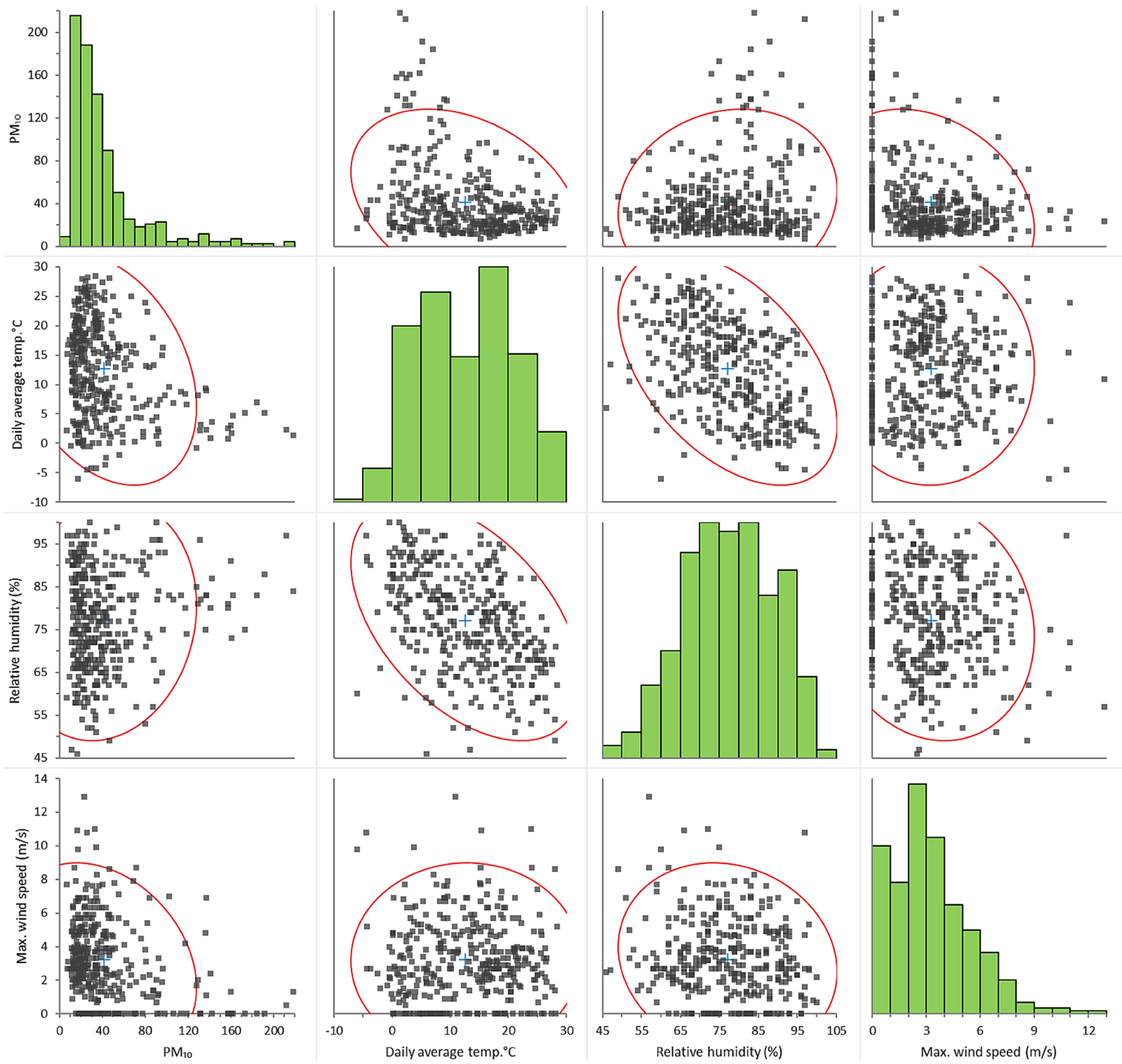

Figure 5. Correlation of PM_{10} values with meteorological parameters

"good" or "fair," mainly during the warm season. In contrast, "poor" to "extremely poor" categories occurred predominantly in late autumn and winter, with December and November showing the highest frequency of polluted days. These results demonstrate a pronounced seasonal contrast between clean summer conditions and degraded winter air quality (Figure 5).

The temporal co-variation between PM_{10} concentrations and mean daily air temperature is shown in Figure 6, illustrating their clear inverse relationship. PM_{10} levels rise sharply during colder months and decline with increasing temperatures, confirming the temperature-dependent nature of coarse particulate accumulation in Prishtina.

Table 3 presents the correlation coefficients between PM_{10} concentrations and the main meteorological parameters daily mean air temperature, relative humidity, and maximum wind speed calculated using Pearson, Spearman, and Kendall correlation tests. The results show a moderate negative correlation between PM_{10} and air temperature, a moderate negative correlation with wind speed, and a weak positive correlation with relative humidity. These patterns indicate that cold and calm atmospheric conditions favor particulate accumulation, whereas warmer and windier weather enhances the dispersion of coarse particles in Prishtina's urban atmosphere.

Similar to $PM_{2.5}$, PM_{10} concentrations also show a pronounced seasonal pattern (Figure 7). During the summer months, PM_{10} levels are low, with a mean of 22.8 μg m^{-3}, whereas in the winter months, the mean concentration increases to 67.2 μg m^{-3}.

Correlation analysis (Table 3) revealed a moderate inverse relationship between PM_{10} concentrations and mean air temperature (r = –0.327), indicating reduced particle levels during warmer periods. A similar negative association was observed with wind speed (r = –0.295), highlighting the role of air movement in dispersing coarse particulates. Relative humidity exhibited a weak positive correlation (r = 0.130), suggesting limited direct influence on PM_{10} variability. Collectively, these results show that higher temperatures and stronger winds favor lower PM_{10} concentrations in Prishtina.

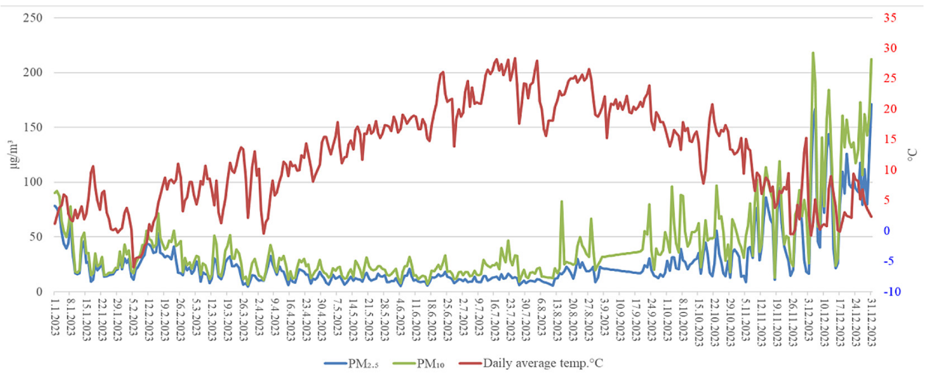

Figure 6. The relationship between mean daily air temperature with $PM_{2.5}$, and PM_{10} concentrations during 2023

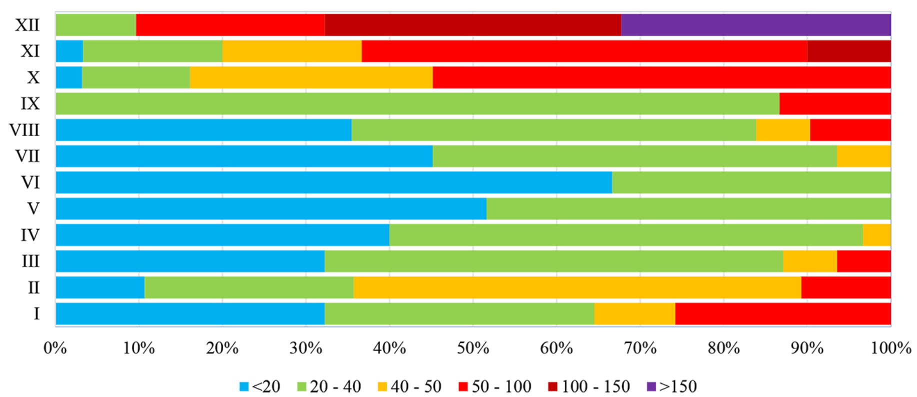

Figure 7. Distribution of days across PM_{10} air quality categories in 2023

Principal component analysis

To identify the dominant meteorological controls on particulate concentrations, a principal component analysis was performed using standardized variables for $PM_{2.5}$, PM_{10}, air temperature, relative humidity, maximum wind speed, and air pressure. The first two principal components (PC_1 and PC_2) explained 63.7% of the total variance. PC_1 (43.8%) was mainly associated with air temperature and wind speed, while PC_2 (19.9%) reflected relative humidity and air pressure.

The PCA biplot (Figure 8) displays the orientation of variable vectors. Temperature and wind speed point opposite to $PM_{2.5}$ and PM_{10}, confirming their inverse relationships, whereas humidity and air pressure align in the same direction as particulate matter, indicating positive associations. The clustering of $PM_{2.5}$ and PM_{10} vectors within the same quadrant demonstrates their shared emission sources and similar atmospheric behaviour.

Figure 8 demonstrate that the spatial distribution of variables along the first two principal components (PC_1 = 43.8% and PC_2 = 19.9%). The horizontal axis (PC_1) separates parameters linked to thermal and dynamic dispersion processes air temperature and wind speed from those associated with stagnation and accumulation conditions $PM_{2.5}$, PM_{10}, humidity, and pressure. The vertical axis (PC_2) distinguishes humidity-related variability from pressure-related effects. Vectors for temperature and wind speed extend in the opposite direction to $PM_{2.5}$ and PM_{10}, confirming that higher temperatures and stronger winds correspond to lower particulate concentrations. Conversely, relative humidity and air pressure project toward the same quadrant as $PM_{2.5}$ and PM_{10}, suggesting that moist and stable air masses favor pollutant accumulation. The close proximity of $PM_{2.5}$ and PM_{10} vectors confirms their common emission origins and synchronous atmospheric behavior.

Topographic setting and inversion conditions relevant to air pollution accumulation

To complement the statistical analyses, the physical setting of Prishtina and its surrounding area was examined to visualize the meteorological

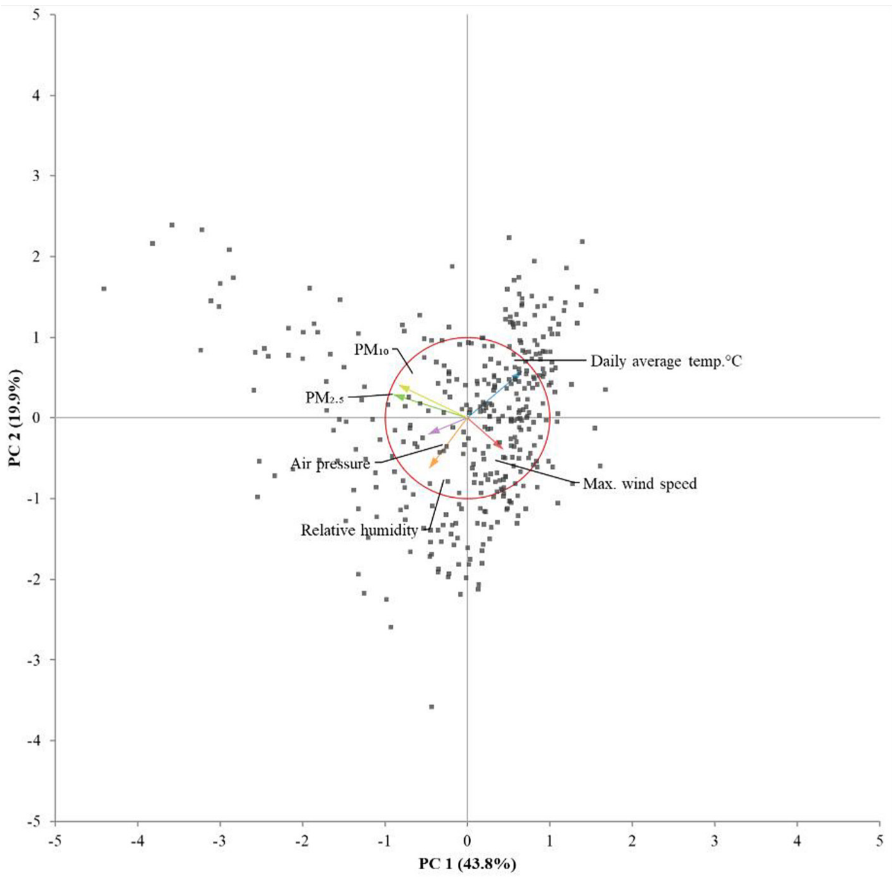

Figure 8. PCA biplot of $PM_{2.5}$/PM_{10} values and meteorological parameters

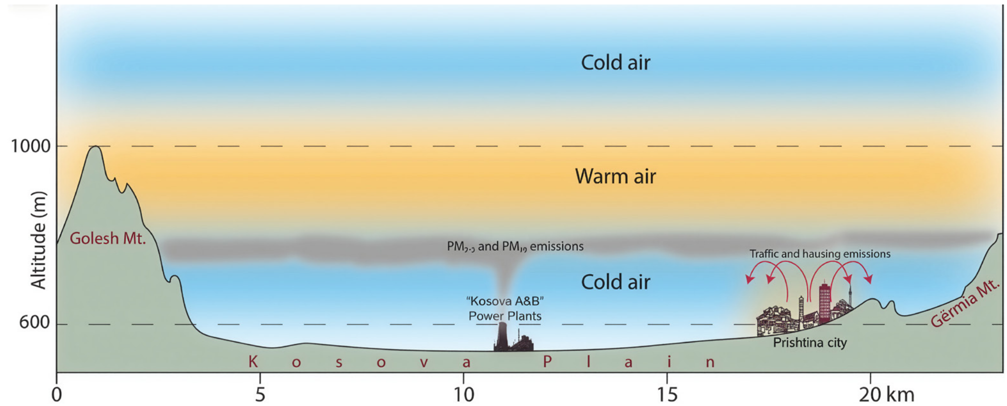

Figure 9. Cross section of Kosova Plain with Prishtina city and powerplants during an air temperature inversion

conditions favoring particulate accumulation. The Kosova Plain is encircled by moderately elevated mountain ranges, with an altitude difference of approximately 480 m between the plain (average elevation ≈ 530 m a.s.l.) and the most surrounding peaks. This topography facilitates the formation of temperature inversions, particularly during winter, when cold air masses settle near the surface beneath a warmer layer aloft (Figure 9).

Under such stable atmospheric conditions, vertical air mixing is suppressed, allowing suspended particulate matter to accumulate within the lower atmospheric layer. Figure 9 presents a schematic cross-section of the Kosova Plain showing the typical inversion structure, highlighting the location of Prishtina city and the Kosova A & B power plants where the highest pollution levels are observed. However, estimates indicate that the Kosovo A plant emits approximately 4,851 tonnes of PM2.5 annually, while Kosovo B emits around 3,687 tonnes per year. To put these figures into broader context, these plants release roughly four times more PM2.5 than most other coal power plants in the Balkan region (iqair.com)

DISCUSSION

The results of this study reveal that particulate matter ($PM_{2.5}$ and PM_{10}) variability in Prishtina is jointly regulated by meteorological dynamics and anthropogenic emissions. Temperature, relative humidity, and wind speed were identified as the principal meteorological controls, with cold, stagnant, and humid conditions promoting particulate accumulation, while warm and windy days enhanced dispersion. The observed negative correlations between air temperature and $PM_{2.5}$ (r = –0.444) and PM_{10} (r = –0.327) clearly demonstrate the sensitivity of particulate levels to thermal and dynamic atmospheric conditions. These seasonal and meteorological patterns are consistent with Zhang et al. (2025), who reported in Xiamen, China, that particulate-phase PAHs increased nearly two orders of magnitude in winter compared with summer due to suppressed dispersion and enhanced combustion. Likewise, Yin et al. (2025) found that severe winter haze in Xuzhou was dominated by nitrate formation and regional dust transport under cold, calm conditions. Both studies emphasized that limited boundary-layer mixing amplifies particulate persistence mechanisms equally evident in Prishtina's winter episodes. In contrast to the monsoonal setting of Xiamen, Prishtina's location intensifies inversion longevity, revealing that topographic confinement further aggravates stagnant-air pollution episodes.

The strong correlation between $PM_{2.5}$ and PM_{10} (r = 0.955) in Prishtina reflects common emission sources and similar atmospheric behaviour. Comparable co-emission dynamics were observed by Omokpariola et al. (2025), who reported strong positive correlations between organic and black carbon (r = 0.78–0.95) in Nigerian cities, confirming the combustion origin of fine particles. Similarly, Katawole et al. (2025) identified that $PM_{2.5}$ and PM_{10} levels near metal-recycling industries exceeded WHO guidelines, with PCA confirming anthropogenic and crustal source influences. The dominance of lignite-based power generation in Prishtina parallels these findings, though the meteorological modulation is more pronounced in its continental climate.

Principal component analysis (PCA) in this study showed that the first two components explained 63.7 % of total variance, with PC_1 primarily linked to temperature and wind speed, and PC_2 to humidity and pressure. This mirrors Kolawole et al. (2025) and Zhang et al. (2025), who similarly found that elevated temperature and stronger ventilation consistently reduce particulate accumulation. Gürtepe et al. (2025) further demonstrated using machine-learning models that temperature and wind speed are the most predictive variables for $PM_{2.5}$ dynamics in Turkey fully consistent with our PCA-based inference for Prishtina. Beyond long-term variation, recent studies confirm that short-term meteorological disturbances can trigger acute pollution-related health risks. Beaufils et al. (2025) revealed that rises in PM_{10} under low-wind conditions preceded episodes of reversible cerebral vasoconstriction syndrome in Europe, reinforcing that particulate concentrations respond rapidly to meteorological shifts. This finding parallels the observed PM_{10} peaks during cold, calm periods in Prishtina, emphasizing the direct public-health relevance of local meteorology.

The role of emission type and chemical composition also warrants consideration. Seo et al. (2025) demonstrated that the toxicity of combustion-generated PM varies by fuel source and combustion condition, with coal and wood emissions producing the most toxic fractions. This supports the assertion that Prishtina's reliance on lignite-based energy and residential wood burning contributes disproportionately to wintertime health risks, and is associated with increased DNA damage in the human population (Alija et al., 2015). Particulate matter (PM_{10} and $PM_{2.5}$) harms the respiratory system by depositing in the alveoli and entering lung cells, where it triggers oxidative stress that can injure or kill cells. This leads to airway inflammation and reduced lung function. Long-term exposure to $PM_{2.5}$ further heightens oxidative stress, increasing vulnerability to infections and contributing to asthma, chronic bronchitis, and COPD (Millaku et al., 2025). According to the Air Pollution Country Fact Sheet for Kosovo (EEA, 2024), deaths attributable to PM2.5 exposure in 2022 were estimated at 2,370. Similarly, Naghizade et al. (2025) advanced analytical approaches for quantifying PM-bound metals via HPLC-MS/MS, showing that chemical profiling is essential for understanding toxicity drivers. While such detailed compositional analysis was beyond the scope of this study, future research incorporating trace metal and organic compound data could provide further insights into the toxicological implications of Prishtina's particulate burden. Geographical and topographic factors further intensify the effects of emissions. Prishtina's position within the Kosovo Plain, surrounded by moderately elevated mountain ranges, facilitates frequent temperature inversions during cold seasons. These inversions trap cold air below warmer layers, restricting vertical mixing and prolonging pollution episodes. Similar meteorology-emission couplings were noted by Omokpariola et al. (2025) and Yin et al. (2025), illustrating that boundary-layer stability universally amplifies particulate retention. From an urban management perspective, mitigation strategies identified in Della Casa et al. (2025) offer valuable insight: their assessment in Barcelona demonstrated that expanding green infrastructure and reducing vehicular density significantly improved air-quality indices. Integrating such evidence with our findings suggests that promoting vegetative buffers, reducing coal dependence, and optimizing city ventilation could yield substantial health and environmental co-benefits in Prishtina.

From a global standpoint, the synthesis of evidence from China (Yin et al., 2025; Zhang et al., 2025), South Asia (Kayes et al., 2019), Iran (Kermani et al., 2020), Africa (Kolawole et al., 2025), Turkey (Ilten & Selici, 2007, Birim et al., 2023), Europe (Żyromski et al., 2014; Silva et al., 2022; Szatyłowicz et al., 2023; Rowland, 2024; Kupiec & Góra, 2025), Kosovo (Alija et al., 2016; Panxhaj et al., 2024) reveals that regardless of geography, particulate dynamics are shaped by the same triad: combustion intensity, boundary-layer stability, and emission-meteorology coupling. Prishtina's continental topography intensifies this interplay, leading to longer pollutant residence times than in coastal or tropical regions. Compared to some Asian megacities, Prishtina's seasonal modulation may lean more heavily on local inversion and heating emissions, because the city likely experiences strong winter stagnation and has significant residential heating contributions. Taken together, these findings confirm that effective mitigation requires an integrated strategy combining emission reduction (through cleaner energy, heating modernization, and sustainable transport) with meteorology-aware spatial planning (improving urban ventilation corridors and reducing inversion risks). The convergence of multi-regional evidence underscores that addressing air-quality degradation demands both emission control and atmospheric management simultaneously.

CONCLUSIONS

This study demonstrates that air quality in Prishtina is jointly controlled by meteorological dynamics and anthropogenic emissions. Fine particulate matter ($PM_{2.5}$ and PM_{10}) showed a strong interdependence, indicating shared sources such as lignite combustion, domestic heating, and urban traffic. Among meteorological factors, air temperature and wind speed emerged as the key regulators of particulate dispersion, while relative humidity played a minor and inconsistent role. Cold, calm, and humid conditions during winter were identified as the most critical periods for pollution accumulation.

The influence of temperature inversions and the city's topographic enclosure further exacerbate air stagnation, explaining the persistence of high particulate levels in the colder months. These findings confirm that meteorological variability amplifies the effects of emission sources rather than acting independently. By integrating correlation and principal component analyses, this research provides the first comprehensive statistical evidence of how climatic dynamics and anthropogenic activity interact to shape air pollution in Kosovo.

To mitigate recurrent pollution episodes, strategic actions are required including the modernization of thermal power plants, gradual transition away from lignite-based energy, promotion of cleaner household heating, and development of sustainable public transport. Given that nearly 40% of Prishtina's population belongs to vulnerable health groups, improving air quality must be treated as both an environmental and public health priority.

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