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Seasonal variations of particulate matter in two size fractions ($PM_{2.5}$ and PM_{10}) and their relationship with meteorological parameters in Lahore, Pakistan

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Air pollution is rising globally in megacities, due to the human population pressure index, expanding automotive industries, factories, and the burning of fossil fuels that have a detrimental influence on the climate and public health. The current research work explores the study of fine and coarse mode particulate matter ($PM_{2.5}$ and PM_{10}) and the impact of meteorological parameters such as temperature, pressure, relative humidity, rainfall, and wind speed in Lahore (Pakistan) during 2019. The value of $PM_{2.5}$ ranged from 11.55 to 187.77 $\mu g\ m^{-3}$ with a mean value of 55.49 ± 32.85 $\mu g\ m^{-3}$. Similarly, the value of PM_{10} varied from 8.57 to 334.26 $\mu g\ m^{-3}$, with an average value of 101.49 ± 60.78 $\mu g\ m^{-3}$ during the study period. The coefficients of determination between $PM_{2.5}$ and PM_{10} had higher values during autumn (R^2 = 63.88%), followed by R^2 = 57.84% (winter), R^2 = 27.25% (spring), and R^2 = 22.41% (summer), respectively. Regression of $PM_{2.5}$ and PM_{10} with temperature shows a negative correlation during winter and autumn while a positive correlation was observed during spring and summer seasons. Similarly, $PM_{2.5}$ and PM_{10} are positively correlated with pressure in all four seasons. Throughout all four seasons, relative humidity (RH) has a positive association with $PM_{2.5}$ and a negative correlation with PM_{10}. Similarly, in winter, summer, and fall, RF is found to have a negative correlation with both $PM_{2.5}$ and PM_{10}. Wind speed shows a negative correlation with both size fractions of PM during all seasons.

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Environmental significance

This research investigates the correlation between PM *i.e.* $PM_{2.5}$ and PM_{10}, and meteorological parameters in urban areas of Lahore during 2019. Air pollution is comparatively more severe in Asian countries, in general, and in South Asian countries, including Pakistan in particular. Our research can enhance the precision of air pollution forecasting in various climatic scenarios and provide a deeper understanding of the mechanisms that mitigate pollution by phasing out high-energy utilization in mobile sources and industries, and by using clean energy sources instead of conventional energy to reduce emissions from local and non-local sources of air pollutants.

Introduction

Air pollution is one of the most significant environmental challenges across the globe. In urban areas, more than 80% of the population is exposed to air quality that does not meet the standards established by the World Health Organization (WHO). Approximately seven million deaths per year around the globe are due to the invisible killer *i.e.* outdoor and indoor air pollution.[1–3] Atmospheric Particulate Matter (PM) consists of tiny particles (solid or liquid matter) with aerodynamic diameters ranging from nanometers to several micrometers, suspended in the Earth's atmosphere from hours to weeks.[3] Based on their size (aerodynamic diameter), they are classified as ultrafine PM_1 (≤1 μm), fine $PM_{2.5}$ (≤2.5 μm), and coarse PM_{10} (≤10 μm).[4–6] PM greatly affects human health, climate change, ecosystems, and economic development.[7,8] Airborne PM can originate from various sources, including geogenic, anthropogenic, and biogenic.[4,9] Air pollution may occur due to stagnant meteorological conditions, open burning incidents, trans-boundary interference, and emissions from vehicles, factories, *etc.* in regions.[4,6,9–12]

Both $PM_{2.5}$ and PM_{10} pose a significant challenge to the environment, mostly because of their adverse effects on human health. Fine particulate matter, *i.e.* $PM_{2.5}$, which could penetrate deep into the respiratory tract, subsequently increases the mortality risk from respiratory infections and diseases, lung

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cancer, and cardiovascular disease.[3,7] Particulate matter could become more toxic if it is produced by the formation of certain gases such as sulfur dioxide and nitrogen oxide. Particulate matter could also affect urban and regional air quality, and reduce visibility and it has a significant impact on global climate change.[4,6,9,10]

Previous studies have demonstrated that both $PM_{2.5}$ and PM_{10} are influenced by meteorological parameters. Researchers have identified a correlation between PM and meteorological parameters across various geographical locations.[11,13,14] The relationships between air pollutants like ambient PM and meteorological parameters not only vary with geographical locations but also with seasons.[5,10,11,14–16]

In recent winters, hundreds of kilometers of fog have frequently covered northern India and north-eastern Pakistan. The region—including north-eastern India and adjacent areas of Punjab in Pakistan—experiences a high-pressure system during winter, which leads to dry conditions and low wind speeds. These factors create an environment that promotes the accumulation of atmospheric pollutants.[17]

Lahore, the capital of Punjab, Pakistan, is the country's second-largest city and a key hub for culture, history, and economy. Located 217 meters (712 feet) above sea level, it has a hot semi-arid climate with scorching summers, a monsoon season, and dry, mild winters. Many researchers have explored the relationship between ambient PM levels and meteorological factors in Lahore's environment.[6,12,17] However, this study explores the association between $PM_{2.5}$ and PM_{10}, and meteorological parameters in Lahore's urban areas throughout the different seasons of 2019. Air pollution is comparatively more severe in Asian countries, in general, and in South Asian countries, including Pakistan in particular. Our research can enhance the precision of air pollution forecasting in various climatic scenarios and provide a deeper understanding of the mechanisms that mitigate pollution by phasing out high-energy utilization of mobile sources and industries, and utilization of clean energy resources instead of conventional energy to reduce emissions from local and non-local sources of air pollutants.

Materials and methods

Description of the study area: Lahore (31.32°N; 74.22°E) is the historical, cultural, administrative, and capital city of Punjab (Pakistan), with a population of about 12 million (Fig. 1). It is located near the Indian border along the River Ravi and experiences a variable climate during the whole year. It remains excessively hot and humid in the summers and dry-cold during winter. Lahore has diverse sources of pollution like clay bricks, and manufacturing industries like steel, chemicals, motor vehicles, engineering products, pharmaceuticals, and construction materials. Due to intense pollution, the urban environment of Lahore was chosen as the study area in the present research work. Sampling was conducted on the rooftop of the Center of Excellence in Solid-State Physics, Punjab University.

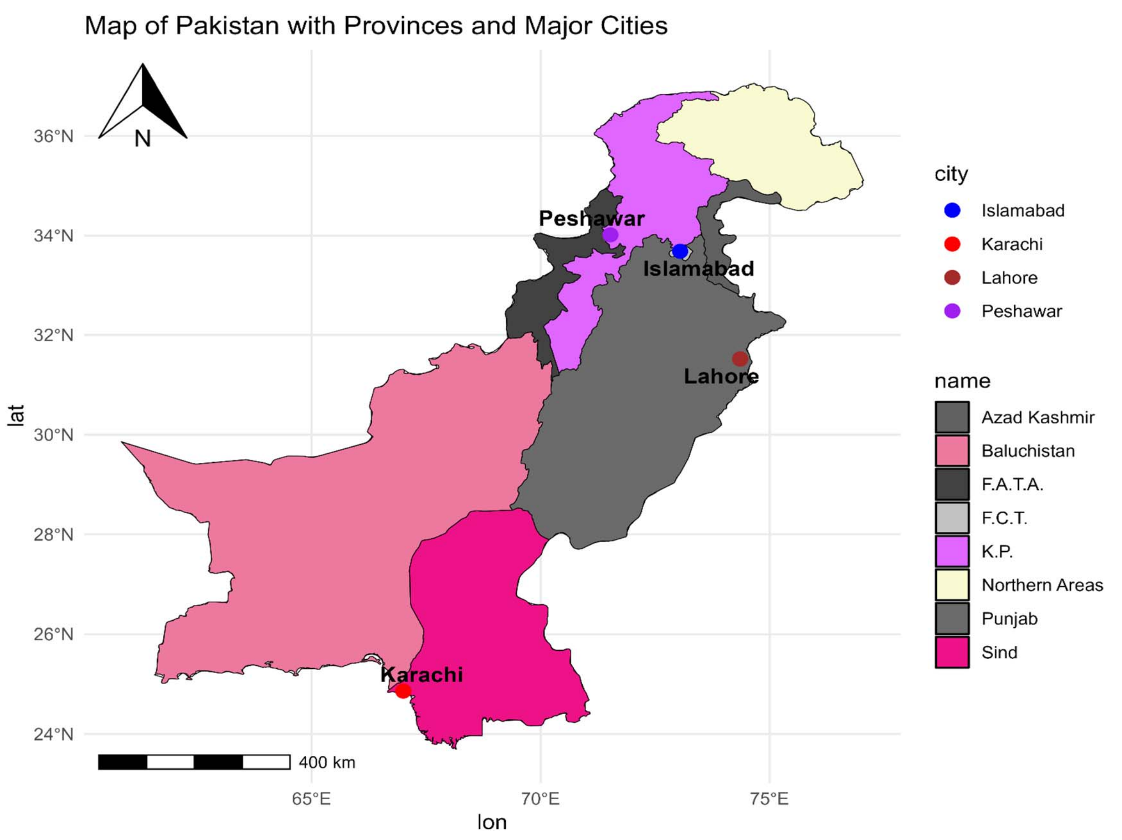

Fig. 1 Map of the study area.

Research area meteorological conditions

Throughout the study period, the temperature ranged from a minimum value of 10 °C (Dec) to a maximum value of 38 °C (June) with an average value of 24.80 ± 7.55 °C (Fig. 2(a–e)). Likewise, the maximum and minimum pressure during the study periods was 1022.7 hPa (Jan) and 991 hPa (July) with an average value of 1007.22 ± 8.36 hPa. Relative humidity has a minimum value of 16% (May) and a maximum value of 100% (Dec), with a mean value of 51.66 ± 18.65%. Rainfall (RF) varied from 0 mm (Nov) to 74.80 mm (July) with an average value of 2.48 ± 9.10 mm during the study period. Similarly, the maximum recorded wind speed was found to be 22 knots during December, and a minimum of 0 knots during March with an average value of 2.54 ± 2.90 knots.

Sample collection

A low-volume sampler (LVS) (Leckel, Germany) was used for the collection of particulate matter in two-size fractions of fine $PM_{2.5}$ and coarse PM_{10}. Sampling was carried out at a constant flow rate of 16.00 liters per minute daily from 1 January to 31 December (2019).

Particulate matter was collected using 47 mm diameter quartz fiber filter paper (Tissuquartz, Pall Life Sciences). Pre-weighed and conditioned quartz fiber filters were inserted into the sampler's filter holder and tightly fastened.

The loaded filters were kept in a refrigerator at 4 °C to prevent contamination and moisture absorption. From the difference between loaded and unloaded filter masses, we found the ambient gravimetric mass concentrations of PM. A single-pan top-loading digital balance (Denver, Model TB-2150) with a precision of ±10 μg was used to weigh each filter paper before and after sampling.[4,6,11]

Analysing the interaction between airborne particulate matter and meteorological variables using regression

The particulate matter in two size fractions (fine, and coarse) and meteorological parameters data for one year, from January 1 to December 31, 2019, were arranged using an Excel worksheet in Microsoft (2018). The data were organized into four seasons: winter (December, January, and February), spring (March, April, and May), summer (Jun, July, and August), and autumn (September, October, and November).

Descriptive statistics were used to analyze the data, and Graph Pad version 8 was used to display the results shown in Fig. 2. Regression analysis was used to determine the association between particulate matter and meteorological parameters, with PM as the dependent variable on the *Y*-axis, and the meteorological variables are independent variables along the *X*-axis (Fig. 3–7). R-software (version 4.01) and R-Studio were utilized to conduct the regression analysis and other plots.

Results and discussion

Mass concentration of $PM_{2.5}$ and PM_{10}

In the current study, the annual average concentrations of both $PM_{2.5}$ and PM_{10} in Lahore city were found to be 55.24 ± 32.85 μg m^{-3} and 101.09 ± 60.78 μg m^{-3}, respectively (Table 1). Likewise, the mean concentrations of fine particulate matter ($PM_{2.5}$) were found to be 79.29 ± 42.37, 42.26 ± 16.06, 58.09 ± 21.80, and 54.84 ± 34.96 μg m^{-3} during winter, summer, spring, and autumn, respectively. While coarse mode PM_{10} has average concentrations of 104.94 ± 53.75, 135.83 ± 63.86, 105.95 ± 57.67, and 87.80 ± 57.46 μg m^{-3} during winter, summer, spring, and autumn, respectively. The mass concentrations of both $PM_{2.5}$ and PM_{10} were found to be higher than the average threshold values set by the World Health Organization (WHO)[1] *i.e.* $PM_{2.5}$ = 25 μg m^{-3} and PM_{10} = 50 μg m^{-3} during all seasons.[2] Seasonal average $PM_{2.5}$ concentrations peaked in winter, followed by spring, autumn, and summer. Similarly, PM_{10} concentrations were found to be highest in the summer, followed by spring, winter, and autumn, respectively. The highest investigated values in winter for $PM_{2.5}$ exceeded the NEQSAA level by 2.2 times and the WHO level by 5.28 times, while PM_{10} exceeded the WHO threshold limit by 2.12 times in summer.[1]

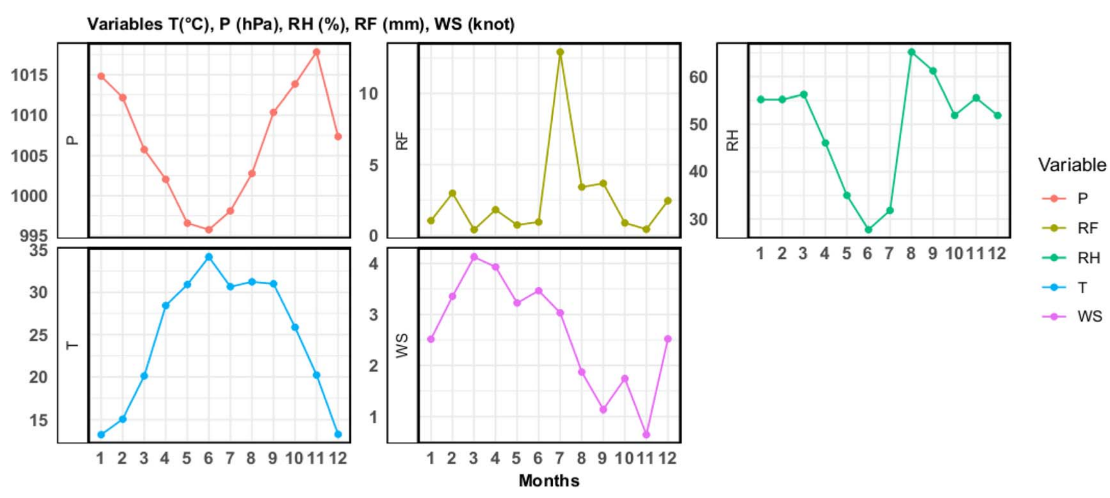

Fig. 2 Representation of meteorological parameters during the study.

Table 1 Mass concentrations of fine ($PM_{2.5}$) and coarse (PM_{10}) particulate matter in Lahore during the study period

	$PM_{2.5}$ ($\mu g\ m^{-3}$)					PM_{10} ($\mu g\ m^{-3}$)				
Seasons	Winter	Summer	Spring	Autumn	Yearly	Winter	Summer	Spring	Autumn	Yearly
Mean	79.29[a]	42.26[c]	58.09[b]	54.84[b]	55.24[b]	104.94[b]	135.83[a]	105.95[b]	87.8[c]	101.09[b]
±SD	42.37	16.06	21.8	34.94	32.85	53.75	63.86	55.67	57.46	60.78
Min	17.72	11.55	15.28	14.69	11.55	20.59	223.47	8.57	20.69	8.58
Max	187.77	114.29	123.08	177.35	187.77	299.01	334.26	277.38	299.01	334.26
Range	170.05	99.59	107.8	162.66	176.22	278.42	310.79	268.81	278.42	325.72
Median	79.22	39.48	56.57	38.43	77.45	106.35	131.21	110	65.02	80.01
[a]WHO (24 h per annual)	5.28	2.82	3.87	3.65	11.04	2.09	2.71	2.12	1.76	5.05
[a](15/05) for $PM_{2.5}$		[a](50/20) for PM_{10}								

[a] Different superscripts show significant differences based on *t*-tests (*p*-value < 0.01).

Numerous variables like dense population, the usage of three- and four-wheeled vehicles, transboundary interference, and metrological characteristics are the causes of high PM concentration at the sampling site. Temperature inversions also play an important role during winter causing particulate matter to disperse and scatter less, raising the ambient air mass concentrations.[11]

The ambient air quality in Lahore and other locations across the world was established by earlier research. According to a study conducted between 2007 and 2011, the average summertime $PM_{2.5}$ concentrations at Town Hall and Township (Lahore) were 99 and 115 $\mu g\ m^{-3}$, respectively.[17] According to Alam *et al.*[12] the average PM_{10} concentration in the Lahore metropolitan region during the spring was 406 $\mu g\ m^{-3}$ (254 to 555 $\mu g\ m^{-3}$).

The exceedance factor analysis revealed that the health effects of PM exposure are particularly alarming, especially for populations in urban areas. $PM_{2.5}$ has received significant attention due to its ability to penetrate deep into the respiratory system and enter the bloodstream. Prolonged exposure to $PM_{2.5}$ has been linked to various respiratory and cardiovascular diseases, including asthma, chronic obstructive pulmonary disease (COPD), lung cancer, heart attacks, and strokes. Similarly, PM_{10} has been extensively studied for its detrimental effects on human health. Research has established strong correlations between airborne PM_{10} and increased mortality rates, hospital admissions, and respiratory complications, particularly in industrialized and highly polluted urban areas.

Table 2 provides a comparative view of fine $PM_{2.5}$ and coarse PM_{10} mass concentrations in urban environments across different study sites in Pakistan, as well as other countries including India, China, Iran, Korea, Bangladesh, and Nigeria. The PM concentrations are higher in Lahore as compared to other locations like Swat, Pune, Shanghai, Ulsan, and Port Harcourt. On the other hand, the present site mass concentration was lower as compared to Peshawar, Beijing, and Wuhan.

Table 2 Comparison of $PM_{2.5}$ and PM_{10} mass concentrations with different locations in Pakistan and abroad

Country	City	Characteristics	$PM_{2.5}$ ($\mu g\ m^{-3}$)	PM_{10} ($\mu g\ m^{-3}$)	Reference
Pakistan	Lahore	Urban (winter)	79.29 ± 42.37	104.94 ± 53.75	Present study
	Peshawar	Monthly (2016)	286 ± 00	638 ± 00	4
	Swat	Max (2019)	56.00 ± 00	78.00	11
	Lahore	Mean 24 h (2018)	170 ± 54.90		18
	Lahore	November (2019–21)	271.80 ± 00		19 and 20
	Faisalabad		297.20 ± 00		
	Gujranwala		201.60 ± 00		
India	Pune	Yearly (2012)	73.60	121.40	21
	Delhi	Yearly (2013–14)	108.0 ± 86.5	233.0 ± 124.6	22
	Delhi	Yearly (2012)	135.16 ± 41.34	—	13
	Delhi	Yearly (2016–18)	107.32 ± 71.06	210.61 ± 95.90	22
	Varanasi	Yearly (2019–20)	111.34 ± 00	180.70 ± 00	23 and 24
Iran	Tehran	Yearly (2016)	104.30	39.50	25
China	Beijing	Yearly (2013–14)	87.00	109.40	14 and 26
	Shanghai	-do-	56.10	79.90	
	Wuhan	Yearly (2013–16)	80.00	118.00	
Korea	Ulsan	Yearly (2011–12)	20.90	38.50	27
Nigeria	Port Harcourt	Yearly (2019)	58.80	164.50	28
Bangladesh	Khulna	Mean 24 h (2018–20)	302 ± 109.89	415 ± 184.01	29
	Dhaka	Yearly (2013–15)	76.34 ± 34.12	136.25 ± 68.94	30

Statistical analysis of $PM_{2.5}$ and PM_{10}: regression and frequency distribution with meteorological parameters

First, the temperature in 2019 was divided into six intervals, 10–15, 15–20, 20–25, 25–30, 30–35, and 35–40, as shown in Fig. 3(a). The high-temperature interval (35–40 °C) has the lowest frequency of 6% and the 30–35 °C interval has the highest frequency of 29%. In the range of 20 and 35 °C, the plot illustrates a declining trend in fine PM concentration.

Also as shown in the plot the greatest average concentration of fine $PM_{2.5}$ is 145 μg m^{-3} in the 20–25 °C interval, and the lowest value of $PM_{2.5}$ is 73 μg m^{-3} at a temperatures of 15 °C. Additionally, the lowest PM_{10} concentration of 35 μg m^{-3} occurs at 30 °C, while in the temperature range of 15–20 °C, a maximum mass concentration of 87 μg m^{-3} was observed. In cities like Lahore, Delhi, and Beijing, winter pollution spikes due to frequent temperature inversions, trapping pollutants. In the winter, when temperatures are between 10 and 15 degrees Celsius, inversions would prevent vertical mixing, causing $PM_{2.5}$ to accumulate, whereas in the summer, warmer temperatures would prevent inversions, allowing pollutants to disperse and wet depositions.[30–32]

Likewise, Li *et al.*[32] also noted that fine mode ($PM_{2.5}$) concentration decreases from 42 to 10 μg m^{-3} due to strong air convection in the region, our results also agreed with Usman *et al.*[11] and Elminir *et al.*[33]

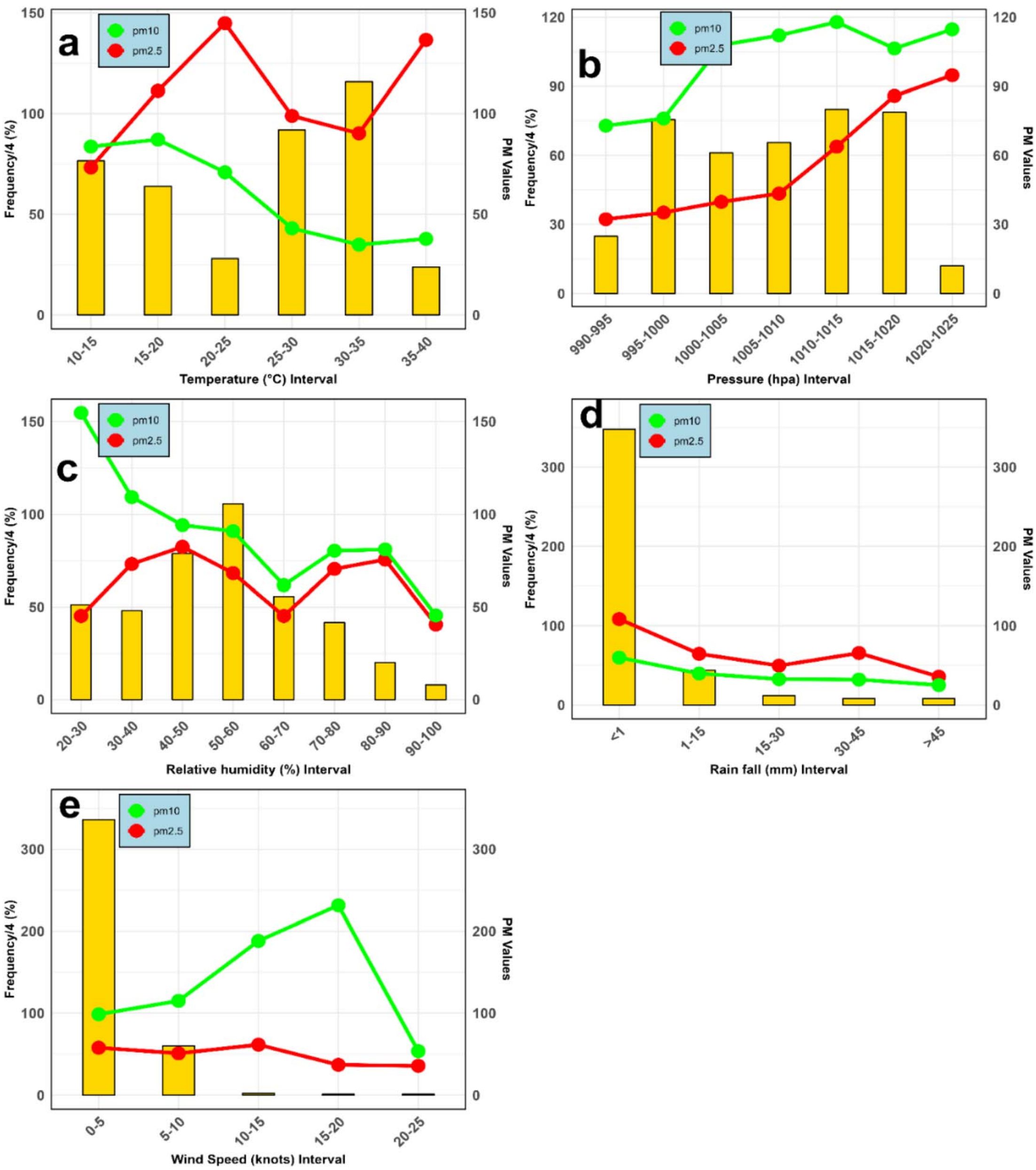

Fig. 3 Frequency/4 distributions (%) of five metrological parameters: (a) temperature, (b) pressure, (c) relative humidity, (d) rainfall and (e) wind speed.

The pressure ranges between 995 and 1020 hPa, as seen in Fig. 3(b). As pressure increases, $PM_{2.5}$ and PM_{10} concentrations often do as well. The center generates an upward wind that helps disperse pollution because surrounding air masses with high pressure gravitate toward it when pressure is low. Conversely, when high pressure predominates near the surface, downward airflow occurs in the middle zone. This condition prevents the dilution and dispersion of pollutants, increasing the ambient PM mass concentrations.[33]

The frequency distribution with respect to RH is shown in Fig. 3(c). The largest frequency, 26%, occurs in the 50–60 interval, while the lowest frequency, 2%, occurs in the 90–100 range. Examining the findings, it can be shown that as relative humidity rises, the concentrations of $PM_{2.5}$ and PM_{10} fall.[11,32,34,35]

The rainfall frequency distribution is shown in Fig. 3(d), with 87% of rainfall occurring at intervals less than 1 mm and 2% occurring at intervals more than 45 mm. Increased rainfall often results in lower mass concentrations of both fine and coarse mod PM. $PM_{2.5}$ and PM_{10} concentrations significantly decreased from 60 to 39 μg m^{-3}, particularly when rainfall varied from less than 1 to 1–15. Rainfall can effectively remove particulate matter from the atmosphere.[11,32,34–36]

Similarly, Fig. 3(e) illustrates that 84% of wind speed occurs in the intervals between 0 and 5 knots. While PM_{10} concentrations rise and subsequently fall in the final interval, $PM_{2.5}$ concentrations fall as wind speed increases. The transport of PM from nearby contaminated regions shows no dilution effect, leading to increased mass concentrations of coarse PM.[15,16]

Seasonal regression analysis of $PM_{2.5}$ and PM_{10} with meteorological parameters

During winter, as shown in Fig. 4(a and g), fine ($PM_{2.5}$) and coarse (PM_{10}) particulate matter exhibit a significant negative association with temperature having coefficients of determination of $R^2 = 41.44\%$, and $R^2 = 17.46\%$ for fine $PM_{2.5}$, and coarse PM_{10} particulate matter, respectively. High temperatures

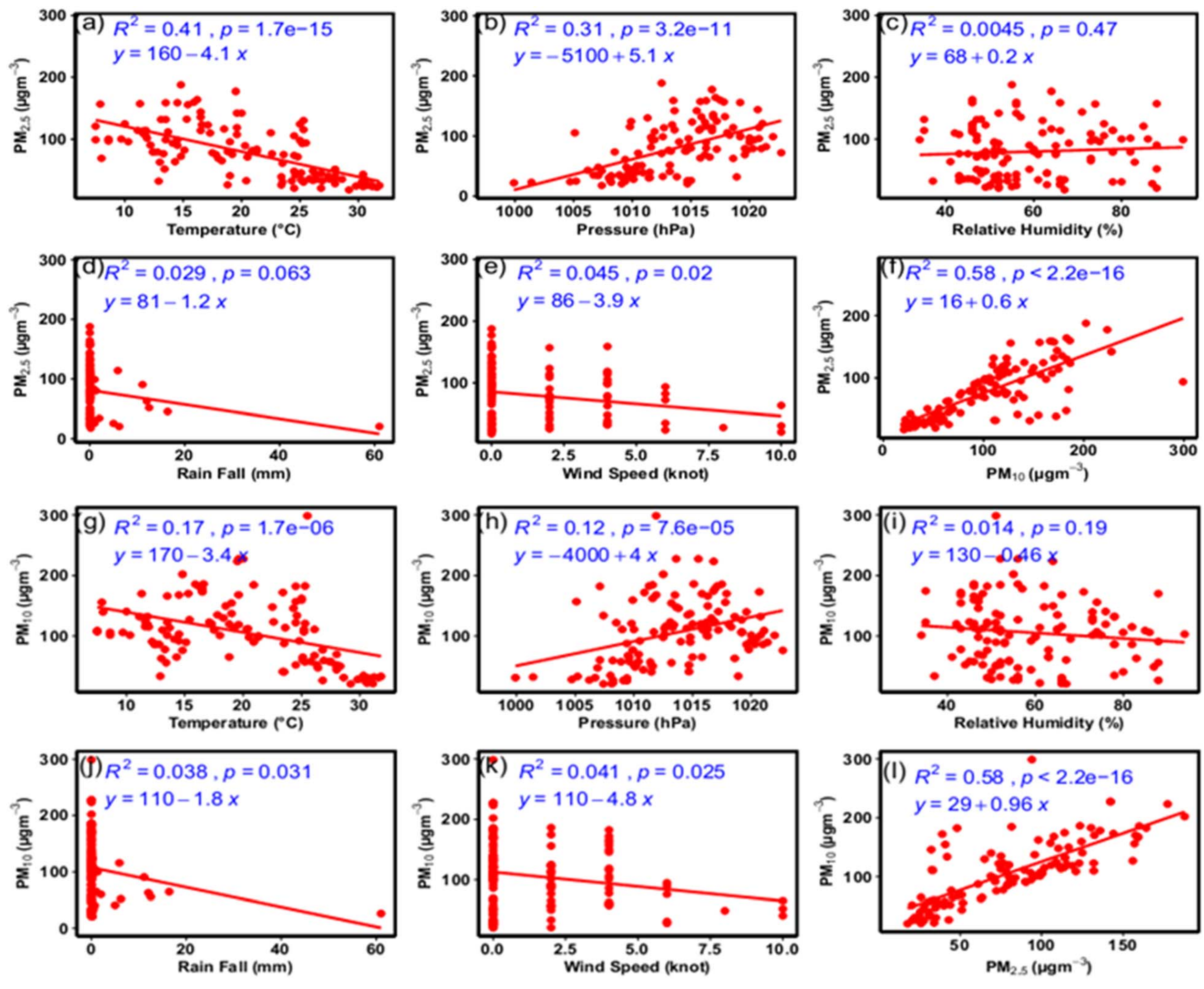

Fig. 4 Linear regression of $PM_{2.5}$ and PM_{10} with meteorological parameters in winter, *i.e.*, (a) $PM_{2.5}$ *vs.* temperature, (b) $PM_{2.5}$ *vs.* pressure, (c) $PM_{2.5}$ *vs.* relative humidity, (d) $PM_{2.5}$ *vs.* rain fall, (e) $PM_{2.5}$ *vs.* wind speed, (f) $PM_{2.5}$ *vs.* PM_{10}, (g) PM_{10} *vs.* temperature, (h) PM_{10} *vs.* pressure, (i) PM_{10} *vs.* relative humidity, (j) PM_{10} *vs.* rain fall, (k) PM_{10} *vs.* wind speed, and (l) PM_{10} *vs.* $PM_{2.5}$.

promote strong convection currents, which transport PM swiftly and effectively through the atmosphere, causing PM to disperse quickly.[11,28,32,35]

Because of the high ambient temperature in winter, Nguyen *et al.*[27] found that nitrate and ammonium concentrations were much lower than in summer. As a result, a significant decrease in the ambient PM occurs as the temperature rises throughout the winter. Similar findings were reported by Li *et al.*[32] for Hong Kong's wintertime temperature and $PM_{2.5}$, which showed a correlation coefficient of 0.044.

Likewise, Fig. 4(b and h) reveal that fine mode $PM_{2.5}$ has a coefficient of determination of $R^2 = 31.05\%$ with pressure, and coarse PM_{10} has a moderate value of $R^2 = 12.25\%$ respectively. Particulate matter (PM) at the sampling location falls because of a converging updraft at low pressure that promotes the dispersion of PM from the ground into the air. On the other hand, a downdraft that happens at high pressure slows the upward flow of PM, which causes an accumulation of particles in the atmosphere.[32,37]

Additionally, Fig. 4(c and i) show that $PM_{2.5}$ has non-significant relationships with RH having a coefficient of determination $R^2 = 0.45\%$, while PM_{10} also has different value of $R^2 = 1.20\%$. Akyüz *et al.*[38] found that relative humidity and PM in two size fractions have weak and negative correlations throughout winter and summer in Zonguldak, Turkey, from January to December 2007, having non-significant *r*-values of -0.1108 for $PM_{2.5}$ and -0.230 for PM_{10} in the winter season.

Kliengchuay *et al.*[39] reported that there was a negative correlation between PM_{10} and relative humidity in Thailand (2009–2017). Increased atmospheric humidity promotes aqueous processing to produce bigger particles and causes hygroscopic growth to produce larger particles. Relative humidity may also remove air particles, according to similar findings by other studies.[14,15]

Furthermore, Fig. 4(d–j) illustrate that PM and rainfall have a moderately negative coefficient of determination $R^2 = 2.88\%$ for fine $PM_{2.5}$, and $R^2 = 3.82\%$ for coarse PM_{10}. Similar results were reported by Nguyen *et al.*[27] in Ulsan, Korea, indicating that throughout the winter (2011–12), a negative correlation was observed between PM and RH, with values of -0.56 for $PM_{2.5}$ and -0.55 for PM_{10} . Liu *et al.*[15] similarly reported comparable non-significant results for PM and RF in Beijing: $r = -0.03$ for PM_{10} and $r = -0.01$ for $PM_{2.5}$ during the winter season in their nine-year study.

Rainfall has two main effects on the ambient PM in the atmosphere. First, moist deposition of PM results from interactions between raindrops and PM through microphysical processes such as impact and adsorption. Second, the quantity of PM suspended in the air is greatly decreased by rainfall.[11,31]

The coefficient of determination is moderately negative for fine $PM_{2.5}$ having the value of $R^2 = 4.48\%$ with wind speed; on the other hand, $R^2 = 4.10\%$ for PM_{10}, as shown in Fig. 4(e and k). Usman *et al.*[11] also documented in a similar study conducted in Swat (Pakistan) that a negative regression exists between the fine and coarse mod PM with wind speed in the winter season. PM disperses due to wind speed in the sampling site and as a result, the decrease in PM occurs in both fine and coarse modes. The findings of Zhou *et al.*[40] also show that the correlation between $PM_{2.5}$ and PM_{10}, and WS during winter in Beijing and Nanjing (China) are -0.42 and -030 for $PM_{2.5}$ and -0.43 and -0.32 for PM_{10}.

Likewise, the regression analysis between both PM fractions ($PM_{2.5}$ and PM_{10}) showed a coefficient of determination of $R^2 = 57.84\%$ during winter (Fig. 4(f and l)). Yadav *et al.*[21] in Pune, India, reported the coefficient of determination $R^2 = 45\%$ between the two size fractions of PM during winter (2011–12).

Li *et al.*[31] also noted a strong positive regression between PM_{10} and $PM_{2.5}$ in Chengdu during 2009–11, similar to our findings. Similarly, Trivedi *et al.*[41] noted, in Delhi, a strong positive correlation exists between two size fractions of PM in winter seasons, having a value of 0.95. Similarly, the findings of Zhou *et al.*[16] show a strong positive correlation between PM_{10} and $PM_{2.5}$ having a coefficient of determination $R^2 = 92\%$, in Northern China and for Southern China $R^2 = 87\%$, during winter (2012).

As seen in Fig. 5(a and g), the coefficient of determination between PM and temperature throughout the summer season reveals non-significant values of $R^2 = 0.25\%$ for fine $PM_{2.5}$, and $R^2 = 2.83\%$ for coarse PM_{10}, respectively. The results of Zhang *et al.*[14] for three Chinese megacities during 2013–14 correlations of -0.26 for $PM_{2.5}$ and -0.06 for PM_{10} in Beijing, 0.10 for $PM_{2.5}$ and 0.39 for PM_{10} in Shanghai, and 0.37 for $PM_{2.5}$, and 0.48 for $PM_{10,}$ in Guangzhou which are consistent with our findings for the same season. In summer, higher temperatures significantly raise sulfate concentrations while lowering nitrate concentrations, according to Nguyen *et al.*;[27] consequently increasing the secondary PM concentration.

Likewise, as depicted in Fig. 5(b and h), in the summer season, $R^2 = 1.25\%$ for fine $PM_{2.5}$ and $R^2 = 0.005\%$ for coarse PM_{10} respectively, with respect to pressure. The findings of Chithra *et al.*[42] also show a poor association between pressure and PM ($R^2 = 0.16$–0.21) in Chennai, India. Large pressure fluctuations usually result in convection, which spreads contaminants globally instead of affecting their microscopic movements. Liu *et al.*[15] also documented similar findings in Beijing in their nine-year study (2004–12) having a non-significant correlation of $r = -0.05$ for PM_{10} and $r = -0.04$ for $PM_{2.5}$ during the summer season.

Furthermore, as shown in Fig. 5(c and i), the regressions between PM and relative humidity are again non-significant and distinct having R^2 values of 1.52% for $PM_{2.5}$, while for PM_{10} $R^2 = 1.44\%$, respectively. These results agree with the findings of Yang *et al.*[10] having correlation values of 0.30 and 0.06, respectively in north and central China.

Akyüz *et al.*[38] relative humidity and PM in two size fractions have weak and negative correlations in summer, having non-significant *r*-values of -0.053 for $PM_{2.5}$ and -0.104 for PM_{10} in the summer season. Kliengchuay *et al.*[39] noted in Thailand from 2009 to 2019, a negative correlation between RH and PM_{10} having $r = -0.26$. The findings of Liu *et al.*[15] also revealed similar results in summer, reporting a correlation of 0.11 for PM_{10} and 0.26 for $PM_{2.5}$ with RH in Beijing (China).

Besides, in the hot summer season the relationship between PM and rainfall is non-significant, with determination

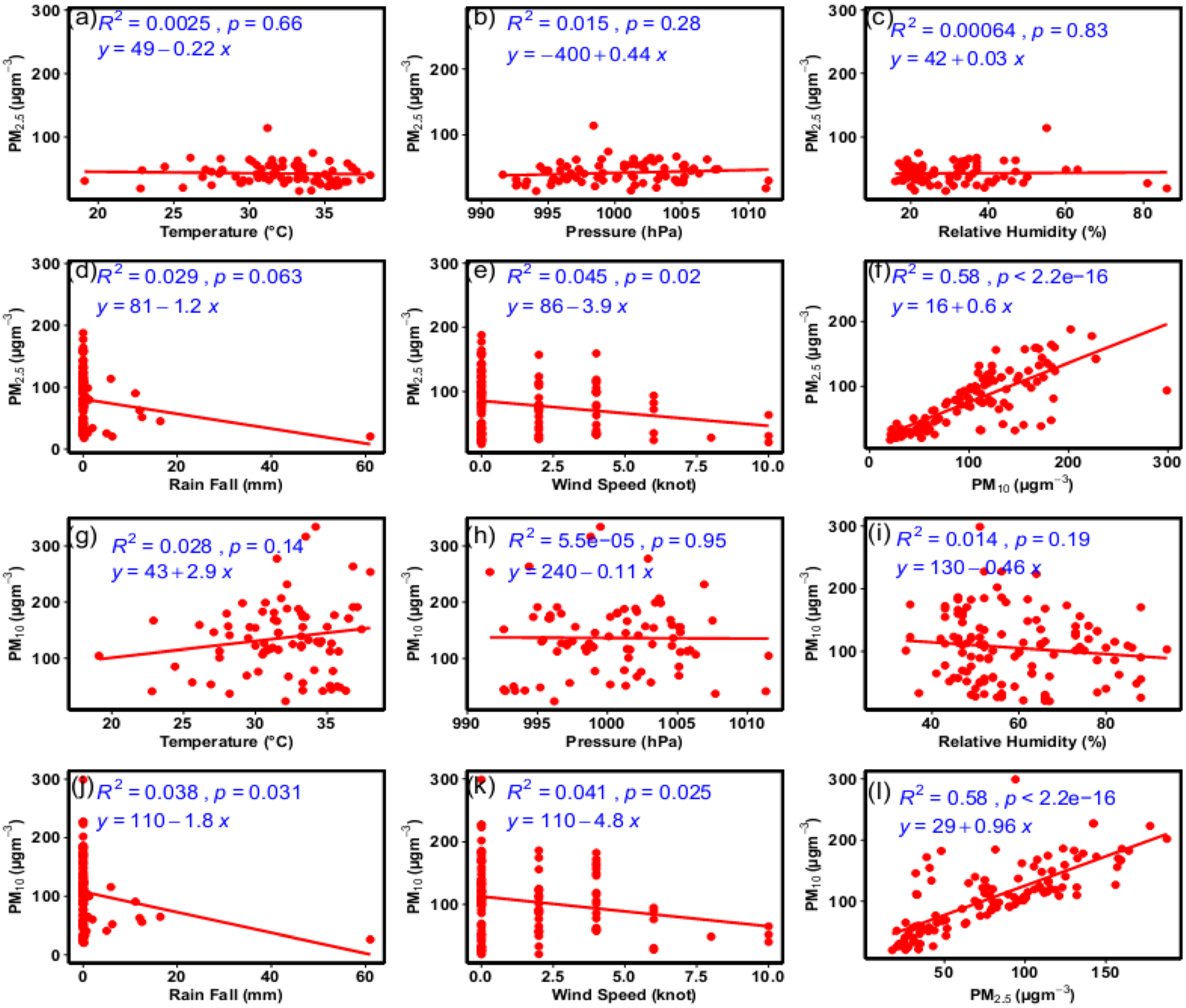

Fig. 5 Linear regression of $PM_{2.5}$ and PM_{10} with meteorological parameters in summer, *i.e.*, (a) $PM_{2.5}$ *vs.* temperature, (b) $PM_{2.5}$ *vs.* pressure, (c) $PM_{2.5}$ *vs.* relative humidity, (d) $PM_{2.5}$ *vs.* rain fall, (e) $PM_{2.5}$ *vs.* wind speed, (f) $PM_{2.5}$ *vs.* PM_{10}, (g) PM_{10} *vs.* temperature, (h) PM_{10} *vs.* pressure, (i) PM_{10} *vs.* relative humidity, (j) PM_{10} *vs.* rain fall, (k) PM_{10} *vs.* wind speed, and (l) PM_{10} *vs.* $PM_{2.5}$.

coefficients of $R^2 = 2.91\%$ for fine $PM_{2.5}$, and $R^2 = 3.80\%$ for coarse PM_{10} as shown in Fig. 5(d and j). Li *et al.*[31] pointed out that rainfall at the sample location significantly affects the elimination of contaminants from the atmosphere. According to Mkoma *et al.*[43] when daily rainfall was within the 5 mm range, the mass concentration of PM_{10} was continuously low during rainstorm events and did not exceed 20 μg m^{-3}.

In addition, fine and coarse PM *versus* wind speed in the summer season has an R^2 value of 4.50%, for fine $PM_{2.5}$, and while an R^2 value of 4.10% for PM_{10} respectively, as shown in Fig. 5(e and k).

Zhang *et al.*[14] documented that in Shanghai China a negative correlation exists between PM and WS having values of $R^2 = -0.68$ for fine $PM_{2.5}$, while $R^2 = -0.58$ for PM_{10}. Similarly, the findings of Usman *et al.*[11] also documented a negative correlation having a correlation coefficient of -0.34 for $PM_{2.5}$ and -0.39 for PM_{10} during a study conducted in Swat Pakistan (2019), and with the increase in WS, particulate matter disperses in the atmosphere and hence reduces its concentration causing negative correlation.

Likewise, in Fig. 5(f and l) the regression between $PM_{2.5}$ and PM_{10} is significantly positive having a coefficient of determination of $R^2 = 22.41\%$, While for PM_{10} and $PM_{2.5}$ is 22.41% during summer. Li *et al.*[31] also documented $r = 0.92$ between two size fractions of PM in Chengdu (China) and the findings of Yadav *et al.*[21] in Pune (India) show a strong positive regression having values of $R^2 = 69\%$ between PM fractions during summer (2011–12). Our findings are consistent with previous results of Trivedi *et al.*[41] Additionally, Zhou *et al.*[16] noted a strong positive association between PM_{10} and $PM_{2.5}$ $R^2 = 68\%$, Northern China and Southern China $R^2 = 97\%$, during summer (2012) analogous to our results.

Throughout the spring season, as depicted in Fig. 6(a and g) a non-significant negative value of $R^2 = 1.30\%$ was observed for fine $PM_{2.5}$ and a strong positive value of $R^2 = 22.31\%$ was observed for coarse PM_{10}. Our results are in line with the

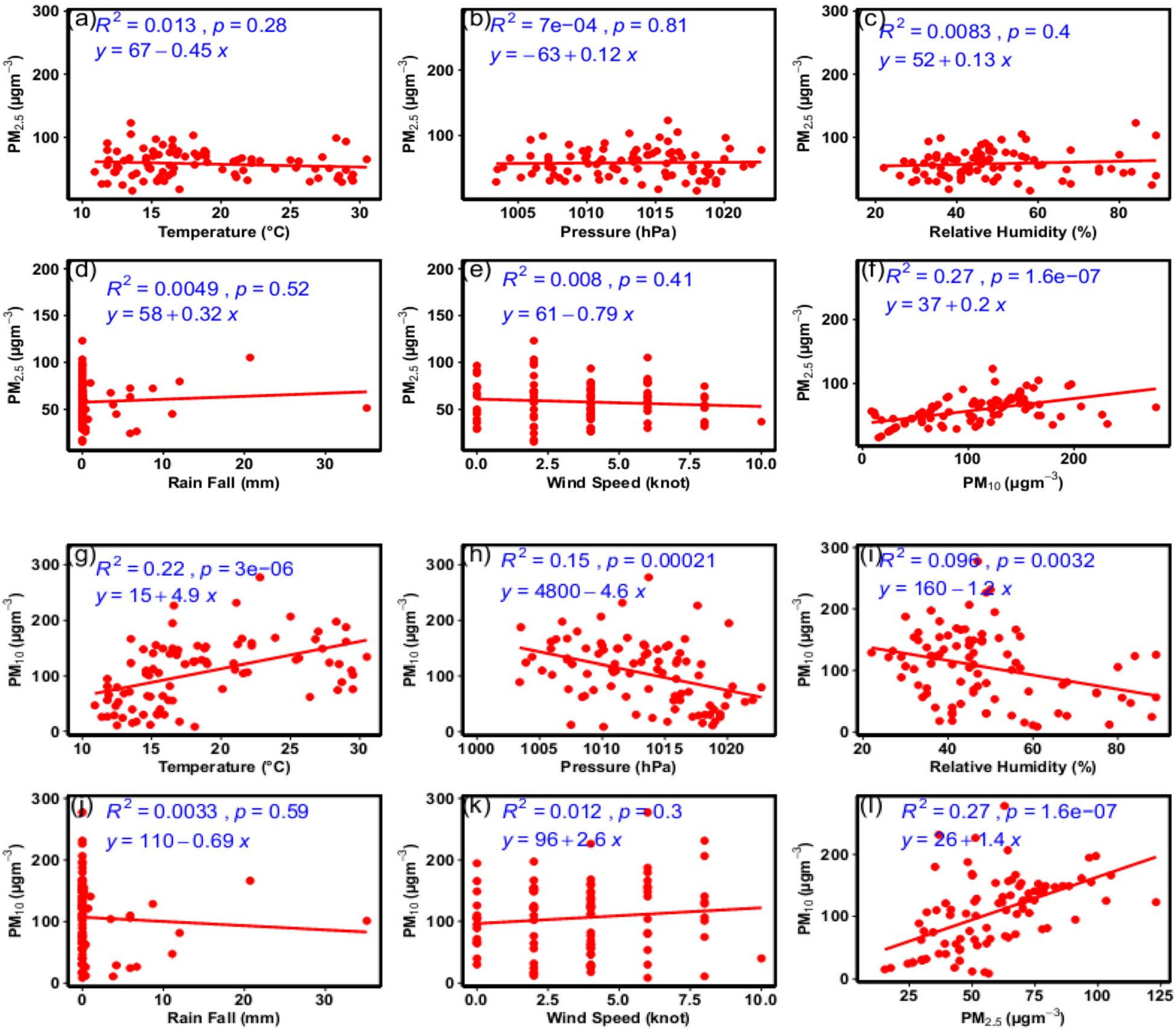

Fig. 6 Linear regression of $PM_{2.5}$ and PM_{10} with meteorological parameters in spring, *i.e.*, (a) $PM_{2.5}$ *vs.* temperature, (b) $PM_{2.5}$ *vs.* pressure, (c) $PM_{2.5}$ *vs.* relative humidity, (d) $PM_{2.5}$ *vs.* rain fall, (e) $PM_{2.5}$ *vs.* wind speed, (f) $PM_{2.5}$ *vs.* PM_{10}, (g) PM_{10} *vs.* temperature, (h) PM_{10} *vs.* pressure, (i) PM_{10} *vs.* relative humidity, (j) PM_{10} *vs.* rain fall, (k) PM_{10} *vs.* wind speed, and (l) PM_{10} *vs.* $PM_{2.5}$.

findings of Zhang *et al.*[26] in Beijing, China, during the spring, $PM_{2.5}$ has a negative correlation ($r = -0.03$) and PM_{10} has a positive correlation ($r = 0.21$) with temperature.

Likewise, PM and pressure revealed a non-significant positive value of $R^2 = 0.07\%$ for $PM_{2.5}$ while a significant negative value of $R^2 = 15.00\%$ for PM_{10} as clear from Fig. 6(b–h). The findings of Chithra *et al.*[42] also revealed a weak association ($R^2 = 0.0237$) between PM and pressure. Liu *et al.*[15] also documented similar findings in Beijing (2004–12), in their nine-year research work that the association of PM and pressure is significant during spring having correlation coefficients for $PM_{2.5}$ ($r = -035$) and PM_{10} ($r = -0.31$), respectively.

Furthermore, in Fig. 6(c–i) again the regression of PM *versus* relative humidity has different values of $R^2 = 0.85\%$ for fine $PM_{2.5}$ while, $R^2 = 9.58\%$ for $PM_{10.}$ Similar findings were observed by Zhang *et al.*[14] in Shanghai (−0.33 for PM10) and Beijing (0.65 for $PM_{2.5}$).

As shown in Fig. 6(d and j), the non-significant values for $PM_{2.5}$ are $R^2 = 0.49\%$ and for PM_{10} is $R^2 = 0.33\%$ with RF in the spring season. In the same way, Li *et al.*[31] found that while $PM_{2.5}$ concentrations decreased less than PM_{10}, PM_{10} concentrations dropped sharply during periods of intense rain. While there was an insignificant positive association between $PM_{2.5}$ and rainfall having values of $r = 0.06$ and $p = 0.733$.

Additionally, the non-significant value of the coefficient of determination for fine $PM_{2.5}$ is $R^2 = 0.79\%$, and for coarse PM_{10} $R^2 = 1.22\%$ demonstrating a negligible regression between PM and WS during the spring season as shown in Fig. 6(e and k). However, there was a considerable correlation ($p < 0.05$) between wind speed and PM_{10}. Even when the city's ambient air is clean, the wind from the surrounding areas may bring pollutants to the sample location, which is the exception cause of the positive correlation between PM_{10} and WS.[10] Similarly, Liu *et al.*[15] also documented that the correlation is not significant for PM_{10} having $r = -0.07$, while significant for $PM_{2.5}$ having $r = -0.38$ during spring.

Likewise, both $PM_{2.5}$ and PM_{10} show a significant positive coefficient of determination ($R^2 = 27.25\%$, for PM_{10} and 27.25% for $PM_{2.5}$) during spring as shown in Fig. 6(f and l). Li *et al.*[31] noted that the correlation between two size fractions of PM each other during the research period in Chengdu (China) had a correlation coefficient ($r = 0.92$). Yadav *et al.*[21] also documented that the coefficient of determination was strongly positive between PM_{10} and $PM_{2.5}$ having $R^2 = 61\%$, in Pune (India), similar to our results. Trivedi *et al.*[41] also documented the significant correlation between two size fractions of PM, revealing that the sources of these PM were the same and originated from the same regions in the case of different sources. Similarly, Zhou *et al.*[16] investigated a strong positive correlation between PM_{10} and $PM_{2.5}$ having an R^2 value of 54%, Northern China and Southern China $R^2 = 88\%$, during spring (2012) similar to our results.

In a similar way in the autumn season a negative coefficient of determination is observed between PM and temperature, with $R^2 = 42.00\%$ for $PM_{2.5}$, and $R^2 = 43.00\%$ for PM_{10}, as shown in Fig. 7(a and g). The research work of Usman *et al.*[11] Mukta *et al.*[36] and Onuorah *et al.*[28] revealed that due to a rise in temperature convection plays its role because of rapid dispersion of ambient PM and hence causes a reduction in the mass concentration. Our findings agree with the results of Zhang *et al.*[14] in Guangzhou (China) having correlation values between PM and temperature of $r = -0.38$ for fine $PM_{2.5}$ and $r = -0.33$ for coarse PM_{10} respectively, during the autumn season.

Likewise, the R^2 value of fine $PM_{2.5}$ is 34.42%, while the R^2 value of 29.49% for PM_{10} between PM and pressure as shown in Fig. 7(b and h). The results of Li *et al.*[31] show that during autumn the correlation between $PM_{2.5}$ and pressure is positive having $r = 0.42$, in Hong Kong. Similarly in Beijing, Liu *et al.*[15] also noted in their nine-year research the correlation coefficients are $r = -0.18$ for PM_{10} and $r = -0.14$ for $PM_{2.5}$ during the autumn season.

Besides, PM in both fine and coarse modes shows a non-significant negative correlation with relative humidity having R^2 values of 0.06% for $PM_{2.5}$, and $R^2 = 9.60\%$ for PM_{10}, as shown in Fig. 7(c and i). The findings of Onuorah *et al.*[28] in Nigeria showed that the correlation values of relative humidity are $r = -0.01$ for $PM_{2.5}$ and $r = 0.04$ for PM_{10}, which are non-significant values. This suggests that as relative humidity increases, $PM_{2.5}$ concentrations experience a slight reduction. This minor

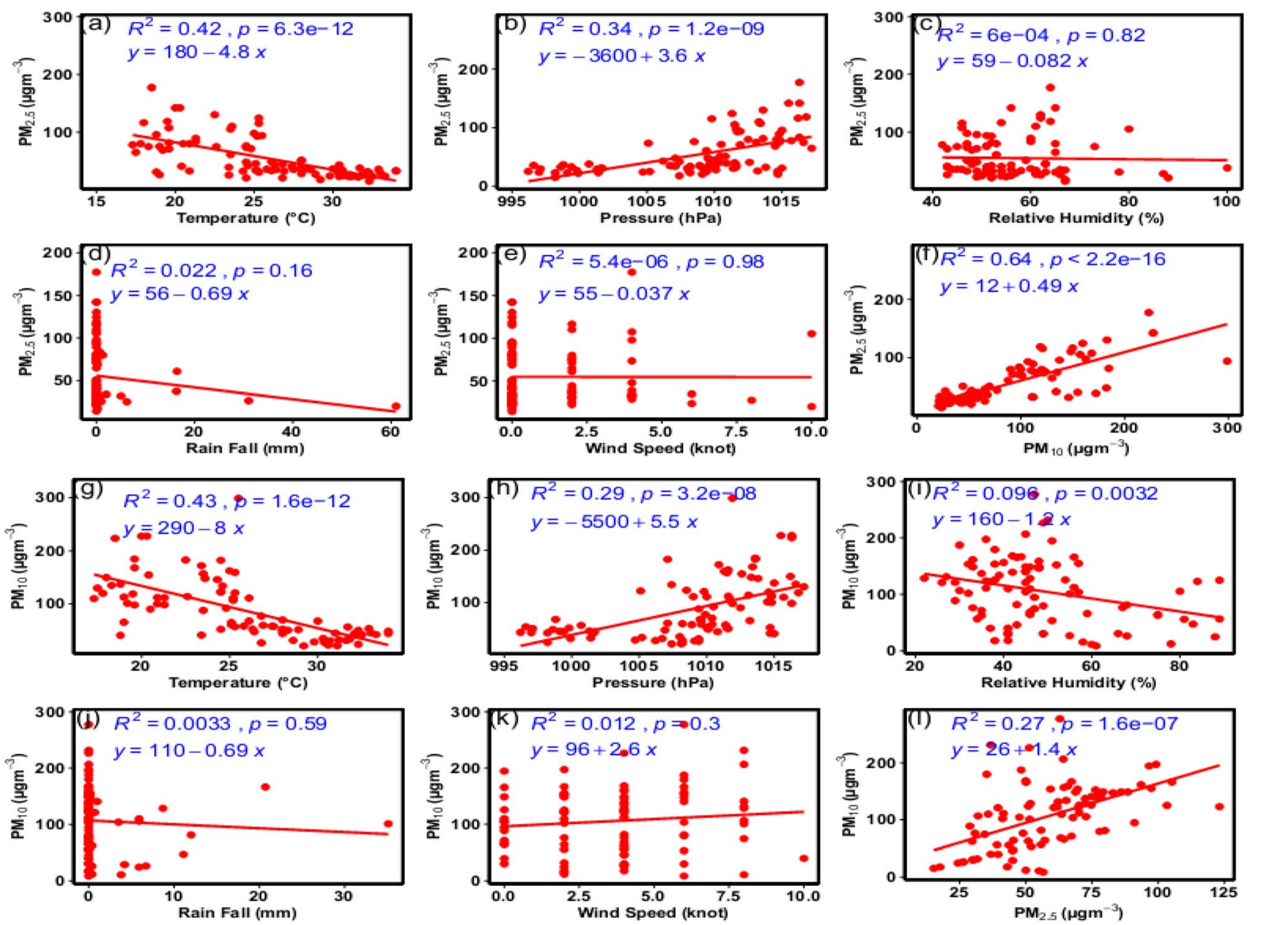

Fig. 7 Linear regression of $PM_{2.5}$ and PM_{10} with meteorological parameters in autumn, *i.e.*, (a) $PM_{2.5}$ *vs.* temperature, (b) $PM_{2.5}$ *vs.* pressure, (c) $PM_{2.5}$ *vs.* relative humidity, (d) $PM_{2.5}$ *vs.* rain fall, (e) $PM_{2.5}$ *vs.* wind speed, (f) $PM_{2.5}$ *vs.* PM_{10}, (g) PM_{10} *vs.* temperature, (h) PM_{10} *vs.* pressure, (i) PM_{10} *vs.* relative humidity, (j) PM_{10} *vs.* rain fall, (k) PM_{10} *vs.* wind speed, and (l) PM_{10} *vs.* $PM_{2.5}$.

decrease occurs because particles absorb moisture, increasing their mass, which subsequently promotes dry deposition.

Similarly, a negative correlation having values of $r = -0.43$ for $PM_{2.5}$ and $r = -0.53$ for PM_{10}, during autumn was reported in Guangzhou.[14,40] Likewise, the findings of Liu *et al.*[15] also revealed $r = 0.40$ for PM_{10} and $r = 0.47$ for $PM_{2.5}$ in Beijing China during autumn.

As shown in Fig. 7(d and j), a non-significant negative correlation is observed having values of $R^2 = 2.27\%$ for fine $PM_{2.5}$, and $R^2 = 0.33\%$ for coarse PM_{10} with rainfall during the autumn season. Similarly, the findings of Li *et al.*[31] recognized that PM_{10} concentrations intensely drop during heavy rain, although fine $PM_{2.5}$ concentrations declined to a lesser extent as compared to coarse PM_{10}. The washout process during rainfall is responsible for the reduction of PM concentration in the atmosphere.

Similarly, the coefficient of determination between fine and coarse mod PM and wind speed revealed non-significant negative and non-significant positive values of 0.005%, and 1.20% respectively, as shown in Fig. 7(e and k). The ambient air at the study site is clean, but the wind from the surrounding areas might transport contaminants to the sampling location, due to this a positive association between PM_{10} and WS exists.[10]

Likewise, during autumn both fine $PM_{2.5}$ and coarse PM_{10} show strong positive regression having a coefficient of determination value of $R^2 = 64.00\%$, while $R^2 = 27.00\%$ between PM_{10} and $PM_{2.5}$, as revealed in Fig. 7(f and l). In Pune, India, the findings of Yadav *et al.*[21] showed strong positive regressions between fine and coarse PM fractions having an R^2 value of 61%, for the whole study period. Our results are consistent with the previous results of Zhou *et al.*[16] that showed a strong positive

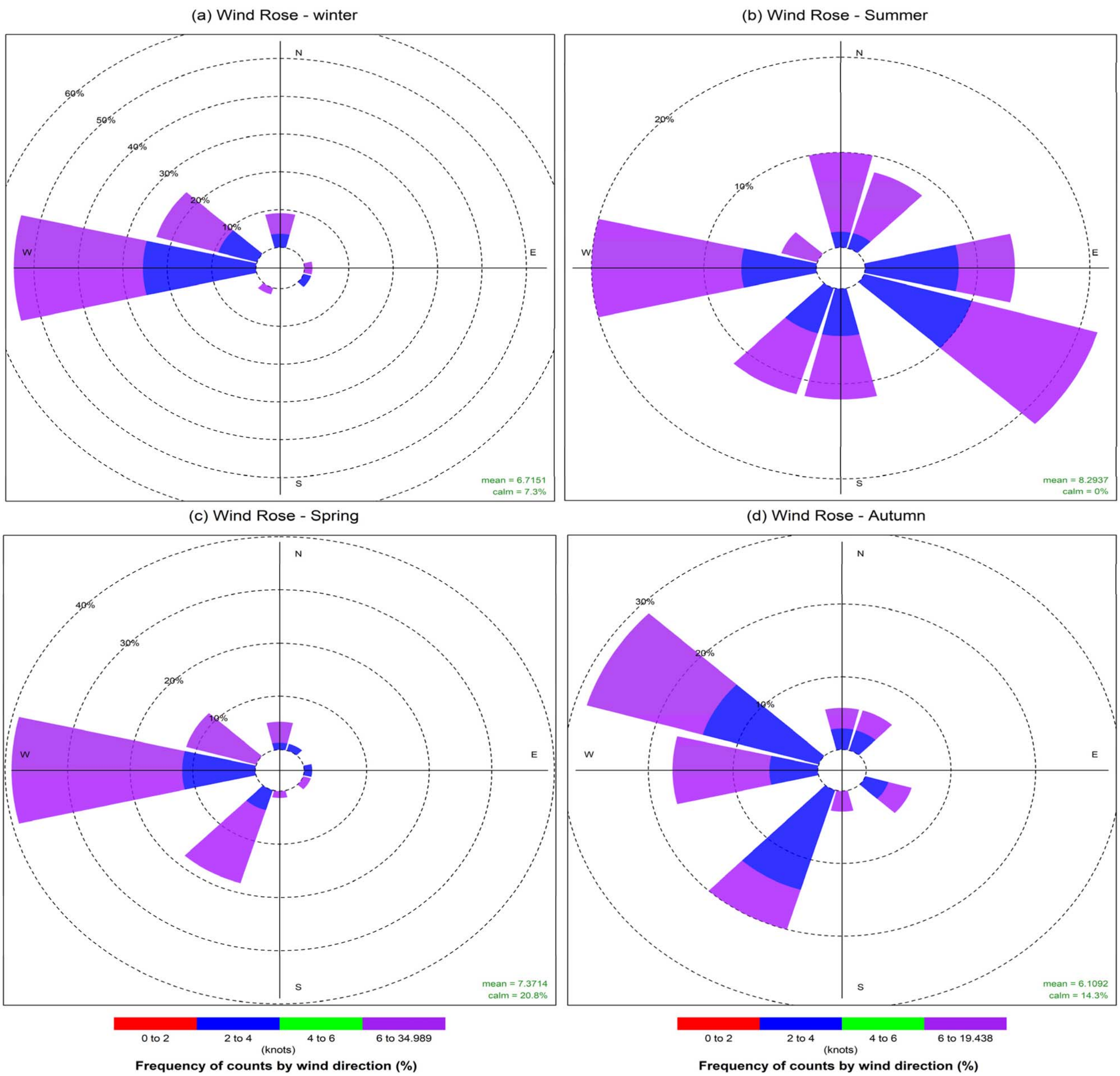

Fig. 8 Wind rose plot for (a) winter, (b) summer, (c) spring and (d) autumn seasons (2019) at 5.00 PM (PST).

correlation between PM_{10} and $PM_{2.5}$ with an $R^2 = 85\%$, and $R^2 = 98\%$ in Northern China and Southern China, during autumn (2012).

Fig. 8 reveals wind rose plots for winter, summer, spring, and autumn seasons during 2019. Most air masses reach the facility from a westerly or south-easterly direction. The wind rose for winter indicates that winds predominantly originate from the west (W) direction. The most frequent wind speed range observed was 6–10 knots, with occasional gusts reaching 10 knots. Periods of calm winds accounting for 7.30% contribute to the accumulation of pollutants; a slow speed of 40% (2–3.9 knots) also localized pollutants accumulation, and a high wind speed (4–10 knots), having a frequency of 52.70% of the total time during winter, promotes the movement of air masses across regions and facilitates the long-range transport of pollutants. Moreover, in summer the winds originate from the south-easterly and west directions. Periods of calm winds were 0%, slow winds occurred 38.33% (2–4 knots) of the time, and high speed (4–10 knots) accounted for 61.66% of the total duration during summer. Similarly in spring, periods of calm winds were 20.77%, slow speed was 19.48% (2–4 knots), and high speed (4–10 knots) had a frequency of 59.74%, and winds predominantly originate from the west (W) direction. Furthermore, the wind rose for autumn indicates that winds predominantly originate from the north-westerly and south-westerly directions. Periods of calms were 14.30%, slow speed 42.85% (2–4 knots), and high speed (4–10 knots) having a frequency of 42.86% of total time during the autumn season. The findings of Pawar *et al.*[44] also agree with our results.

There are also some limitations and uncertainties in our study. First, the relationships between PM concentration and meteorological factors are very complex, and we cannot figure out the specific interaction process only through regression analysis. More multivariate analyses are needed. In addition, physical models such as the Chemical Transport Model (CTM) can also simulate and describe the complex relationship better. In the future study, we will pay more attention to multivariate analysis and CTM; the combination of these two different methods would also be very interesting and worth further research.

Conclusions

The present study investigated the relationship between meteorological parameters and ambient PM ($PM_{2.5}$ and PM_{10}) concentrations during 2019 in Lahore, Pakistan. The average mass concentration of fine $PM_{2.5}$ was highest in winter, followed by spring, autumn, and summer, whereas PM_{10} concentration was highest in summer, followed by spring, winter, and autumn. The reported concentrations were above the threshold levels of WHO, *i.e.*, the yearly average of $PM_{2.5}$ is 11 times and PM_{10} is 5 times the interim targets of WHO. Regression between $PM_{2.5}$ and PM_{10} revealed that the autumn season had the highest coefficient of determination ($R^2 = 63.88\%$), followed by the winter season ($R^2 = 57.84\%$), spring ($R^2 = 27.25\%$), and summer ($R^2 = 22.41\%$).

Temperature, pressure, relative humidity, rainfall, and wind speed were among the meteorological parameters that affected the mass concentration of particulate matter $PM_{2.5}$ and PM_{10}. In winter and summer, the regressions between $PM_{2.5}$ and PM_{10}, and climatic factors including temperature and rainfall were negative; however, it was weak and negative during spring and autumn. Both fine and coarse PM have positive regressions with pressure, RH, and WS in winter but have a weak positive correlation during spring. Similarly, a negative correlation of $PM_{2.5}$ and PM_{10} was found to exist with RH and WS during autumn.

Therefore, we concluded that both meteorological parameters and local anthropogenic activities have an impact on the PM mass concentrations at the research site. These findings can also be used to develop plans to reduce PM pollution in the area for the protection of human health and the environment. Integrated management involving citizens and organizations (governmental and non-governmental) must play its role in controlling aerial pollution to improve the overall health of the densely populated area of Lahore, Pakistan. There is a need for the proper air quality management of vehicular and industrial sources as well as emission factors should be calculated for the proper control and abatement of air pollution sources. Moreover, legislation and political dialogues between the nations (Pakistan and India) are key to controlling the transboundary interference of air pollution along the border as most of the pollutants are transported through atmospheric air movement.

Data availability

Data will be made available on reasonable request from the corresponding author.

Author contributions

Shafiq Ahmad: writing – original draft, visualization, validation, software, resources, methodology, investigation, formal analysis, data curation, conceptualization. Bahadar Zeb: writing – review & editing, visualization, validation, supervision, software, resources, project administration, methodology, funding acquisition, formal analysis. Farooq Usman: writing – review & editing, visualization, validation, software, resources, project administration, methodology, formal analysis, conceptualization. Khan Alam: writing – review & editing, visualization, validation, software, resources, project administration, methodology, formal analysis, conceptualization. Iftikhar Ahmad: writing – review & editing, visualization, validation, software, resources, project administration, methodology, formal analysis, conceptualization. Allah Ditta: writing – review & editing, visualization, validation, software, resources, project administration, methodology, formal analysis, conceptualization. All authors read and approved the final manuscript.

Conflicts of interest

There are no conflicts to declare.

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