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ORIGINAL ARTICLE

Investigating the association between air pollutants' concentration and meteorological parameters in a rapidly growing urban center of West Bengal, India: a statistical modeling-based approach

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Abstract
The ambient air quality in a city is heavily influenced by meteorological conditions. The city of Siliguri, known as the "Gateway of Northeast India", is a major hotspot of air pollution in the Indian state of West Bengal. Yet almost no research has been done on the possible impacts of meteorological factors on criterion air pollutants in this rapidly growing urban area. From March 2018 to September 2022, the present study aimed to determine the correlations between meteorological factors, including daily mean temperature (℃), relative humidity (%), rainfall (mm), wind speed (m/s) with the concentration of criterion air pollutants ($PM_{2.5}$, PM_{10}, NO_2, SO_2, CO, O_3, and NH_3). For this research, the trend of all air pollutants over time was also investigated. The Spearman correlation approach was used to correlate the concentration of air pollutants with the effect of meteorological variables on these pollutants. Comparing the multiple linear regression (MLR) and non-linear regression (MLNR) models permitted to examine the potential influence of meteorological factors on concentrations of air pollutants. According to the trend analysis, the concentration of NH3 in the air of Siliguri is rising, while the concentration of other pollutants is declining. Most pollutants showed a negative correlation with meteorological variables; however, the seasons impacted on how they responded. The comparative regression research results showed that although the linear and non-linear models performed well in predicting particulate matter concentrations, they performed poorly in predicting gaseous contaminants. When considering seasonal fluctuations and meteorological parameters, the results of this research will definitely help to increase the accuracy of air pollution forecasting near future.

Keywords Air pollutants · Seasonal fluctuations · Particulate $matter_{2.5}$ · Particulate $matter_{10}$ · Relative humidity · Regression analysis

Introduction

Urban air pollution is a severe and escalating environmental issue, particularly in developing nations. It also has a significant impact on global public health, notably on respiratory and cardiovascular diseases (Mage et al. 1996; Bernard et al. 2001; Shi et al. 2020). Despite the significant progress achieved in the prevention and management of air pollution over the past several years, the majority of inhabitants continue to be quite concerned about such crucial ambient exposure (WHO 2021; Leung et al. 2020; Molina 2021). Many nations in the developing world have air pollution levels that are dangerously close to, or even over, the threshold recommended by the World Health Organization (Tiwari et al. 2014; Doreswamy et al. 2020; Srivastava 2022). Since the industrial revolution and widespread urbanization, air pollution has risen to the top of the environmental concerns list in both developed and developing nations (Anwar et al. 2021; Wei et al. 2021; Zhang et al. 2022). The key source of pollutants that contribute to the degradation of air quality are various human activities, such as fossil fuel combustion to drive production processes, motor vehicles, and industrial plants (Pachón et al. 2018; Rajput et al. 2021; Munsif et al. 2021; Molina 2021). In addition, the primary factors contributing to the degradation of air quality in developing nations are

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the tremendous expansion of the urban population and the changes in land use carried on by urban development (Liang et al. 2019; Surya et al. 2020). Because of this, the quality of the air, both indoors and outdoors, varies from what is considered normal in urban settings. This implies that a large number of urban inhabitants are continually exposed to an unhealthy amount of air pollution (Chen et al. 2020). In metropolitan areas, more than 80% of people are exposed to pollutants at levels exceeding WHO standards, and 98% of metropolitan areas in middle as well as low-income countries fail to fulfill air quality standards (Manju et al. 2018; Glazener and Khreis 2019; Afghan et al. 2022). In 2012, there were almost 7 million air pollution-related deaths, with 4.2 million of such mortalities being directly linked to exposure to outdoor air pollution (Sharma et al. 2013; Kayes et al. 2019; Piracha and Chaudhary 2022).

India is experiencing problems pertaining to a growing population and poor air quality. India ranked third worldwide for PM pollution-related deaths in 2017 (Mitoma et al. 2021). There were about 1.1 million avoidable fatalities in India in 2017 due to air pollution (Jat and Gurjar 2021), with 56% attributable to outdoor PM2.5 and 44% to indoor air pollution (Pal et al. 2022). According to WHO (2016), 10 of the 20 most populous cities are in India. After analyzing PM2.5 emissions from all countries, WHO (2019) categorize India as the fifth most polluting country, with 21 of the top 30 most polluted cities being situated in India. Considering 2016 statistics, at least 140 million Indians breathe air ten times or more above the WHO acceptable limit (Chatterji 2021), while 13 of the world's top 20 cities with the greatest yearly air pollution are already in India (Agarwal et al. 2020; Roy and Singha 2021). Due to an increase in industry, population concentration, anthropogenic influences, and automobile usage, India's air quality has been worse over time (Gurjar et al. 2008; Jain et al. 2018; Jat and Gurjar 2021). In recent decades, greenhouse gas emissions (GHGs) and other pollutants have increased in both megacities and small to medium-sized urban centers (Kulkarni et al. 2018; Kumar and Gurjar 2019; Wen et al. 2020). Siliguri isn't an exception in this case (Roy and Singha 2020; Biswas et al. 2020; Halder and Bandyopadhyay (2022). Constant population growth has resulted in excessive energy consumption, which has a negative influence on the environment and the air quality in big as well as medium-sized cities like Siliguri (Bose and Chowdhury 2020; Roy and Singha 2020; Biswas et al. 2020).

Urban air quality is affected by meteorological factors (Gualtieri et al. 2015; Manju et al. 2018; Seo et al. 2018; Suhaimi et al. 2020; Peng et al. 2020; Haddad and Vizakos 2020). Atmospheric pollutants are affected by a variety of factors, including temperature, humidity, wind speed, and direction, including the processes of generation and diffusion (Whiteman et al. 2014; Hoek et al. 2015; Seo et al. 2018; Jain et al. 2018). They are very important for controlling pollution levels (Peng et al. 2020; Haddad and Vizakos 2020). The chemical interactions in the atmosphere between precipitation and air pollutants may remove gaseous pollutants and deposit particles, although rain's impact on air quality varies greatly (Dayan and Levy 2005; Elperin et al. 2011; Ouyang et al. 2015; Kayes et al. 2019). Evidence from numerous research indicate that air quality may indeed be altered by meteorological conditions (Jhun et al. 2015; Manju et al. 2018; Borge et al. 2019; Castelhano et al. 2022). West Bengal has seasonal changes in temperature, precipitation, and humidity due to its subtropical monsoon climate (Bhunia et al. 2019; Kundu 2020). Seasonal changes in air quality may be seen across the state (Biswas et al. 2020). PM2.5 and PM10 levels are higher than acceptable during the dry season but are lower during the monsoon, according to national regulations (Jain et al. 2020; Roy and Singha 2020). Numerous studies on the effects of weather have been conducted in China (Kan et al. 2012; Li et al. 2014, 2020; He et al. 2017; Song et al. 2017; Lin et al. 2020; Liu and Wang 2020; Gao et al. 2021) and India especially at the national level and large cities (Ramanathan and Feng 2009; Bhaskar and Mehta 2010; Jayamurugan et al. 2013), but it is understudied in medium-sized urban areas like Siliguri. This research aimed to examine the links between air pollutant concentration and meteorological factors, assess seasonal fluctuations in air pollutant concentration and perform a time series assessment of air pollutant concentration in Siliguri city.

Study area

Siliguri is a rapidly expanding city with a solid foundation of trade as well as commerce and substantial economic activity. At an elevation of approximately 122 m (400 feet), it is situated in the Himalayan foothills on the banks of the river Mahananda. It has had substantial population growth in recent years, and the Siliguri Municipal Corporation's geographic area is about 41.9 km2 and is bounded by 47 wards that have grown by five times since 1931. Siliguri, in West Bengal, is indeed the third-largest urban agglomeration after Kolkata and Asansol. By luring a sizable number of migrants over the course of time, Siliguri has transformed from a small village into a financially advanced city. This amazing expansion of the city is a result of the city's tremendous population expansion (Bose and Chowdhury 2020). Evidence from the results of the 2011 Census showed that the city's population increased at a quicker pace, from 4.72 lakh in 2001 to more than seven lakhs in the 2011 census report (District Census Handbook 2011). The research area was chosen because of its advantageous position as a center for trade and business, tourist activity, population expansion, the hub of employment, and essential supply to the entire northeast region (Roy et al. 2022a, b). Because of this, the city's air quality suffers as traffic levels increase, which in turn creates more air pollution (The Statesman 2018b; Roy and Singha 2020). Being the connecting point between the north-eastern states and the rest of India, Siliguri has earned the titles like "Gateway of North-east India" and "The chicken's neck" (Bose and Chowdhury 2020; Roy et al. 2022b). This rapidly urbanized city extends over the Jalpaiguri and Darjeeling districts of West Bengal. The city of Siliguri is located between the coordinates of 26°39′57.88" and 26°46′19.03"N and 88°25′16.47" and 88°26′53.62"E. In Siliguri, air pollution is a serious problem that is mostly caused by the city's fast urbanization and population expansion, which is also related to enormous spikes in the vehicle population plying on the road (CDP Report Siliguri 2015; CRCAP Report 2018; The Telegraph 2018; The Statesman 2018a; Roy and Singha 2020). According to experts, the vast majority of diesel-powered vehicles operating in the city are the prime cause of ambient air pollution in the city (CDP Report Siliguri 2015; The Telegraph 2018; The Statesman 2018b; Roy and Singha 2020). Along with it, extensive road construction and poor road dust management procedures are causing particle pollution levels in the city to climb (Fig. 1).

Database

To ascertain the connection between the air pollutants and meteorological factors of Siliguri city, all the data were collected and analyzed based on the data and information accessible from the Central Pollution Control Board (CPCB) and West Bengal Pollution Control Board (WBPCB). There is just one continuous ambient air quality monitoring station in Siliguri at present, and it is situated in Babupara (Ward 32), near Tinbatti more. The daily mean (24 h average) concentration of seven air pollutants, i.e., Particulate Matter ($PM_{2.5}$, PM_{10}), Nitrogen Dioxide

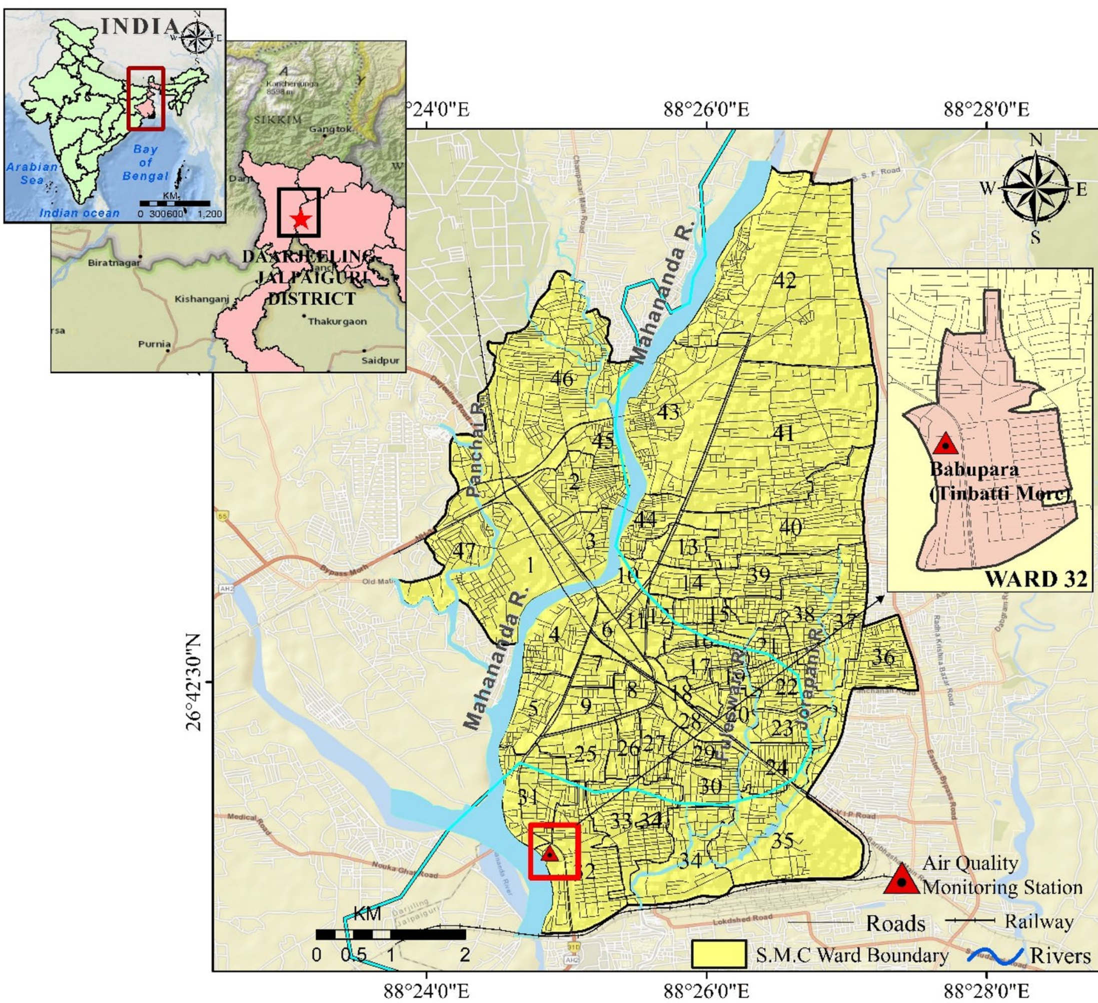

Fig. 1 The geographic location of Siliguri city showing the continuous ambient air quality monitoring (CAAQM) station situated in Babupara (Ward 32)

(NO_2), Sulphur Dioxide (SO_2), Carbon Monoxide (CO), Ozone (O_3), and Ammonia (NH_3), as well as four meteorological factors, i.e., Temperature, Relative humidity, Rainfall as well as Wind speed, have been obtained from the CPCB online portal for data acquisition from March 2018 to September 2022. CPCB implements stringent processes for sampling, analysis, and calibration in order to deliver data quality assurance with quality control programs.

Methodology

Initially, descriptive statistics were computed for both meteorological parameters and air pollutants. To find patterns in the concentration of air pollutants during the same time period, the Mann–Kendall trend analysis has been used. Tukey's HSD multiple comparisons were used to test for seasonal changes in air pollution concentration throughout the years at a 5% threshold of significance. The Spearman correlation analysis was evaluated to identify any associations between the air pollutants and the meteorological factors. Seasonal classifications used in this study, i.e., pre-monsoon (March–May), monsoon (June–September), post-monsoon (October–November), and winter (December–February), were taken from the study conducted by Sivaprasad and Babu (2014) and Dutta and Gupta (2021). Finally, in order to investigate the possible effects of temp, RH, RF, and WS on air pollutants' concentration, multiple linear as well as non-linear models were used. Yin et al. (2016) also considered only two parameters, i.e., Temp and RH as predictive factors to determine the daily PM concentration in Beijing, China.

$$\hat{Y} = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_4 X_4 \tag{1}$$

$$\hat{Y} = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_4 X_4 + \beta_5 X_1^2 + \beta_6 X_2^2 + \beta_7 X_3^2 + \beta_8 X_4^2 \tag{2}$$

Here, β_0 = model constant β_1, β_2, β_3, β_4, β_5, β_6, β_7 and β_8 = model parameters, $\hat{Y}$ = dependent variables (pollutants), and X_1, X_2, X_3, X_4 = independent variables (Temp, RH, RF, and WS, respectively). The overall methodology is illustrated in Fig. 2 through a flow chart for clear and comprehensive understanding.

Results and discussion

The outcomes of this study, together with discussions of the criterion air pollutants as well as meteorological parameters, are presented in the following sub-sections.

Descriptive statistics

The data regarding air pollutants, as well as meteorological parameters in Siliguri city ranging from March 2018 to September 2022, are summarized in Table 1, Fig. 3. Overall, the mean intensity of air pollutants, i.e., $PM_{2.5}$, $PM_{10,}$ $NO_{2,}$ $SO_{2,}$ CO, $O_{3,}$ and NH_3 ranged from 6.02 to 290.38 µg/m3, 14.76 to 393.80 µg/m3, 2.16 to 113.31 µg/m3, 1.35 to 60.89 µg/m3, 0.1 to 2.04 mg/m3, 6.10 to 75.61 µg/m3, 1.06 to 166.41 µg/m3, respectively, from 2018 to 2022. Furthermore, meteorological factors, i.e., temp, RH, RF, and WS, ranged from 11.55 to 33.38 °C, 36.29 to 97.77%, 0.00 to 2.19 mm, 0.21 to 12.55 m/s, respectively.

Trends of air pollution levels and meteorological parameters

The trends of all seven air pollutants, as well as meteorological variables considered for this study (Temp, RH, RF, and WS) from March 2018 to September 2022 in Siliguri, are illustrated in Fig. 3. There was a noticeable tendency of fluctuations in the concentrations of air pollutants and in the meteorological parameters during the period of the research (Fig. 3). Mann–Kendall (MK) trend analysis was used to look at whether or not the concentration of air pollutants has a trend (increasing or decreasing) over time. The final findings of the MK trend test are shown in Table 2. Here, the alpha and *Z* values denote the statistical significance of the rising or falling trend in air pollution, while the tau value indicates the direction of the trend. Sen's slope's value reveals how quickly the trend is rising or falling on a daily basis.

Since the estimated *p*-values were less than the significance threshold of alpha = 0.05 and the null hypothesis of the Mann–Kendall analysis is that there was no trend in the concentration of air pollutants during the relevant period of the study, the research rejected the null hypothesis (Except NO2) and accepted the alternative hypothesis. With the exception of NO_2 and O_3, all air pollutants had statistically significant trends at a 99% confidence level. At a 95% confidence level, the trend of O_3 is significant, but the trend of NO_2 is not significant. It is evident from Table 2, Fig. 4, that every pollutant had a trend over time. All of the pollutants, with the exception of NH_3, exhibit a declining trend over time. The trend of NH_3 has been rising over the sands of time.

Comparison of regression models

Multiple linear regression (MLR) and non-linear regression (MNLR) were compared to identify the possible impacts of meteorological factors (Temp, RH, RF, and WS) on the concentrations of air pollutants (See Table 3).

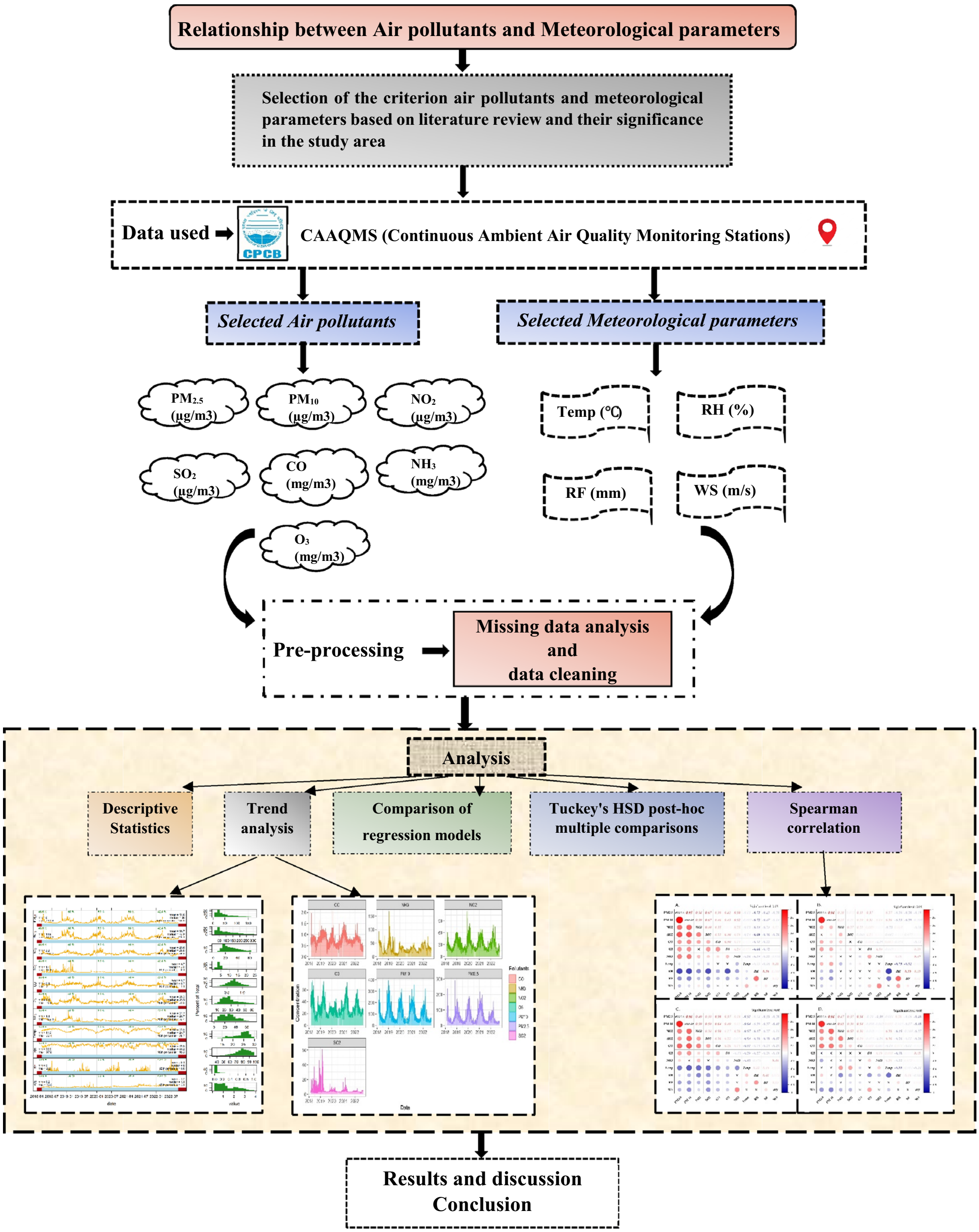

Fig. 2 Methodological flow chart adopted for the present study

The Coefficient of determination (R^2) of both models has been calculated in order to evaluate their efficacy. Table 3 compares the two models and demonstrates that the multiple non-linear regression (MNLR) model performed slightly better than the multiple linear regression (MLR) model. Considering all four meteorological factors as explanatory variables in the model, variations in $PM_{2.5}$ concentration are best explained by the meteorological parameters ($R^2 = 0.65$ and 0.67, respectively), followed by PM_{10} ($R^2 = 0.61$ and 0.62, respectively), while variations in SO_2 concentration are least explained by temperature, relative humidity, rainfall, as well as wind speed

Table 1 An overview of the criterion air pollutants and meteorological parameters based upon daily mean in Siliguri city from March 2018 to September 2022

Statistic	$PM_{2.5}$ (ug/m3)	PM_{10} (ug/m3)	NO_2 (ug/m3)	SO_2 (ug/m3)	CO (mg/m3)	O_3 (ug/m3)	NH_3 (ug/m3)	Temp*	RH*	RF*	WS*
Minimum	6.02	14.76	2.16	1.35	0.1	6.10	1.06	11.55	36.29	0.00	0.21
Maximum	290.38	393.80	113.31	60.89	2.04	75.61	166.41	33.38	97.77	2.19	12.55
Range	284.36	379.04	111.15	59.54	1.94	69.51	165.35	21.83	61.48	2.19	12.34
Median	35.30	71.33	26.17	3.68	0.73	25.77	26.39	24.87	80.35	0.13	1.06
Mean	51.57	96.70	29.56	4.69	0.74	28.22	27.71	23.80	79.54	0.01	1.38
SD	40.77	68.86	13.95	4.20	0.23	11.77	15.69	3.89	10.67	0.23	0.99
SE	1.01	1.70	0.34	0.10	0.01	0.29	0.39	0.10	0.26	0.01	0.02

*Temp, temperature (℃); RH, relative humidity (%); RF, rainfall (mm); WS, wind speed (m/s)

(R^2 = 0.09 and 0.11, respectively). Yin et al. (2016) demonstrated superior MNLR model performance in explaining $PM_{2.5}$ concentration in connection to meteorological factors in China. For CO, O_3, and NH_3, however, no model did well enough. However, NO_2 shows a significant link with meteorological factors than they do. As per Table 3, R^2 values for MLR and MNLR vary from 0.09 to 0.65 and 0.11 to 0.67, respectively. Wise and Comrie (2005) showed coefficient of determination (R^2) values between 0.1 and 0.5 when modeling the impacts of meteorological data on particulate matter concentration in the United States.

Seasonal fluctuations of air pollutants concentrations

A one-way between-groups ANOVA was carried out to ascertain if there is a variation in the concentrations of air pollutants between the seasons (pre-monsoon, monsoon, post-monsoon, as well as winter). The mean difference in the amounts of pollutants throughout the seasons was then shown using Tuckey's HSD post-hoc multiple comparisons (see Table 4).

The concentration of each and every pollutant varied across the four seasons, and this variation was statistically significant at the 0.05 level. The seasonal concentrations of $PM_{2.5}$ and PM_{10} over the years showed significant maximum differences (mean score) according to Tukey's HSD multiple comparison tests (See Table 4). In contrast, NO_2, CO, O_3, and NH_3 show moderate variation across seasons, whereas SO_2 shows negligible variation. It is important to note that the difference in concentration between pre- and post-monsoon for $PM_{2.5}$ and SO_2 and between monsoon and post-monsoon for NH_3 is not statistically significant at all (see Table 4). Although the seasonal concentration varies depending on the various pollutants, the monsoon season depicts the minimum concentration of air pollutants, and the winter portrays the maximum (see Table 4). When evaluating seasonal fluctuations of particulate matter, it is obvious that, for all years, the mean concentrations of $PM_{2.5}$ and PM_{10} were much greater in the winter than they were during the monsoon seasons (Table 4). When compared to monsoon, the amounts of fine particulate matter increased every year during post-monsoon season. Winter and pre-monsoon CO, NO_2, SO_2, and NH_3 concentrations were greater than the monsoon and post-monsoon seasons over the years, notwithstanding the little changes. O_3 levels during pre-monsoon were consistently greater than during other times of the year. In addition to seasonal changes, meteorological variables primarily contribute to the causes of the seasonal swings in the pollutants level (Manju et al. 2018). In addition, winter pollution levels may be higher due to road dust, vehicle exhaust during the dry winter, and

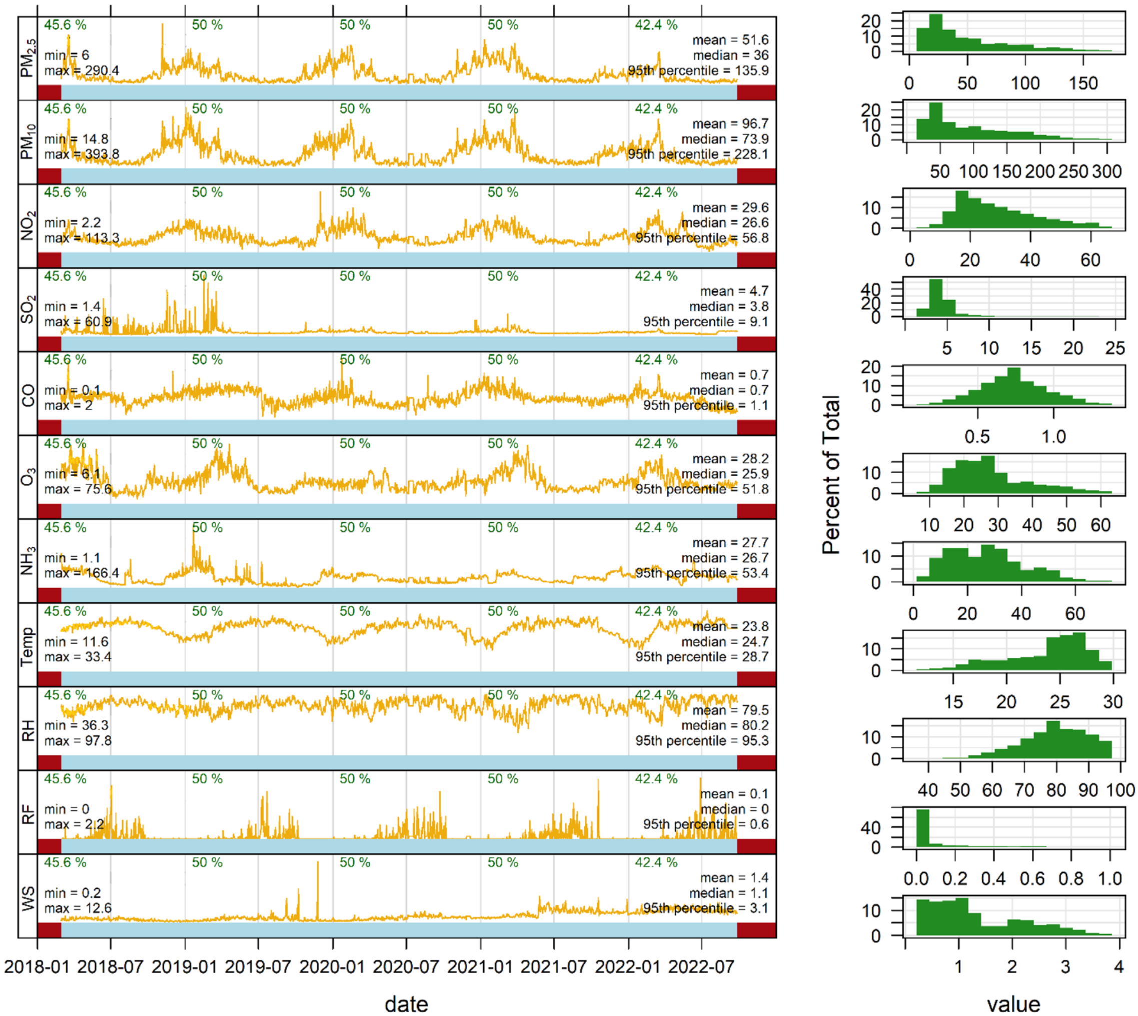

Fig. 3 Trends of concentration and descriptive statistics of criterion air pollutants as well as meteorological parameters from March 2018 till September 2022

Table 2 Mann–Kendall (MK) trend analysis of criterion air pollutants

Statistic	$PM_{2.5}$ (ug/m3)	PM_{10} (ug/m3)	NO_2 (ug/m3)	SO_2 (ug/m3)	CO (mg/m3)	O_3 (ug/m3)	NH_3 (ug/m3)
Tau value	−0.0803	−0.0649	−0.0088	−0.0434	−0.109	−0.0357	0.12
Sen's slope	−0.0059	−0.0089	−0.00034	−0.00014	−0.000078	−0.0012	0.00594
Z value	−4.9167***	−3.9711***	−0.54357	−2.6515***	−6.6515***	−2.188**	7.3724***
p-value	<0.01	<0.01	0.5867	<0.01	<0.01	<0.05	<0.01

*** and ** means the trend is statistically significant at the 0.01and 0.05 level, respectively

urban construction activities. On the other hand, the moist deposition of particles during the monsoon season is linked to lower concentration levels in that season (Roy and Singha 2020; Biswas et al. 2020).

Association between changes in meteorological parameters and the levels of air pollutants concentration

The relationship between seasonal fluctuations in air pollution concentrations and meteorological factors, i.e., Temp, RH, RF, and WS, were examined using a 5% significant level of spearman correlation analysis. The values of the

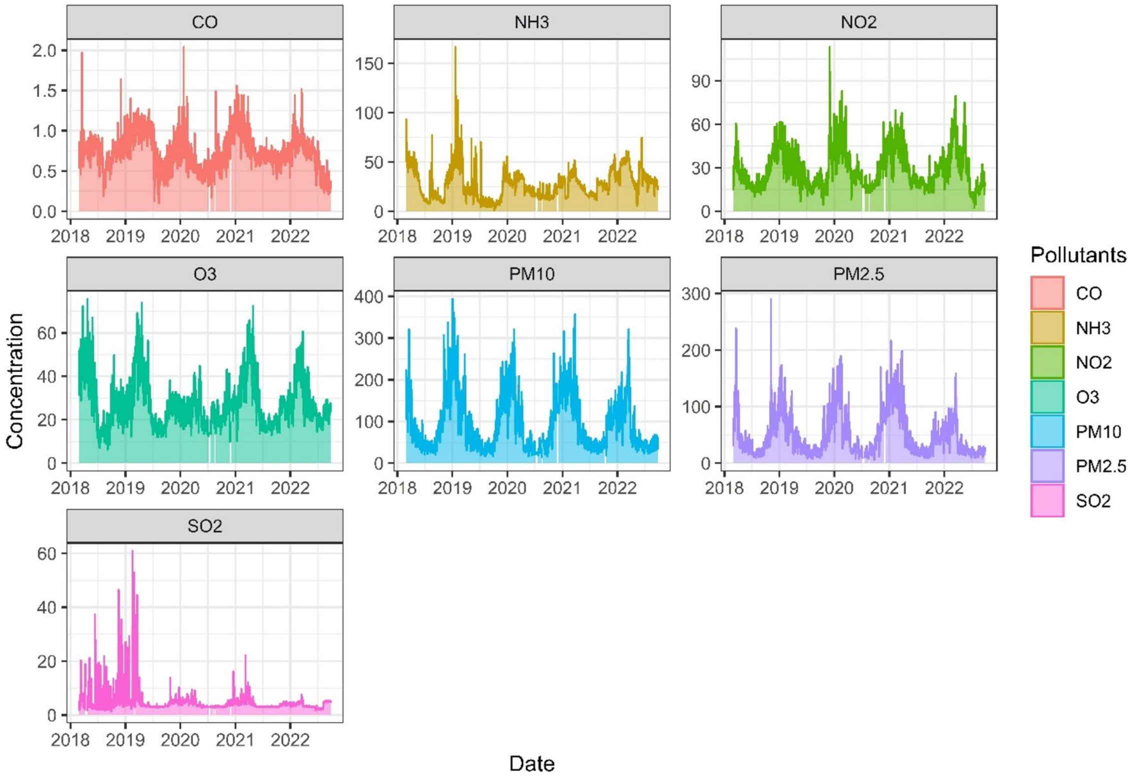

Fig. 4 Area trend diagram showing the concentration of air pollutants in Siliguri city

Table 3 Assessment of the multiple linear regression and multiple non-linear regression models in light of their comparative outcomes

Pollutants	MLR*		MLNR*	
	Equation	R^2	Equation	R^2
$PM_{2.5}$	$Y=290.13-5.41X_1-1.26X_2-9.81X_3-6.18X_4$	0.65	$Y=580.30-11.79X_1-7.15X_2-29.77X_3-13.06X_4+0.15X_1^2+0.04X_2^2+11.52X_3^2+1.15X_4^2$	0.67
PM_{10}	$Y=546.07-9.48X_1-2.66X_2-17.56X_3-7.24X_4$	0.61	$Y=801.10-12.74X_1-8.50X_2-43.77X_3-17.99X_4+0.08X_1^2+0.04X_2^2+16.52X_3^2+2.02X_4^2$	0.62
NO_2	$Y=119.85-1.73X_1-0.63X_2-0.22X_3+0.46X_4$	0.51	$Y=92.28+3.01X_1-1.28X_2-1.72X_3-0.29X_4-0.11X_1^2+0.004X_2^2-0.93X_3^2+0.18X_4^2$	0.53
SO_2	$Y=15.05-0.15X_1-0.08X_2+0.23X_3-0.57X_4$	0.09	$Y=20.81+0.51X_1-0.42X_2-0.12X_3-1.13X_4-0.01X_1^2+0.002X_2^2-0.33X_3^2+0.11X_4^2$	0.11
CO	$Y=1.73-0.02X_1-0.005X_2-0.05X_3-0.02X_4$	0.25	$Y=2.77-0.07X_1-0.02X_2-0.01X_3-0.03X4+0.001X_1^2+0.00005X_2^2-0.02X_3^2+0.002X_4^2$	0.26
O_3	$Y=93.86-0.28X_1-0.77X_2+3.17X_3+1.24X_4$	0.45	$Y=77.75+4.38X_1-1.73X_2+1.54X_3+2.43X_4-0.11X_1^2+0.006X_2^2-1.41X_3^2-0.26X_4^2$	0.48
NH_3	$Y=100.53-1.57X_1-0.50X_2+2.15X_3+3.21X_4$	0.27	$Y=75.53+1.26X_1-0.70X_2+0.61X_3+5.54X_4-0.06X_1^2+0.001X_2^2+0.04X_3^2-0.49X_4^2$	0.28

*MLR and MLNR denotes multiple linear regression as well as multiple non-linear (polynomial) regression, R^2 denotes the coefficient of determination

correlation coefficient are shown in Table 5. Insignificant relationships are denoted by a cross (*X*) in Fig. 5, which shows the season-wise correlation matrix between air pollution concentration and meteorological factors. However, Fig. 6, 7, 8, and 9 show graphical presentations of the correlation between air pollutant levels and seasonal Temp, RH, RF, and WS.

Table 5 shows that during the post-monsoon and monsoon seasons, $PM_{2.5}$ and PM_{10} had strong negative as well as moderate positive correlations associated with atmospheric

Table 4 Tukey's HSD multiple comparison tests for determining the seasonal differences among the concentration of air pollutants across the years

Seasons (I)	Seasons (J)	Dependent variables													
		$PM_{2.5}$		PM_{10}		NO_2		SO_2		CO		O_3		NH_3	
		M-diff (I–J)	Sig.	M-diff (I–J)	Sig.	M-diff (I–J)	Sig.	M-diff (I–J)	Sig.	M-diff (I–J)	Sig.	M-diff (I–J)	Sig.	M-diff (I–J)	Sig.
Pre-M	M	34.17*	0.000	57.81*	0.000	16.01*	0.000	1.52*	0.000	0.19*	0.000	19.77*	0.000	13.67*	0.000
	Post-M	1.39	0.938	−10.19*	0.038	8.19*	0.000	0.55	0.317	0.10*	0.000	13.26*	0.000	14.89*	0.000
	W	−38.04*	0.000	−71.84*	0.000	−8.17*	0.000	−0.74*	0.047	−0.11*	0.000	10.23*	0.000	−5.15*	0.000
M	Pre-M	−34.17*	0.000	−57.81*	0.000	−16.01*	0.000	−1.52*	0.000	−0.19*	0.000	−19.77*	0.000	−13.67*	0.000
	Post-M	−32.78	0.000	−68.00*	0.000	−7.82*	0.000	−0.97*	0.009	−0.08*	0.000	−6.51*	0.000	1.22	0.611
	W	−72.21*	0.000	−129.66*	0.000	−24.18*	0.000	−2.26*	0.000	−0.30*	0.000	−9.54*	0.000	−18.82*	0.000
Post-M	Pre-M	−1.39	0.938	10.19*	0.038	−8.19*	0.000	−0.55	0.317	−0.10*	0.000	−13.26*	0.000	−14.89*	0.000
	M	32.78*	0.000	68.00*	0.000	7.82*	0.000	0.97*	0.009	0.08*	0.000	6.51*	0.000	−1.22	0.611
	W	−39.43*	0.000	−61.66*	0.000	−16.36*	0.000	−1.29*	0.001	−0.22*	0.000	−3.03*	0.000	−20.04*	0.000
W	Pre-M	38.04*	0.000	71.84*	0.000	8.17*	0.000	0.74*	0.047	0.11*	0.000	−10.23*	0.000	5.15*	0.000
	M	72.21*	0.000	129.66*	0.000	24.18*	0.000	2.26*	0.000	0.30*	0.000	9.54*	0.000	18.82*	0.000
	Post-M	39.43*	0.000	61.66*	0.000	16.36*	0.000	1.29*	0.001	0.22*	0.000	3.03*	0.000	20.04*	0.000

Pre−M, M, Post−M and W represents Pre−Monsoon, Monsoon, Post−Monsoon and Winter seasons, respectively. M−Diff represents the mean difference

*The Mean difference is significant at the 0.05 level

Table 5 Summary of season wise Spearman correlation coefficient (r) values between air pollutants as well as meteorological parameters

MP*	Seasons	Air pollutants						
		$PM_{2.5}$	PM_{10}	NO_2	SO_2	CO	O_3	NH_3
Temp*	Pre-M	−0.12	−0.10	−0.13	−0.14	0.03	0.07	−0.26
	M	0.27	0.36	−0.23	−0.08	0.08	−0.05	0.00
	Post-M	−0.51	−0.64	−0.57	−0.54	−0.41	−0.29	−0.43
	W	−0.08	0.08	0.38	0.36	−0.14	0.10	0.20
RH*	Pre-M	−0.71	−0.72	−0.44	−0.69	−0.31	−0.66	−0.34
	M	−0.20	−0.33	0.07	−0.02	−0.06	0.02	0.18
	Post-M	−0.14	−0.29	−0.47	−0.38	−0.15	−0.27	−0.08
	W	0.20	−0.04	−0.45	−0.26	0.07	−0.38	−0.22
RF*	Pre-M	−0.42	−0.47	−0.24	−0.36	−0.22	−0.32	−0.22
	M	−0.28	−0.39	0.02	−0.08	0.00	0.01	0.01
	Post-M	−0.35	−0.37	−0.27	−0.38	−0.23	−0.20	0.01
	W	−0.16	−0.17	−0.10	−0.11	−0.11	−0.02	0.07
WS*	Pre-M	−0.23	−0.14	0.12	−0.26	0.00	0.00	−0.09
	M	−0.19	−0.10	−0.10	0.02	−0.11	0.20	0.47
	Post-M	−0.28	−0.41	−0.16	−0.41	−0.25	−0.19	0.46
	W	−0.40	−0.48	−0.27	−0.26	−0.02	0.35	0.03

*MP=meteorological parameters, Temp= temperature (℃), RH= relative humidity (%), RF= rainfall (mm), WS= wind speed (m/s)

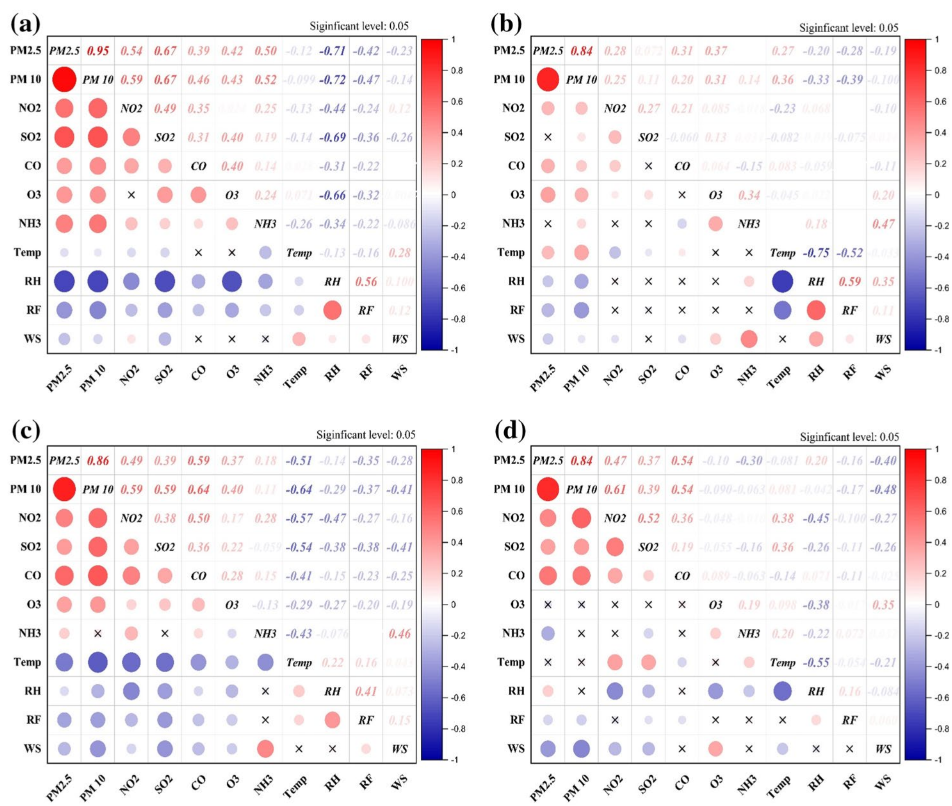

Fig. 5 Correlation matrix showing the season wise (**a,b,c,d** represents pre-monsoon, monsoon, post-monsoon and winter respectively) Spearman correlation coefficient values in between air pollutants and meteorological parameters

temperature, whereas during the pre-monsoon as well as winter seasons, there was negligible or no correlation (Figs. 5, 6). The meteorological features of the monsoon season and their interactions with the particulate matter may be used to explain the positive link between air temperature and particulate matter ($PM_{2.5}$ and PM_{10}) during the monsoon season. Giri et al. (2008) and Kayes et al. (2019) in their study made comparable observations. They said that

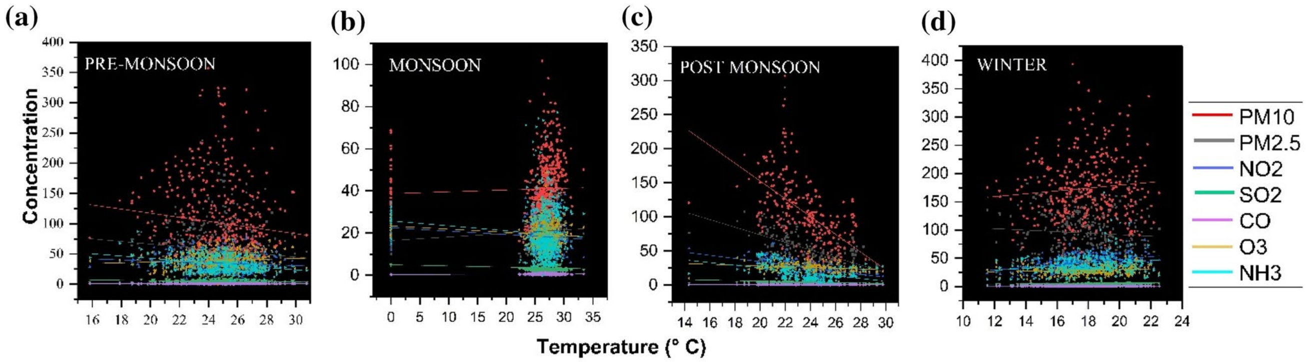

Fig. 6 Correlation plot between season wise air pollutants concentration and temperature, **a** pre-monsoon (March–May), **b** monsoon (June–September), **c** post-monsoon (October–November), **d** winter (December–February)

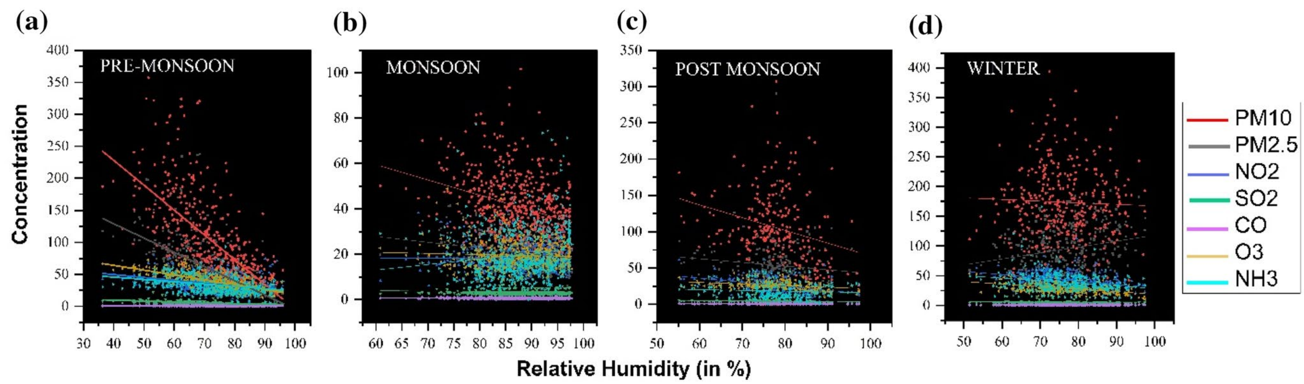

Fig. 7 Correlation plot between season wise air pollutants concentration and relative humidity, **a** pre-monsoon (March–May), **b** monsoon (June–September), **c** post-monsoon (October–November), **d** winter (December–February)

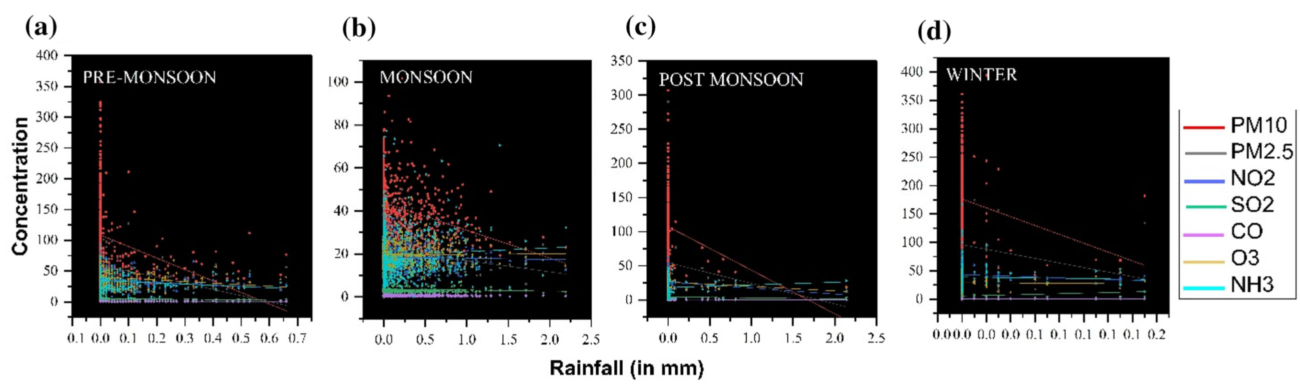

Fig. 8 Correlation plot between season wise air pollutants concentration and rainfall, **a** pre-monsoon (March–May), **b** monsoon (June–September), **c** post-monsoon (October–November), **d** winter (December–February)

since the particulate matter is mostly composed of soil or road dust, it quickly settles to the ground after absorbing water vapor from the atmosphere. Furthermore, this research shows that when compared to other times of the year, $PM_{2.5}$ and PM_{10} concentrations are at their lowest during the monsoon season. The monsoon season of West Bengal is characterized by an intense downpours, gusty winds, and warm temperatures (Chatterjee et al. 2016). Although airborne particles may settle to the ground this time of year due to the abundance of precipitation, their concentration

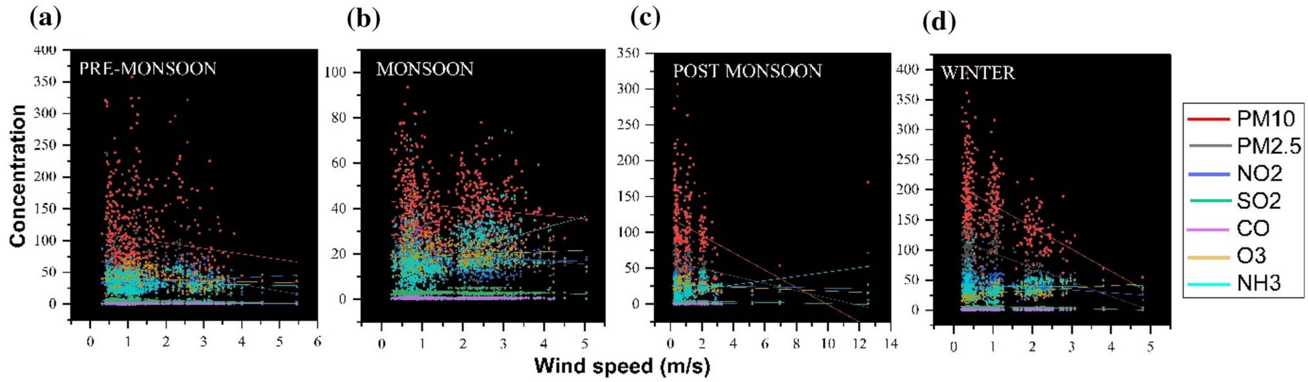

Fig. 9 Correlation plot between season wise air pollutants concentration and wind speed, **a** pre-monsoon (March–May), **b** monsoon (June–September), **c** post-monsoon (October–November), **d** winter (December–February)

might be enhanced by drying up as a consequence of intense summer heat (Kayes et al. 2019). Another factor that may interact with the weather this time of year is the high frequency and intensity of winds. A significant link between fine particulate matter and temperature in the United States was also observed by Tai et al. (2010). It is noteworthy that among other pollutants, NO2, SO2, CO, O3 as well as NH3 resulted in a moderately negative correlation with temperature in post-monsoon season (Table 5).

Most air pollutants' concentrations had a negative association with relative humidity throughout the seasons (Table 5, Figs. 5, 7). In particular, the concentration of fine and coarse particulate matter ($PM_{2.5}$ and PM_{10}) resulted in a negative association during the pre-monsoon, monsoon, and post-monsoon ($r = -0.71, -0.20, -0.14$ and $-0.72, -0.33, -0.29$, respectively); however, there was little positive to no association during the winter ($r = 0.20, -0.04$). This is due to the fact that relative humidity affects the mobility of particles and might lead them to settle on the ground. As a result, the concentration of air contaminants decreases as relative humidity rises (Giri et al. 2008). Similarly, our research discovered that there was often a negative association between relative humidity and particulate matter concentration. However, a positive link between wintertime humidity and fine particulate matter ($PM_{2.5}$) suggests that the lack of precipitation and water vapor in the air may assist PM2.5's ventilation effects (Giri et al. 2008). Again, because of the favorable weather, the majority of construction work is done in the winter. O_3 and NH_3 were always negatively associated, with the exception of the monsoon season. This study's findings on the adverse relationship between O_3 and relative humidity and those of Swamy et al. (2012), Kumar et al. (2014), and Manju et al. (2018) are consistent. According to Ojha et al. (2016), the summer monsoon has greater CO and O_3 concentrations than other times of the year. Similar findings were also reported in China by Zhang et al. (2015), who made the case that the direction of the wind has a big impact on the amount of CO and O3 in the air. Ojha et al. (2016) said that these air pollutants might be carried from the African area to the Indian subcontinent by monsoon wind from the southwestern direction. As an outcome, it exhibits a positive link with humidity during the winter when it is feasible for vehicles to exhale more CO into the atmosphere.

The relationship between the concentration of pollutants and seasonal rainfall throughout time is shown in Figs. 5, 8, and Table 5. Most air pollution concentrations had a negative link with rainfall throughout all seasons when it came to relative humidity (Table 5). For the pre-monsoon and post-monsoon seasons, a moderate to the low negative connection between rainfall and pollutants has been noted. However, research also demonstrates a practically weak negative association between pollutants and rainfall throughout the winter. PM2.5 and PM10 have the strongest reaction (in terms of negative correlation) with rainfall throughout the seasons among all the pollutants.

Table 5 and Figs. 5, 9 show the relationship between wind speed and pollution concentration. Although NH_3 has a moderately positive correlation with wind speed during the monsoon and post-monsoon seasons ($r = 0.47$, 0.46) and particulate matter ($PM_{2.5}$ and PM_{10}) has a moderately negative correlation with wind speed during the winter ($r = -0.40, -0.48$), most air pollutants' concentrations have a weak to negligible negative correlation with wind speed across all seasons. Since NH_3 is a thinner gas than air and tends to rise, it typically does not concentrate in low-lying locations and cannot be fully described by simple meteorological factors, according to research by Osada (2020). In their investigation on the level of particulate matter concentration in winter, Cichowicz et al. (2020) suggested that because of the low wind speed, particulate matter concentration rises throughout the winter. The wind speed slows throughout the winter months in Siliguri as well, increasing particle pollution.

Conclusion

It was necessary to look into the relationship between the concentration of seasonal ambient air pollutants and variations in meteorological parameters throughout time in the city of Siliguri due to the dearth of previous research on this particular area. As shown by other investigations, Siliguri city's air quality is a major problem. When looking at data from 2018 to 2022, the concentrations of all criterion air pollutants in Siliguri city have a decreasing trend; however, the concentration of NH_3 is rising. This could be attributable to COVID-19, the effects of which would be felt in reduced pollution levels in 2020 and 2021 as a result of the continuous lockdown associated with a substantial decrease in vehicle movement and other activities, such as construction works, which contributed to a significant decrease in criteria air pollutants. Although there were other air contaminants present, however, a negative correlation was shown between $PM_{2.5}$ and PM_{10} and the four meteorological parameters. The study found that during the monsoon season, $PM_{2.5}$, PM_{10}, and temperature all have a positive relationship, in contrast to the negative relationships seen during the other seasons. This suggests that the high temperature and humidity experienced during this time contribute to the suspension of particulate matter. However, dry air with reduced humidity aggregates greater pollutants in urban environments; hence winter has the highest concentrations of air pollutants among the seasons. Although not the primary focus of this study, it is worth noting that particulate matters ($PM_{2.5}$ and PM_{10}) were found to be in infringement of the allowable limit established by the National Ambient Air Quality Standards in Siliguri city, posing a serious risk to the city's residents. The high quantities of PM_{10} and $PM_{2.5}$ in the city's air are mostly attributable to air pollution, especially caused by diesel-powered automobiles. Compressed natural gas and electric cars are two examples of greener fuels that need to replace traditional options as quickly as feasible. There has to be an immediate increase in the number of air quality monitoring stations around the city. The renewal period for Pollution Under Control (PUC) certificates should be shortened to encourage more frequent renewal and reduce the number of cars owned by individual households. Meanwhile, construction sites must immediately adopt measures to cut down on dust-particle emissions. Enhancing the public transportation system should also be relevant to improving the efficiency of roads and services. The current study only used four meteorological parameters, including temperature, relative humidity, rainfall, and wind speed, to establish the associations, despite the fact that it is well-known that wind direction, solar radiations, and other factors can have an impact on the concentration of air pollutants. Future research should integrate more parameters to express this issue.

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Data availability The datasets used in the present study are publicly available from the official website of the Central Pollution Control Board (CPCB) and West Bengal Pollution Control Board (WBPCB).

Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Consent to publish Both authors have read the manuscript carefully before submitting it and given consent to submit.

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