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Influence of meteorological variables concerning the concentration of particulate material ($PM_{2.5}$)

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ABSTRACT

Air pollution is a problem in everyday life, where the advancement of industrialization presents potential exacerbation of emissions levels and atmospheric pollutant concentrations. This study evaluated the influence that meteorological variables, temperature, relative humidity, precipitation, wind speed, and direction, exert on the concentration of particulate matter, especially $PM_{2.5}$, in urban areas. Procedures involving air quality monitoring data and meteorological data were established over 45 days period, utilizing data from monitoring stations for both air quality and meteorology installed nearby to evaluate the mean, average standard deviation, and predominance of the collected values. The results showed how atmospheric dynamics directly influence PM concentration levels, since for wind directions coming from the 1st quadrant (N, NNE, NE, and ENE) with low speeds or equal to zero, concentration levels were high; for winds coming from the 3rd quadrant (S, SSW, SW, and WSW) with elevated speeds or different from zero, concentration levels were low. Thus, it was possible to verify that the dynamics of wind speed and direction should be analyzed together since they depend on each other and proved to be determining factors for PM concentration levels.

Keywords: Meteorological variables, particulate material concentration, wind speed, wind direction, current air quality index.

Introduction

Atmospheric pollution is becoming increasingly prevalent in people's daily lives, with more individuals being exposed to pollutant concentration levels outside the standards established by government agencies and organizations. Air quality monitoring is essential to ensure the observed parameters comply with current legislation (Kelly & Fussell, 2015; Ghorani-Azam et al., 2016; Manisalidis et al., 2020).

Particulate matter (PM) is one of the most serious pollutants in urban areas, due to its well-documented adverse effects on human health. The severity of the health impact is linked to the size of the particles, as fine PM can penetrate deeply into the respiratory system, with particles with a diameter ≤ 2.5 μm ($PM_{2.5}$) being particularly notable (Akyüz & Çabuk, 2009; Galindo et al., 2011). Three factors can significantly affect $PM_{2.5}$ mass concentration, including domestic pollutant emission sources, external sources from other countries, and meteorological conditions (Wang & Ogawa, 2015). Studies indicate that climate change can significantly affect air quality, particularly due to interference in dispersion and consequent increases in $PM_{2.5}$ concentrations associated with meteorological conditions (Tai et al., 2010).

Atmospheric environment and air quality (AQ) settings are tools that can assist in monitoring and, in the long term, enable the identification of anthropogenic factors that negatively affect air quality at the local level (Wang et al., 2013; Wood, 2022).

The discussion surrounding air pollution gained prominence following the Industrial

Revolution in the late 18th century, when unregulated population growth and social transformations drove the development of new technologies aimed at intensifying the exploitation of natural resources. As a direct consequence, there was a significant increase in the emission of pollutants, such as soot and sulfur compounds, primarily originating from the industrial sector (Rigo, Colombo, & Grub, 2008).

In Brazil, industrial activities were the main source of atmospheric emissions until the 1980s. However, from the 1990s onwards, there was a marked increase in emissions from vehicular sources, which became predominant, especially in large urban centers (Miraglia & Gouveia, 2014).

Among developing countries, China, India, Indonesia, Brazil, Mexico, and Iran are among the largest contributors to atmospheric emissions, collectively accounting for approximately 38% of global emissions (Kanski, 2015). In this context, it is emphasized that the main sources of air pollution in Brazil are industrial processes, the transportation sector, and biomass burning (Squizzato, et al., 2023).

This study is based on the existing gap in the scientific literature regarding the addressed theme. Considering the significance of air pollution for public health and the environment, this study aimed to investigate the real behavior of pollutant concentration at specific times, in contrast to the conventional approach of analysis based on daily averages stipulated by current legislation. Therefore, this study aimed to evaluate the influence of key meteorological variables, as temperature, relative humidity, precipitation, wind speed, and wind direction, on the hourly concentration of particulate matter ($PM_{2.5}$) in an urban area.

Material and Methods

Sampling site

Criciúma is a Brazilian municipality in the state of Santa Catarina, in the country's southern region (Figure 1). It is situated at a latitude of 28°40'39" south and a longitude of 49°22'11" west, with an average altitude of 46 meters. According to the IBGE (2022), the municipality has approximately 214,493 inhabitants, covering a total area of 234,865 km². Criciúma's climate is subtropical (Cfa) (Alvares et al., 2013), characterized by regular yearly rainfall. Frosts occur almost every winter, mainly in the regions farthest from the city center, with varying frequencies from year to year. The city has an average minimum temperature of 14.2°C and an average maximum of 24.9°C (Wrege et al., 2012).

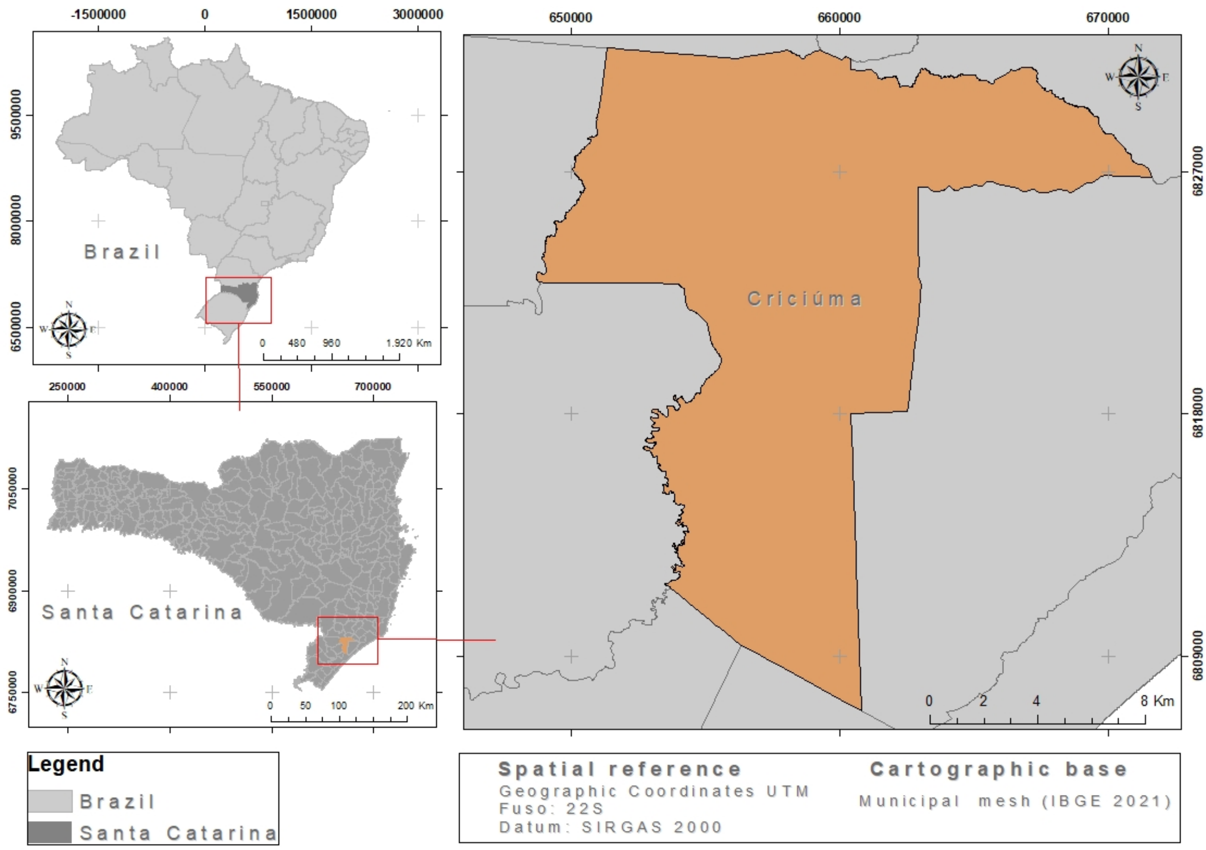

Figure 1. Geographical location of the municipality of Criciúma, state of Santa Catarina, Brazil. Font: IBGE (2021).

Sample collection and measurement

In the study, two meteorological stations in the municipality of Criciúma, Santa Catarina, Brazil, were used: one located at the Parque Científico e Tecnológico (iParque - UTM X 655424.15 m E and Y 6820576.82 m S) of the Universidade do Extremo Sul Catarinense (UNESC), and the second located at the Technological Center of the Sociedade de Assistência aos Trabalhadores do Carvão (SATC - UTM X 654888.61 m E and Y 6823485.93 m S).

According to the municipal zoning regulations of Criciúma, the study area is classified as an Area for Education, Research, and Extension. This designation is attributed to the concentration of educational institutions that characterize the primary land use in this region. The immediate surroundings of this area comprise various urban zones, reflecting a diversity of land uses and occupations. These include: residential zones, primarily designated for housing; industrial zones, intended for productive and manufacturing activities; central zones, which support higher-intensity commercial and service functions; and mixed-use zones, which integrate residential, commercial, and in some cases, industrial uses. This spatial configuration highlights the complexity of local urban dynamics, as well as the potential interactions and conflicts among different land uses, particularly in terms of environmental quality and sustainable urban planning.

Considering air quality monitoring, specifically of particulate matter pollutants (PM_{10}, $PM_{2.5}$, and PM1), the AirLink sampler (Davis Instruments, model 7210, with a declaration of conformity according to ISO/IEC 17050-1 and ISO/IEC 17050-2) was used. The installation was carried out on the campus of the Universidade do Extremo Sul Catarinense (UNESC), at UTM coordinates X 655411.50 m E and Y 6823815.55 m S to investigate the influence of meteorological variables on the hourly concentration of particulate matter in outdoor environments. The analysis also considered other existing conditions, such as the high traffic flow during school periods and its location in a regional hub with a history of contamination due to industrial activities in sectors such as steelmaking, metallurgy, and coal mining, among others. (Figure 2).

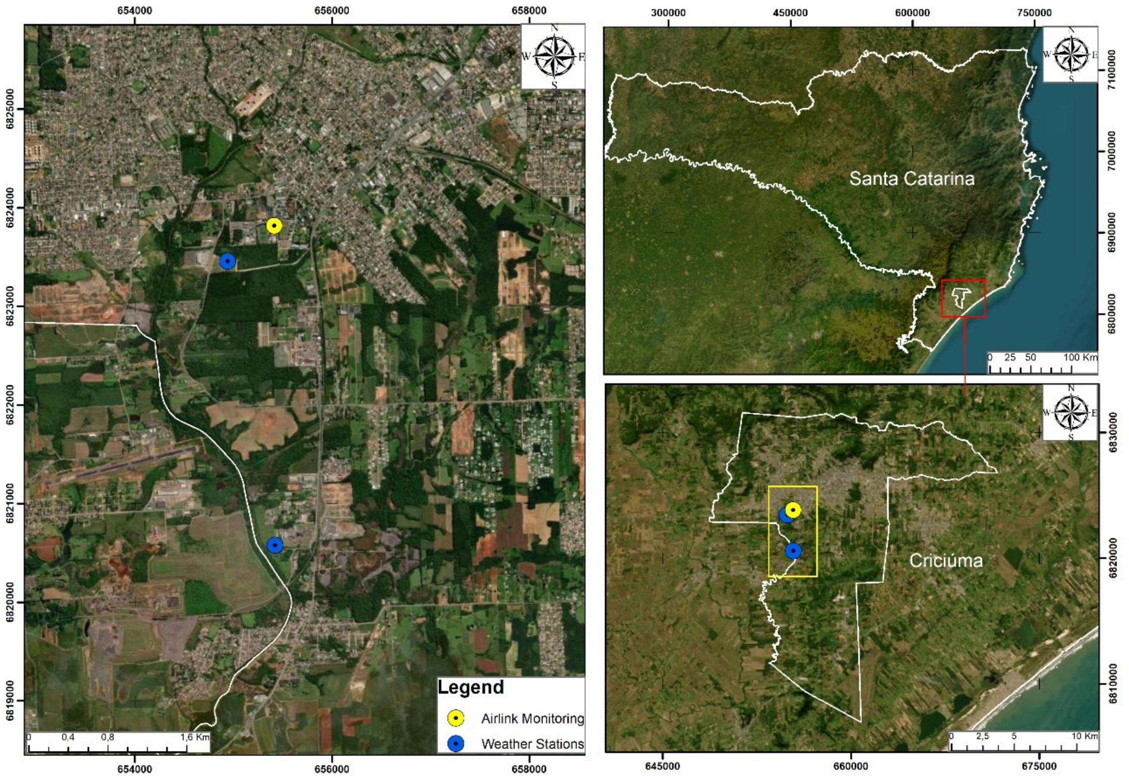

Figure 2. Geographical location of the meteorological stations and air quality monitoring equipment at Criciúma, state of Santa Catarina, Brazil. Font: IBGE (2021).

The meteorological variables chosen for the study evaluation were temperature (°C), relative humidity (%), precipitation (mm), wind direction, and wind speed (km h^{-1}). These meteorological variables were selected based on their influence on particulate matter dynamics in the atmospheric environment.

Two hundred forty collections were conducted over 10 weeks, from March 29, 2023, to June 2, 2023. Five daily collections were established with a 3-hour interval (between 9 a.m. and 9 p.m.). The chosen times accounted for periods of higher vehicular traffic within or near the institution where the air quality monitoring equipment was installed.

Considering the calculation of the Air Quality Index (AQI), the Current AQI was used, which is related to the current record of $PM_{2.5}$ concentration on a given day. Equation 1 (EPA, 1999) was used to calculate the air quality index based on the standards of CONAMA (Conselho Nacional do Meio Ambiente) Resolution No. 491/2018 (Brasil, 2018), as illustrated in Table 1.

$$AQI = \frac{I_f - I_0}{C_f - C_0}(C - C_0) + I_0 \qquad \text{Eq.(1)}$$

where AQI = air quality sub-index, C = concentration value of air pollutants from the measurement, C_o, C_f = minimum and maximum value of the pollutant concentration range with the value C is defined, I_o, I_f = minimum and maximum values of the air quality index range correspond to the calculated sub-index concentration range C.

Table 1. Structure of Air Quality Index proposed by Conselho Nacional do Meio Ambiente- CONAMA. Font: Brasil (2020).

Category	AQI	$PM_{2.5}$	PM_{10}
		(μg m^{-3}) 24 hour	
N1 - Good	0 - 40	0 - 25	0 - 50
N2 - Moderate	41 - 80	> 25 - 50	> 50 - 100
N3 - Bad	81 - 120	> 50 - 75	> 100 - 150
N4 - Very bad	121 - 200	> 75 - 125	> 150 - 250
N5 - Terrible	> 200	> 125	> 250

The AirLink equipment used operates automatically and provides minute-by-minute data on the WeatherLink digital platform, which records temperature index, relative humidity, sunrise and sunset times, and wood smoke adjustment for wildfire occurrences. The air quality index is automatically provided based on standards of the United States Environmental Protection Agency (USEPA, 2018) (

Table 2).

Table 2. Structure of the Air Quality Index proposed by the United States Environmental Protection Agency. Font: USEPA (2018).

Category	AQI	$PM_{2.5}$	PM_{10}
		(μg m^{-3}) 24 hour	
Good	0 - 50	0.0 - 12.0	0 - 54
Moderate	51 - 100	12.1 - 35.4	55 - 154
Unhealthy for Sensitive Groups	101 - 150	35.5 - 55.4	155 - 254
Unhealthy	151 - 200	(55.5 - 150.4)*	255 - 354
	201 - 300	(150.5 - 250.4)*	355 - 424
Hazardous	301 - 400	(250.5 - 350.4)*	425 - 504
	401 - 500	(350.5 - 500.4)*	505 - 604

*If a different SHL for $PM_{2.5}$ is promulgated, these numbers will change accordingly.

Results and Discussion

Temporal variation and response to meteorological conditions

It can be observed that meteorological conditions significantly influenced PM concentrations during the first week (Figure 3). Specific times, such as 6 pm and 9 pm, showed distinct variations correlated with precipitation, wind speed, and temperature. The agreement with pre-existing theories, such as the ability of rain to remove atmospheric pollutants, highlights the robustness of the results (Gomes, 2010).

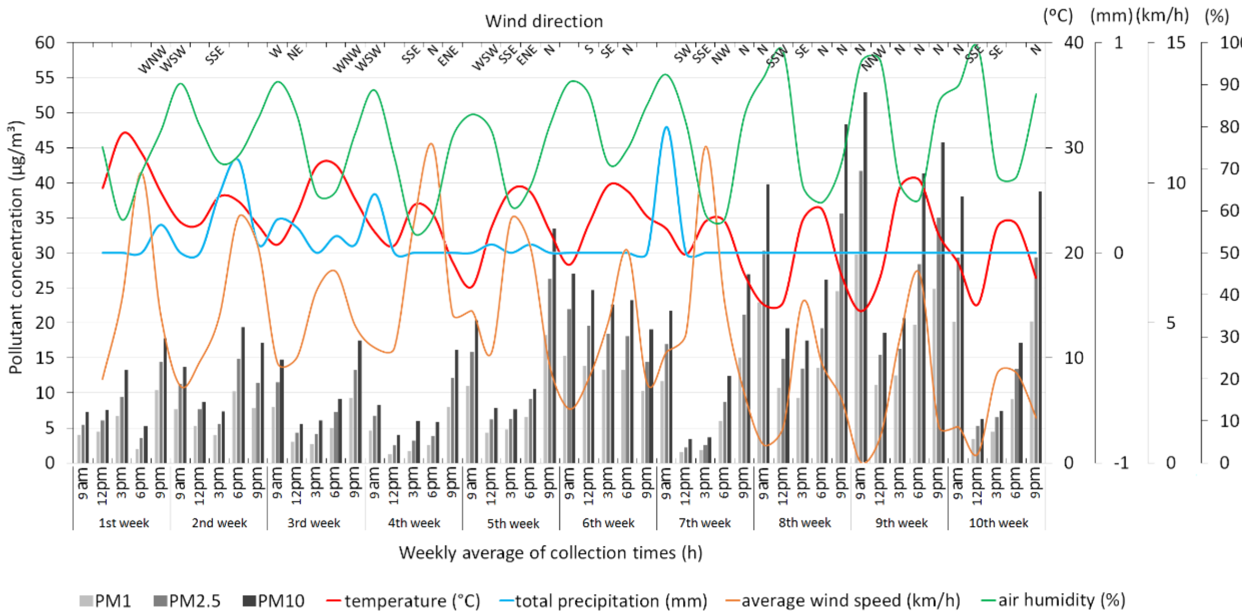

Figure 3. Average relationship between pollutant concentration and the behavior of meteorological variables. Font: Marcello et al. (2024).

The second week revealed consistent patterns, with low concentrations during precipitation events and higher wind speeds. The persistent trend of temperature and relative humidity directly influencing PM concentration reinforces the complexity of the interaction between meteorological variables and pollutants.

Considering the third week, the presence of passing rains influenced the results. The higher variation at 9:00 a.m. and 9:00 p.m. suggests sensitivity to specific changes in weather conditions. Wind direction analysis, particularly at 9:00 a.m., underscores the significance of atmospheric circulation.

The fourth week showed lower PM values at 12:00 p.m., 3:00 p.m., and 6:00 p.m., indicating the influence of temperature and wind speed on the readings. The absence of precipitation and the cloudier weather conditions at the beginning of the week contributed to this pattern.

The fifth week strengthened the influence of rain in reducing PM concentration, especially at 9:00 a.m. The prevalence of south and southeast winds contributed to pollutant dispersion, and the sunnier weather favored dissipation.

The atypical occurrence of more uniform PM values in the sixth week suggests a different dynamic. The presence of precipitation at 9:00 p.m. initiated a decreasing trend. Wind direction maintained consistent patterns.

The seventh week highlighted the influence of dusk on thermal inversion, leading to higher PM concentrations. The decrease in relative humidity and absence of precipitation contributed to this increase. The prevalence of the north wind corroborated atmospheric stability.

The eighth week reflected the sensitivity of PM concentration to variations in relative humidity and temperature. The absence of precipitation kept the levels higher, and the consistent prevalence of north wind reinforced atmospheric stability.

The ninth week follows patterns similar to those of the eighth, with a notable influence from relative humidity and temperature. Thermal inversion during dusk led to higher concentrations. The prevalence of the north wind persisted.

In the tenth week, rain at 9:00 a.m. contributed to reductions in PM concentration. The consistent influence of relative humidity and temperature was again observed, with wind direction maintaining its patterns.

The detailed analysis of the 10 weeks highlights the complexity of the interaction between meteorological variables and PM concentration. The consistency of patterns, such as reduction during rain and the significant influence of relative humidity and temperature, emphasizes the importance of considering multiple factors when addressing air quality issues. These results provide valuable insights for formulating policies and practices to mitigate the effects of atmospheric pollutants in urban environments.

Precipitation was correlated with low levels of pollutants, implying that rain effectively reduces them. Conversely, higher PM concentrations were observed when wind speeds increased, indicating the wind's crucial role in the diffusion of air pollutants. Various climatic factors, such as temperature and relative humidity, also significantly affected the particulate matter accumulated within an atmosphere. Lower readings were found during more relaxed humidities or cooler climates, while unfavorable cloud cover led to larger quantities being recorded. At 9:00 a.m. each day for ten weeks, consistent patterns emerged throughout their investigation, with reduced levels detected due to rainfall and a significant influence from both temperature and relative humidity (RH). Directional movement also proved to be fundamental - south-eastern winds aided dispersion. In contrast, north-dependent thermal inversion saw increases largely without precipitation plus decreased relative dampness, heightening pollution rates considerably greater than any existing pattern monitored precisely till this point.

Air quality management must consider various factors, such as temperature and relative humidity, that affect PM levels. Monitoring precipitation events is also crucial since rain can significantly reduce pollutant concentrations in the air. Wind direction and atmospheric circulation play an important role in pollution dispersion, necessitating their regular monitoring. Thermal inversions adversely affect air quality by increasing pollutant levels; therefore, it's essential to monitor these occurrences.

Hourly peaks of PM concentration

Erro! Fonte de referência não encontrada. highlights 20 days with peak records, mainly distributed at 9:00 p.m. (10 records), followed by 9:00 a.m. (eight records), and 6:00 p.m. (two records). Remarkably, 12:00 p.m. and 3:00 p.m. did not show significant peaks, suggesting a possible influence on weather conditions and relative humidity at certain times of the day.

Table 3. Identification of peak days of $PM_{2.5}$ concentration relative to humidity and weather conditions. Font: Marcello et al. (2024).

Date	Time	$PM_{2.5}$ concentration ($\mu g\ m^{-3}$)	Relative humidity (%)	Weather condition
April 4, 2023	6:00 p.m.	39.3	72.8	Partly clear
April 18, 2023	9:00 p.m.	29.2	92.8	Partly cloudy
April 26, 2023	9:00 a.m.	33.5	94.8	Passing showers
April 27, 2023	9:00 p.m.	41.2	92.5	Partly cloudy
April 28, 2023	9:00 p.m.	34.6	91.4	Partly cloudy
May 4, 2023	9:00 a.m.	27.0	92.1	Scattered clouds
May 5, 2023	6:00 p.m.	34.5	91.6	Cloudy
May 9, 2023	9:00 p.m.	25.8	92.3	Clear skies
May 10, 2023	9:00 p.m.	40.1	93.4	Clear skies
May 15, 2023	9:00 p.m.	39.5	95.0	Mostly cloudy
May 18, 2023	9:00 p.m.	39.2	96.0	Clear skies
May 19, 2023	9:00 p.m.	47.1	96.0	Partly cloudy
May 22, 2023	9:00 a.m.	49.4	98.0	Mostly clear
May 23, 2023	9:00 a.m.	42.5	99.0	Sunny day
May 24, 2023	9:00 a.m.	61.9	99.0	Sunny day
May 25, 2023	9:00 a.m.	25.5	89.0	Sunny day
May 30, 2023	9:00 p.m.	29.5	97.0	Cloudy
May 31, 2023	9:00 a.m.	34.0	99.0	Cloudy
June 1, 2023	9:00 p.m.	34.5	96.0	Clear skies
June 2, 2023	9:00 a.m.	46.3	99.0	Sunny day

A correlation is noted between peak days and cloudy weather conditions, especially at 9:00 a.m., suggesting the presence of mist and fog that hinder the dispersion of particulates in the atmosphere. This observation reinforces the importance of meteorological conditions in $PM_{2.5}$ concentration.

The analysis of wind dynamics (as shown in Figure 3) reveals specific patterns associated with concentration peaks. The predominant wind directions during peaks are associated with the first quadrant of the wind rose (north-N, north-northeast-NNE, northeast-NE, and east-northeast-ENE), with speeds often near zero. This pattern suggests low dispersion of particulates during these times.

It is also observed that winds coming from the third and second/first quadrants, respectively (third quadrant: south-S, south-southwest-SSW, southwest-SW, and west-southwest-WSW; second quadrant: east-E, east-southeast-ESE, southeast p.m.-SE, and south-southeast-SSE; and first quadrant: north-N, north-northeast-NNE, northeast-NE, and east-northeast-ENE), during times of low concentration (12:00 p.m. and 3:00 p.m.), have higher speeds, corroborating the influence of wind speed on the dispersion of atmospheric pollutants. This finding aligns with the literature, as Souza (2010), which emphasizes pollutant dilution in the atmosphere under higher wind speed conditions.

Finally, the results highlight the importance of interacting weather conditions and wind dynamics in forming peaks in $PM_{2.5}$ concentration. Understanding these patterns is essential for developing effective air quality management strategies and mitigating impacts on public health and the environment.

The results underscore the significance of considering weather conditions and wind dynamics in shaping peaks in $PM_{2.5}$ concentration. Understanding these patterns is essential for developing effective air quality management strategies and mitigating impacts on public health and the environment.

By identifying the specific times and weather conditions associated with $PM_{2.5}$ concentration peaks, policymakers and environmental agencies can implement targeted interventions to reduce emissions and improve air quality. This may include traffic restrictions, industrial regulations, and public awareness campaigns.

Furthermore, the findings can inform the development of early warning systems and emergency response plans to protect vulnerable populations during high-pollution episodes. By integrating meteorological data and wind patterns into air quality monitoring and forecasting, authorities can better anticipate and mitigate the risks associated with $PM_{2.5}$ pollution.

Conclusion

The $PM_{2.5}$ concentrations are significantly influenced by meteorological variables, especially temperature, relative humidity, precipitation, and wind dynamics. The hourly data over ten weeks revealed consistent patterns, with lower concentrations typically associated with periods of rainfall, higher wind speeds, and times of day when atmospheric mixing is increased.

Temperature and relative humidity exhibited a recurring pattern that directly impacted particulate levels, with higher humidity and lower temperatures during early morning and late evening correlating with increased $PM_{2.5}$ concentrations. Wind direction and speed also played a significant role: lower wind speeds, particularly those from the north and northeast quadrants, were associated with higher pollutant accumulation, while higher wind speeds, especially from the south and southeast, promoted dispersion.

Peak concentrations were predominantly observed at 9:00 p.m. and 9:00 a.m., times often associated with reduced atmospheric circulation and thermal inversions. These peaks coincided with specific meteorological conditions, such as cloud cover and low wind activity, indicating limited dispersion of pollutants.

This study enabled the evaluation of real-time pollutant concentrations and the identification of the influence of specific climatic factors on these concentrations. The importance of accounting for hourly variations and meteorological interactions in air quality assessments lies in providing valuable insights for enhancing monitoring practices and pollution control strategies.

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