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TEMPORAL DYNAMICS OF AIR POLLUTANTS IN SMOGGIEST LAHORE

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Abstract

Temporal prevalence of air pollutants, responsible smog precursor and influencing meteorological parameters were investigated in the ambient air of Lahore, fourth smoggiest city of the world. For statistical analysis, data set of three years on air quality parameters was obtained from Air Quality Monitoring station (CAAQMS) located on Jail Road, Lahore. According to the results, monthly concentration range of PM_{10}, $PM_{2.5}$, NO, NO_2 in every winter was significantly higher than PEQs and WHO-AQGs whereas the tropospheric ozone was higher in summer but below standard limits. While Mann-Kendall test and Sens-slope estimator showed non-significant declining slope of PM_{10}(SSE=-3.729μg/m^3), $PM_{2.5}$(SSE=-1.408μg/m^3), NO(SSE=-1.318μg/m^3), NO_2(SSE=-2.459μg/m^3), SO_2(SSE=-1.672μg/m^3) over the entire study period. Whereas 60% AQI values of $PM_{2.5}$ were responsible for unhealthy smoggy winter. Upwinds only from northwest of Lahore, where Sheikhupura Industrial Zone, heavy vehicular traffic and agricultural lands are dominant emission sources, contributes in winter season of Lahore. Furthermore, NO, NO_2, SO_2, $PM_{2.5}$, PM_{10} were high in winter due to significantly high ($r \geq 0.7$) air pressure and low ($r \geq -6$) temperature, sunshine, and wind speed while ozone was profoundly high in summer due to ($r \geq 0.8$) high temperature >wind speed >relative humidity >sunshine hour and low air pressure. These findings suggest that meteorological conditions significantly affect the temporal prevalence of air pollutants in Lahore. Particulate matter ($PM_{2.5}$) is major cause of acidic smoggy winters while the emissions from upwind areas contribute in worsening the smoggy winter every year .Therefore, Government require a spatio-temporal emission abatement plan to combat with smog consequences.

Keywords: Lahore Smog, AQI, Meteorological Factors, Particulate Matter.

INTRODUCTION

The deterioration of air quality has emerged as a significant global concern due to its adverse socioeconomic and environmental effects. The pathogenicity of air pollutants depends on factors like their size, concentration, and source. Both biogenic and anthropogenic sources contribute significantly in gaseous emissions.

Empirical data indicates that the industrial revolution, starting in the 18th century, introduced various toxic pollutants into the environment (Manisalidis et al., 2020) the excessive use of low-quality fossil fuels in combustion processes has led to the emission

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of greenhouse gases beyond acceptable levels, with fossil fuels being in high demand across various sectors.

The energy sector (25.5%), agriculture (24.3%), industry (21%), transport (14%), energy-related activities (11%), and buildings (6.7%) all contribute to greenhouse gas emissions globally (Abas et al., 2017).

The increasing levels of greenhouse gases have resulted in adverse environmental consequences such as global warming, climate change, and ozone depletion. World temperature has risen to 0.74C since 1961 and temperature will further rise to 1.8 C (Shu-Yue et al., 2020) these climatic changes have exacerbated the photochemical transformation of air pollutants into hazardous substances, leading to emergence of extraterrestrial hazard in form of smog.

Smog formation involves the mixing of gaseous by-products with fog under specific atmospheric conditions, primarily attributed to pollutants like $PM_{2.5}$, while carbon, nitrogen, and sulfur make the 70-80% mass of $PM_{2.5}$.

Historical incidents of smog, such as those in London and Los Angeles, highlight the severe health impacts and thousands of causalities (Gera & Bhasin, 2023) and now asian countries like China, Egypt, Calcutta, Brlgrade, yogosalavia, India are on the hit list of smog spell due to transboundary effects of gaseous pollutants and unchecked growth of local emission inventories (Shabbir et al., 2019).

In Pakistan the smog was first documented in Punjab in mid-1990 but issue remained unresolved due to lack of data and negligence of authorities. Consequently, the worst episode of smog with 512 AQI, plagued the whole Pakistan in winter 2016. following up 520 AQI in winter 2017, 484 AQI in 2018, 470 AQI in 2019 and 2020, Even the World air quality report has ranked the Lahore as 4th most polluted city of World due to bad AQI level (≥50) of $PM_{2.5}$ which was 133 in 2017, 114.9 in 2018, 89.5 in 2019, 79.2 in 2020, 86.5 in 2021 and 97.4 in 2022 (IQair, 2022; Goshua et al., 2022).

Local emissions and trans-boundary air pollution, particularly from neighbouring India and China, were thought to be the main cause of deterioration of air quality (Shabbir, 2019). Additionally, heat island effect in city and inadequate natural air purification processes the further aggravated local air quality (Zahedifar, & Darabi, 2024). Furthermore, the primary sources of pollution in Pakistan are the combustion of fuels like coal, petroleum, and natural gas for electricity generation, which release significant amounts of CO_2, CH_4, N_2O, CO, and volatile organic compounds into the atmosphere.

These emissions, trapped in stagnant cold air parcels due to meteorological conditions, contribute to the formation of smog (Nawaz et al., 2023). Since 2016, the smog has been consistently reappearing each year with differing levels of intensity and caused a drastic surge in health issues such as allergies, skin irritation, respiratory problems, cardiovascular illnesses and accidents due to low visibility in Lahore (Abbas et al ., 2017).

Elevated air pollution level has led to a reduction in life expectancy by 5.3 and 4.8 years between 1998 and 2016 among residents of Lahore and Faisalabad cities respectively.

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Pakistan experiences a higher-than-average rate of deaths linked to air pollution (inclusive of indoor PM2.5 and ozone) compared to global standards. The World Bank approximates that Pakistan faces approximately 22,000 premature adult deaths annually due to outdoor air pollution-related diseases (Anjum et al., 2021; Raza et al., 2021; Mohammadi et al ., 2022).

Although government has taken several initiative for air pollutant off setting which include shutting down of brick kilns , banning of agricultural residue burning, and solid waste burning, penalties to industries, but these interventions are insufficient.

Despite all initiative taken by Government, public suffering from the worst health impacts of smog every year could not be eliminated. Thus to combat with the issue of smog in Lahore , formulation of an effective timeframe based emission control strategic plan is highly required at decision making level (Saleem et al.,2019; Shabbir et al., 2019; Raza et al.,2020).

This requires a detail baseline data that cover the monthly concentration range of air pollutant, temporal variability trend in air pollutant prevalence, responsible smog precursor for higher air quality index during smog period, contributory meteorological factors and emission source identification. Although several studies have been published on smog in Lahore but none of them cover these aspects of air pollutants.

Therefore in present research paper, time series data set of three years was scrutinized to find the answer of following research questions

i. Temporally prevailing concentration of air pollutants
ii. Identification of most responsible smog precursor for poor AQI
iii. Most influential meteorological factor on temporal prevalence of pollutant
iv. Most contributory upwind direction to evaluate transboundary affect on smog

MATERIALS & METHODS

Temporal variation in the content of smog precursors e.g., NO, NO_2 SO_2, CO_2, CO, Ozone and particulate matter ($PM_{2.5}$ & PM_{10}) was studied in the ambient air of Lahore (31°15′—31°45′ N and 74°01′—74°39′ E) the second-most populous city of Pakistan, and has been experiencing the worst episodes of smog since 2015.

Air Quality Data Gathering

For this study, real time hourly average concentration of each pollutant ($PM_{2.5}$, PM_{10}, NO_2, NO, O_3, SO_2) from November 2017 to April 2020 was obtained from compact ambient air quality monitoring station (CAAQMS: Air pointer MLU Recordum Austria Europe) installed by Environmental Protection Department in the premises of Meteorological Department on Jail Road which is located in the centre of metropolitan area of Lahore (Fig: 1) and depicts the features of commercial zone. To characterize the emission sources in the vicinity of CAAQMS, several visits to Jail Road were made for visual observations.

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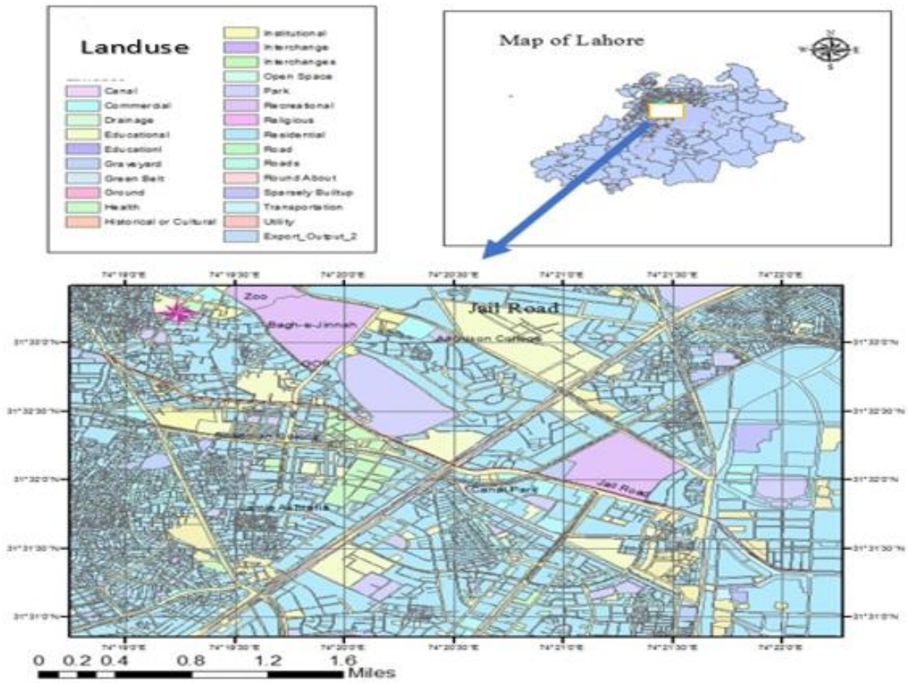

Fig 1: Commercial land use and geographical coordinates of Jail Road, Lahore

Limitation of Data

Current study could examine time series data only from November 2017 to April 2020 because onward continuous time series data was not available due to the malfunctioning of CAAQMS. Moreover, only this single CAAQMS was able to provide data of three continuous years while air quality data of other CAAQMS was non-continuous and only of few months and was not applicable for this study. Furthermore, data on Volatile Organic Compounds in the ambient air of Lahore was not available at CAAQMS

Working Principle of Compact Ambient Air Quality Monitoring Station (CAAQMS)

CAAQMS installed on Jail Road was equipped with analyzing modules and sensors to measure the particulate matter (PM-2.5µg/m^3 and PM-10 2.5µg/m^3), Nitrogen dioxide (NO_2 µg/m^3), Nitrogen monoxide (NO µg/m^3), Sulphur dioxide (SO_2) and Ozone (O_3 µg/m^3) through special sample inlet head installed on the analyser inlet. The ambient air enters the air pointer through sample inlet. Gas goes into the filter inlet and from there it goes into different modules where different kinds of measurements are done. Analysing module for Gas flow of CO use non-dispersive infrared (NDIR) spectrometers which measure the intensity of light absorbed by a sample. Analysing module for Gas Flow of NO/NO_2 use the gas phase chemiluminescence method. Analysing Module for Gas Flow of SO_2 is based on classical fluorescence spectroscopy principles. Analyzing module for Gas flow of Ozone measure the attenuation of light passing through an absorption cell fitted with quartz windows. Whereas sampling of Particulate Matter involve the collection

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and mass determination of particulate matter is through size-selective inlet and through some sort of filter media. Organization follow the QA/QC procedures exactly similar to the manual of monitoring instruments used at each CAAQMs instruments are automatically calibrated /checked every 7 days for span and zero calibrations. While for ambient particulate matter instruments, routine maintenance procedure are performed monthly.

Air Quality Data Validation and Statistical Analysis

Air quality data from CAAQMS, was checked by z-score method to reject temporal outliers due to three reasons: 1) mistakenly entered data, 2) incorrect measurement, 3) intense high concentration of air pollutant .Air quality processing method was applied on CAAQMS data with N70% completeness of total hours. No imputation was used for missing data Because according to guideline of the WHO, CAAQMS should have at least 50% valid data for every year to include their data for trend analysis and if more than 50% hourly data is missing for any air pollutant for a given period at selected station than that defined year would be excluded from the subsequent analysis. Monthly averages of PM_{10}, $PM_{2.5}$, NO_2, NO, SO_2, O_3, were analysed using Non-parametric Mann-Kendall trend test. Mann-kendal test evaluated significant monotonic trend (ascending and descending) in the data and Sen's slop estimator was applied on air quality data to analyze the size and severity of the relationship between time and the pollutant (Barzeghar et al., 2020).While PEQS, 2016 and WHO Air quality guidelines, 2016 were used to observe the conformance of air quality data with standard limits (Table: 1)

Table 1: Punjab Environmental Quality Standards (2016) and WHO Air Quality Guidelines (2021) for ambient air

Sr. no	Parameters	WHO Air Quality Guidelines (WHO-AQG 2021)	Punjab Environmental Quality Standards (PEQS, AQS 2016)
1.	Particulate matter (PM_{10})	45 µg/m^3 24-hour mean	150µg/m^3 24-hour mean
2.	Particulate matter ($PM_{2.5}$)	15 µg/m^3 24-hour mean	35µg/m^3 24-hour mean
3.	Nitrogen Dioxide (NO_2)	25 µg/m^3 24-hour mean	80µg/m^3 24-hour mean
4.	Nitrogen Oxide (NO)	-------	40µg/m^3 24-hour mean
5.	Sulphur Dioxide (SO_2)	40 µg/m^3 24-hour mean	120µg/m^3 24-hour mean
6.	Ozone (O3)	100 µg/m^3 8-hour mean	130µg/m^3 1-hour mean

Air Quality Index

The Air Quality Index (AQI) for all six air pollutants PM_{10}, $PM_{2.5}$, NO, NO_2, SO_2, O_3 was calculated to assess degree of impact of temporally prevailing pollutant on jail road on one's health (Table: 2) by using following equation.

$$AQI_{ap} = \frac{AQI_{UC} - AQI_{LC}}{BP_{UC} - BP_{LC}} (C_{ap} - BP_{LC}) + AQI_{LC} \quad \text{(Jiang } et\ al., 2023)$$

AQI_{UC} and AQI_{LC} represents the air quality index value corresponding to upper and lower break point category (BP), respectively; C_{ap} is the concentration of each air pollutant ;

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BP_{UC} and BP_{LC} are the upper and lower concentration of air pollutant at each breakpoint category respectively.

Table 2: Air Quality Index (AQI) indicating Degree of Impact on Health

Air Quality Index		Degree of Impact on Health
levels of Health Concern	**Numerical Values**	
Good	0-50	Air quality is considered satisfactory, air pollution poses little or no risk
Moderate	51-100	Air quality is acceptable ,however for some pollutant there may be a moderate health concern for a very small number of people who are usually sensitive to air pollution
Unhealthy for sensitive group	101-150	Members of sensitive groups may experience health effects .The general public is not likely to be effected
Unhealthy	151-200	Everyone may begin to experience health effects; members of sensitive group may experience more serious health effects
Very Unhealthy	201-300	Health alert : every one may experience more serious health effects
Hazardous	301-500	Health warnings of emergency conditions. The entire population is more likely to be effected

Meteorological Data Gathering

Climate of Lahore is semi-arid according to Koppen Classification and experience combination of weather with hottest June (< 40°C), wettest July with heavy rainfall and coolest January with dense fog. Therefore, the impact of meteorological factors on the prevalence of air pollutants was also analyzed in the ambient air of Lahore. Meteorological data of sunshine hours, atmospheric temperature (ºC), wind speed (m/s), wind direction, wind pressure (mb) and relative humidity (%) was collected from Meteorological Department, Lahore. Pakistan Meteorological Department uses dry and wet bulb thermometer, maximum and minimum thermometer to measure temperature and humidity and anemometer for wind speed and wind pressure and mercury filled barometer for atmospheric pressure.

Data Processing and Statistical Analysis

Air quality data and meteorological data was subjected to statistical analysis using spss IBM and excel software.

- All data was analyzed for basic descriptive statistics e.g., mean, median, standard error, standard deviations.
- Pearson Correlation of meteorological data with air quality data was analyzed to study the impact of weather parameter on air pollutant prevalence.
- Non-parametric Mann-Kendall trend test and Sen’s slope estimator were employed on the air quality data to scrutinize temporal trends.

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RESULTS AND DISCUSSION

In current study, variability trend in the temporal prevailing gaseous by-products in the ambient air of Lahore was assessed. For this purpose, oxides of nitrogen, sulphur, ozone, and particulate matter were selected as they were identified as instigator for smog with substantial evidences. Result showed (Fig: 2) that mean monthly concentration of PM_{10} (µg/m^3), $PM_{2.5}$ (µg/m^3), NO_2 (µg/m^3), SO_2 (µg/m^3) in year 2018 was comparatively higher throughout the year than year 2017, 2019 and 2020.

Whereas the NO (µg/m^3) monthly concentration range in year 2017 was comparatively higher throughout the year than year 2018, 2019 and 2020. While none of air pollutant showed constant downward or upward trend over the entire study period but overall a declining trend was observed .Non-parameteric man-kendall trend test and sens slop estimator (MKTT-SSE) proves this statistically non-significant declining trend (Table: 3) in PM_{10} (3.729 µg/m^3), $PM_{2.5}$ (1.408 µg/m^3), NO (1.318 µg/m^3), NO_2(2.459µg/m^3), O_3(0.799 µg/m^3) per month.

The decline in the recurring presence of air pollutants can be attributed to governmental initiatives implemented in 2016 following the city's worst smog episode (Hameed et al., 2013). These initiatives included the importation and distribution of low-sulfur fuel to local markets. The fuel sector introduced environmentally friendly low-sulfur diesel with a sulfur content of 500 ppm in 2017, LNG in 2015, and higher-grade gasoline (92/95) in November 2016. Sulfur dioxide, generated by the oxidation of sulfur compounds in petroleum and coal fuels, contributes to acid rain (Afon & Ervin, 2008).

This minor adjustment in fuel quality has visibly reduced sulfur emissions. Additionally, governmental actions involved the strict enforcement of smog policy reforms at the provincial level since 2016. These reforms included halting dust-generating activities, prohibiting stubble and municipal solid waste burning, closing brick kilns during the winter season for three months, imposing fines on pollution-generating vehicles and industries annually throughout the province.

Structural measures such as the widening and construction of signal-free roads in Lahore have also contributed to minimizing fuel combustion emissions (PDMA, 2016), resulting in a decrease in prevailing air pollutant concentrations. Furthermore, during the COVID-19 pandemic lockdown and travel restrictions, reduced industrial activities and vehicular traffic led to lower pollutant emissions, further contributing to the decline in air pollutants.

While assessing compliance with guidelines recommended by WHO-AGS, (2021), it was observed that the interquartile range of PM10 (µg/m3), PM2.5 (µg/m3), and NO2 (µg/m3) remained within permissible limits across all years. However, the monthly interquartile range of SO2 (µg/m3) from November to May in the years 2017, 2018, 2019, and 2020, and the monthly interquartile range of O3 (µg/m3) in summer from June to July in the year 2019 exceeded the permissible limits.

In contrast, compliance with standards (table: 3) recommended by PEQS, (2016) indicated that the monthly interquartile range of PM10 (µg/m3), SO2 (µg/m3), and O3

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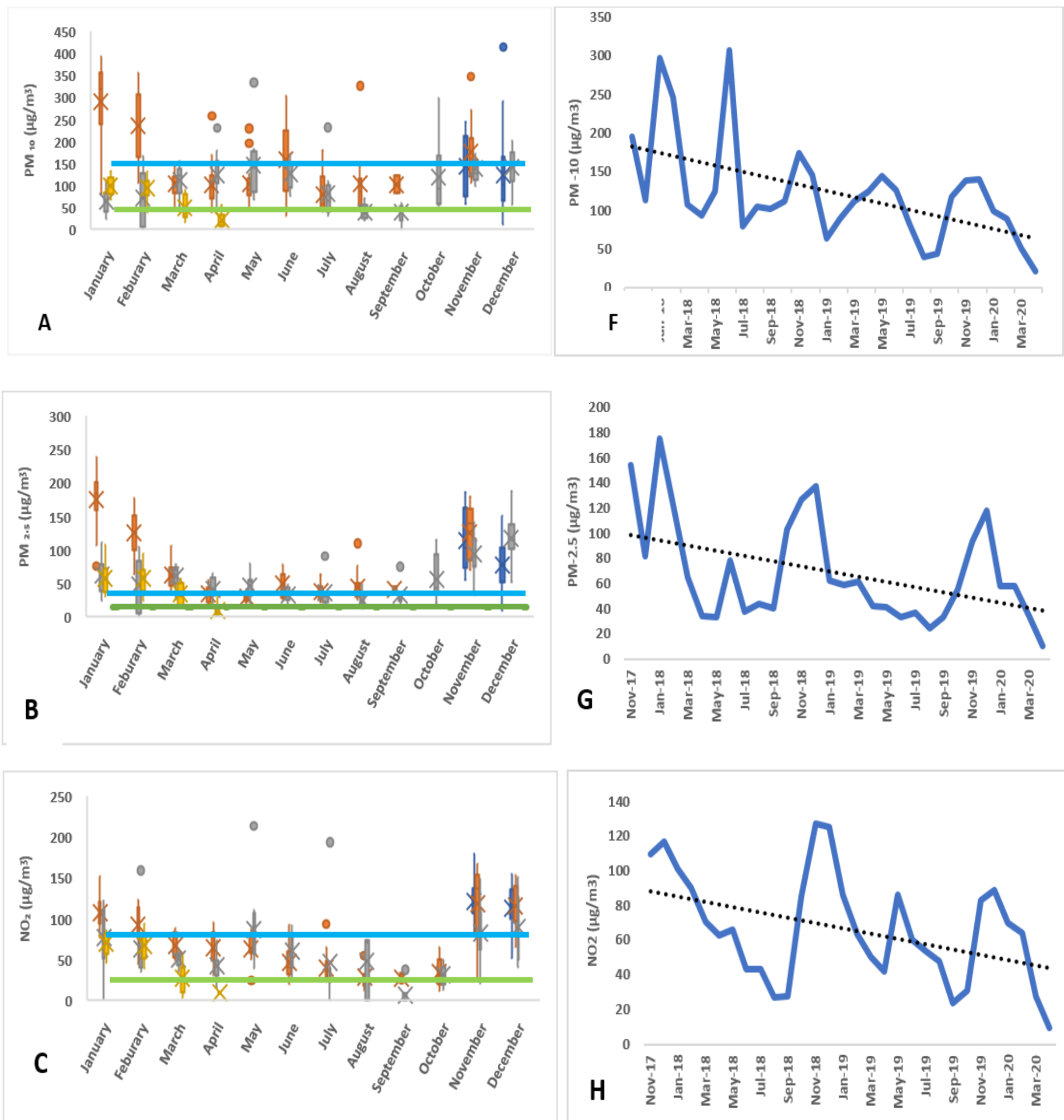
(µg/m3) remained below the permissible limits of 150 µg/m3, 120 µg/m3, and 130 µg/m3, respectively. However, the monthly interquartile range of PM2.5 (µg/m3) and NO (µg/m3) in winter from November to January.



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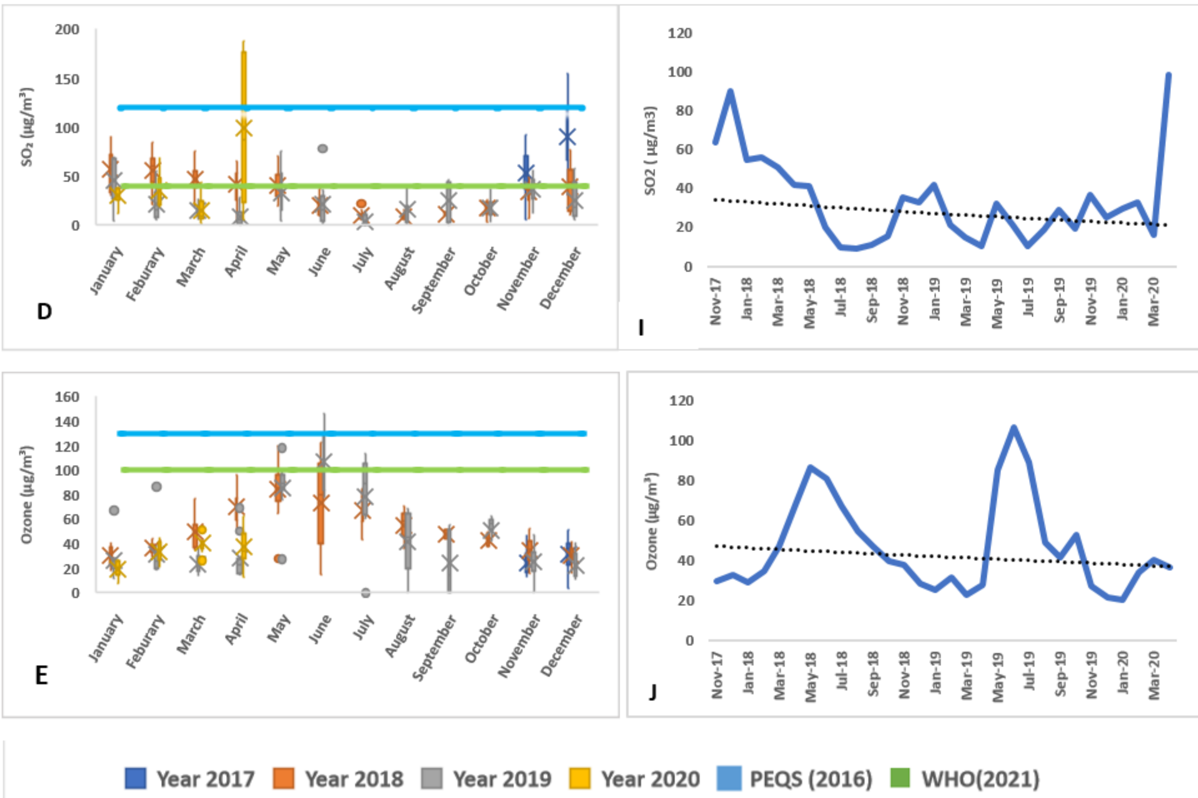

Fig 2: Compliance of monthly concentration range of air pollutant (a,b,c,d,e,f) with PEQS 2016 and WHO-AQG(2021) and temporal variability trend (g,h,I,j,k,l) in monthly mean concentration of PM_{10},$PM_{2.5}$,NO,NO_2,SO_2,O_3.

Table 3: Mann kendall trend and sen's slop estimate of air quality data

Air Pollutant	Mann Kendall Trend (MKT) (s,z test)	Sen's Slop Estimate (SSE) Mean Monthly Concentration	S'
PM_{10}	-0.231	-3.729	-42
$PM_{2.5}$	-0.209	-1.408	-38
NO	-0.110	-1.318	-20
NO_2	-0.209	-2.459	-38
SO_2	-0.220	-1.672	-40
O_3	-0.198	-0.799	-36

In the years 2017, 2018, and 2019, and NO2 (µg/m3) were found to exceed the permissible limits of 35 µg/m3, 40 µg/m3, and 80 µg/m3, respectively, as prescribed by PEQS, (2016).The heightened level of smog precursors observed on Jail Road, Lahore, can be attributed to its characteristics as a 5 km long, 3-lane road situated in a commercial zone. This area hosts various facilities such as hospitals, educational institutes, police stations, departmental stores, restaurants, recreational parks, car showrooms, fuel pump stations, and housing societies along the roadside, where activities like dust generation, burning of biogenic material, improper solid waste management, and combustion of low-

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quality fossil fuels contribute to air pollution. Additionally, being located almost at the center of Lahore city, Jail Road experiences a high influx of vehicles (over 0.1 million), leading to frequent traffic congestion during daytime hours. The majority (over 70%) of vehicles in this area use petrol, followed by compressed natural gas (CNG), liquefied petroleum gas (LPG), and diesel. Scientific evidence suggests that CNG is cleaner in terms of CO2, CO, and SO2 emissions, while LPG is cleaner in terms of NO2 and NO emissions, and petrol is cleaner in terms of hydrocarbon emissions (Hameed, 2013). Moreover, the increase in the number of point sources exacerbates emission factors, as city traffic has risen to 6.2 million vehicles with a 10% annual increase rate since 2005. Out of these, 4.2 million are motorcycles, 2.4 million are non-commercial cars, 0.24 million are rickshaws, and 0.004 million are motorcycle rickshaws, with the rest being delivery vans, buses, and trucks (Butt, 2018; Hameed et al.,2013; Shah et al., 2020). Consequently, 70% of air pollution in the city is attributed to traffic pollution, with poorly maintained vehicles such as auto-rickshaws, pickups, and diesel buses contributing 40% to this pollution

AQI and Responsible Ambient Air Pollutant

Monthly mean AQI of each air pollutant from 2017 to 2020 was calculated and their seasonality trend and health impact category was also studied .According to results (Fig:3), the AQI-$PM_{2.5}$ (Min:43-Max:226) was higher than AQI-PM_{10} (min:19-max:177), AQI-NO_2: (Min:05- Max:65), AQI-SO_2: (Min 04- Max: 52) ,AQI- O_3: (Min:09-Max:50) and showed highest contribution in mean monthly AQI whereas the SO2 and O_3 showed lowest contribution in AQI. Hence a rise in AQI of each pollutant was observed during winter season and fall in summer season except Ozone. Furthermore 60% AQI-$PM_{2.5}$ values remained in and above the category of unhealthy AQI throughout all years.

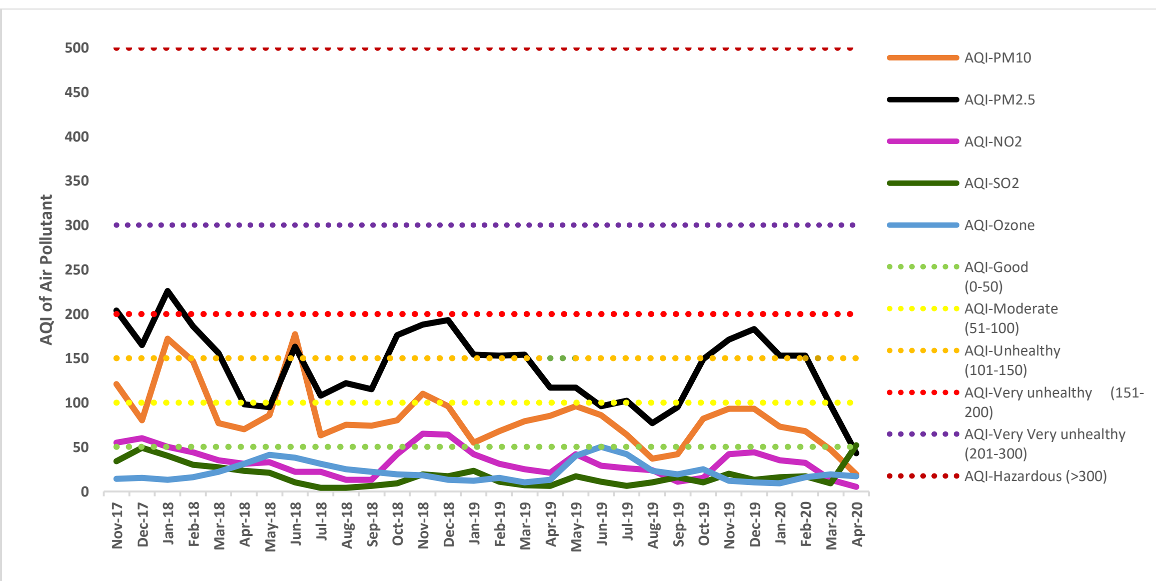

Fig 3: Contribution of each air pollutant in AQI of the ambient air of Lahore during 2017 to 2020

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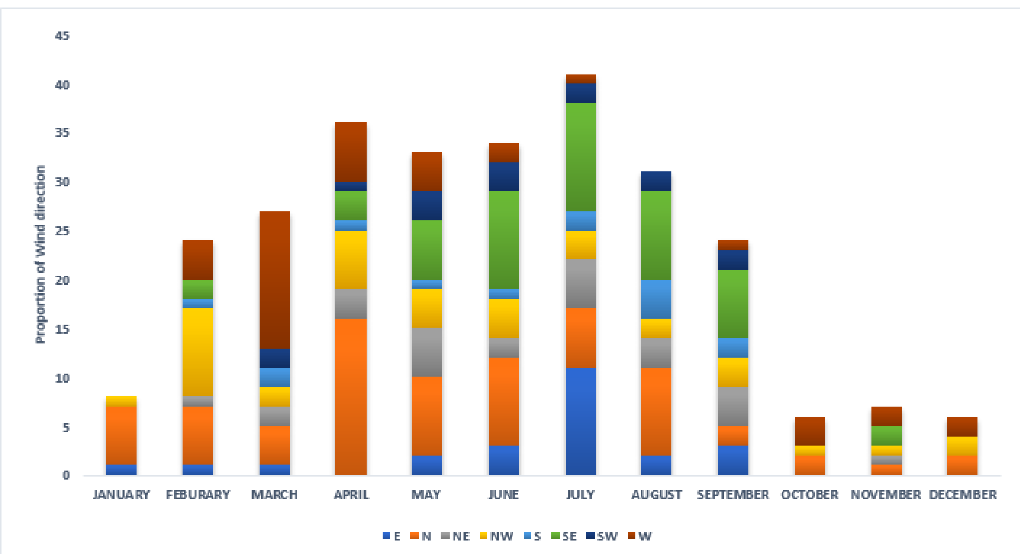
These results are in compliance with the findings of work done by other authors (Faridi et al., 2019)that PM $_{2.5}$ is responsible for smog formation in most cases because $PM_{2.5}$ provide nucleation sites for the condensation of gaseous pollutants and can go undergo chemical reaction, produce secondary aerosols and contribute in the formation of smog. (Javanbakht et al., 2021). Elevated levels of PM $_{2.5}$ contribute to atmospheric stability, trap pollutant near the surface and prevent their dispersion and exacerbate the formation of smog .sulfate, nitrate and carbon are the important component of PM2.5. In some cases, PM $_{2.5}$, can reduce the visibility by scattering or absorbing the sunlight and create characteristic haze of brownish colour. On the base of current findings of AQI, $PM_{2.5}$ is the most significant smog precursor (Ashraf et al., 2022).

Evaluation of Wind Direction as influential factor on temporally prevailing air pollutant

Wind direction has profound effect on the ambient air quality of an area. Wind direction can improve or worsen the air quality by dispersing or concentrating air pollutant due to the fact that upwind either carries away or transport pollutant to downwind area.Result showed (Fig: 4) that Jail Road received not only upwinds from all eight directions but the proportion of winds coming from north (N), north west (NW), west (W), south east (SE), east (E) was higher from February to September. While in October, November, December and January, upwinds moved only from north (N), North West (NW), west (W) of Lahore to Jail Road in small proportions. Because the city is bounded on the north (N) and west (W) by sheikhupora district which is featuring large industrial area and agriculture land whereas on the east (E) by Wahgah border and on the south (S) by Kasur district. Thus, in winter, upwinds travel from Sheikhopura District located on the North West in small proportion, cause stagnant atmosphere, contribute in ambient air pollution of jail Road. Upwinds travel in large proportion from all directions in large proportion and cause dilution of pollutant in downwind area.



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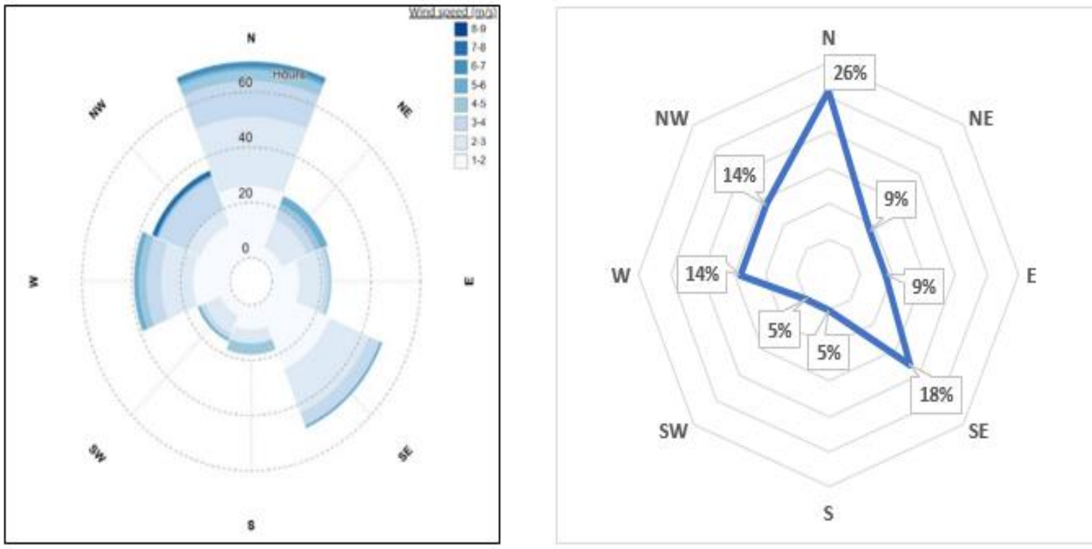

Fig 4: (a) Monthly proportion of prevailing upwind (b) wind speed of upwinds (c) direction and percentage of upwinds

Impact assessment of meteorological factors on the temporal prevalence of ambient air pollutants

Assessing the impact of meteorological factors on the temporal prevalence of ambient air pollutants involved studying various meteorological parameters (Table: 4) such as sunshine hours, temperature (ºC), wind speed (knot), air pressure (mb), and relative humidity (%).

Table 4: Seasonal Variability in meteorological parameters

Season	Months	Monthly Mean Values					
		Sunshine (hrs.)	Relative humidity (%)	Cloud (%)	Wind speed (m/s)	Ambient Temperature (C)	Air Pressure (mb)
Spring	February	7.38	37.9	2.95	4.56	22.15	991
	March	8.3	54	2.675	2.5	27.9	988
	April	9.2	42.5	2.325	2.35	35	984
Summer	May	9.8	34	1.9	2.25	38.45	980.75
	June	8.1	40.5	2.075	2.3	39.5	975.8
Rainy	July	7	73.5	4.025	1.62	34.9	974.1
	August	8.1	68.5	3.975	2	35.5	976.3
Autumn	September	8.4	67	2.725	1.9	34.95	982
	October	8.7	64.7	1.05	1.1	31.65	988.75
Winter	November	6.1	62	2.425	0.65	26.3	991.05
	December	5.3	70	1.45	0.4	19.2	993.55
	January	5	28.6	2.175	3.78	19.85	992.3

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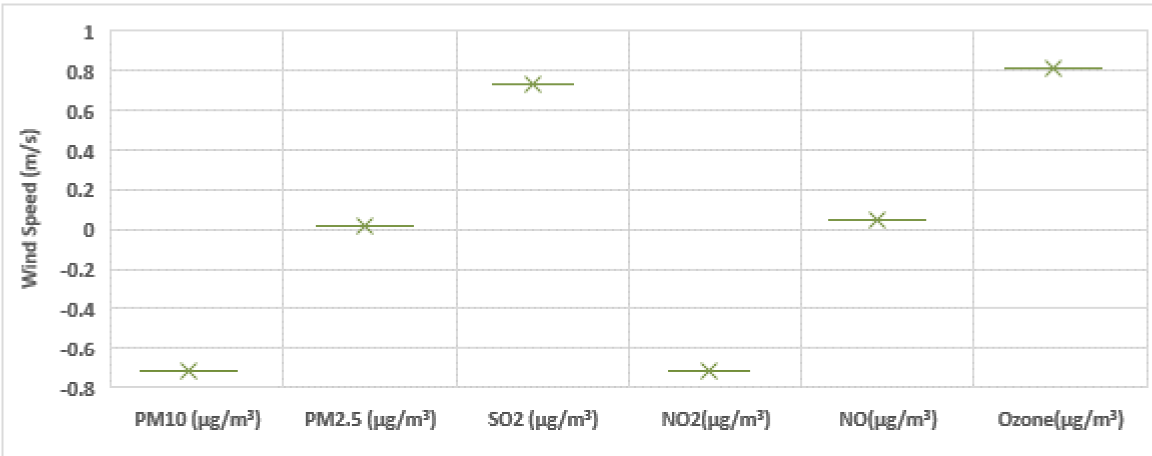
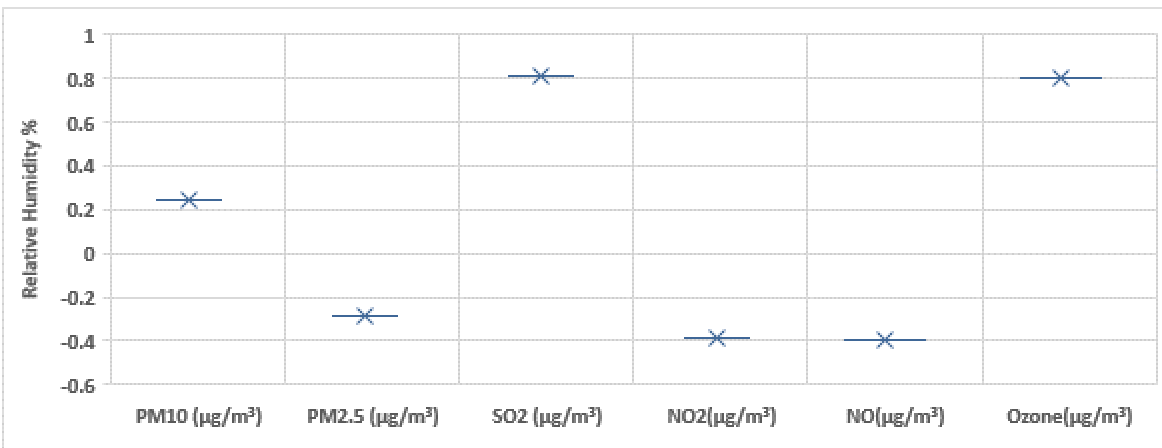
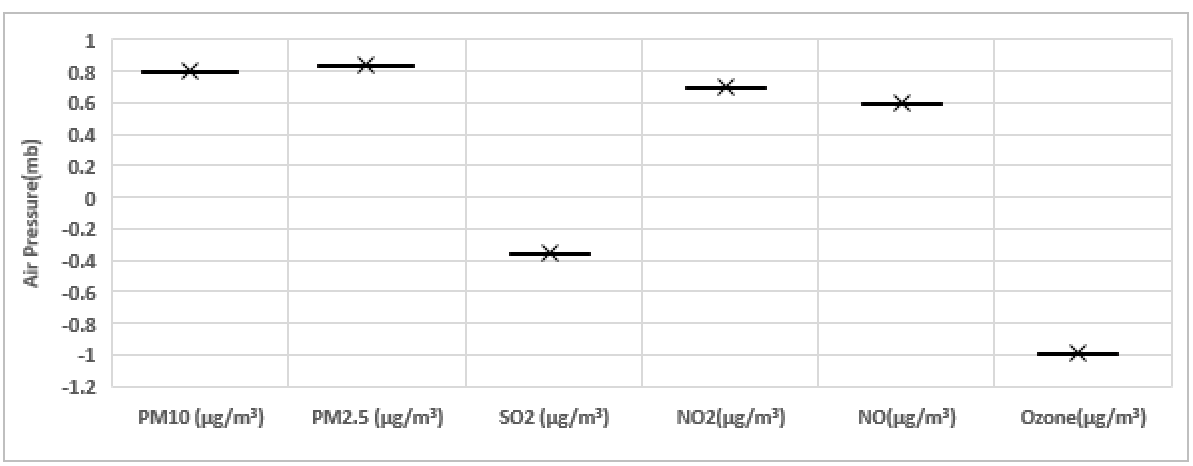
a.



b.



c.



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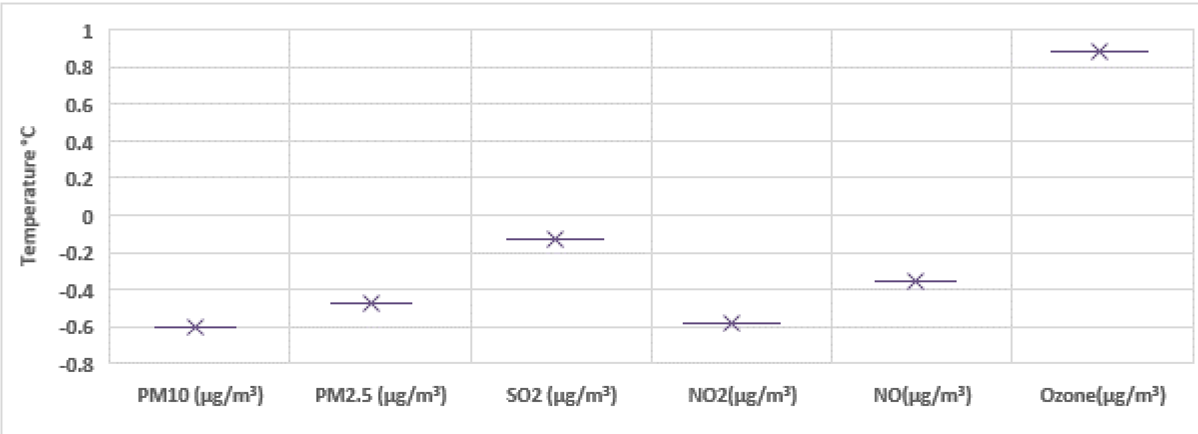
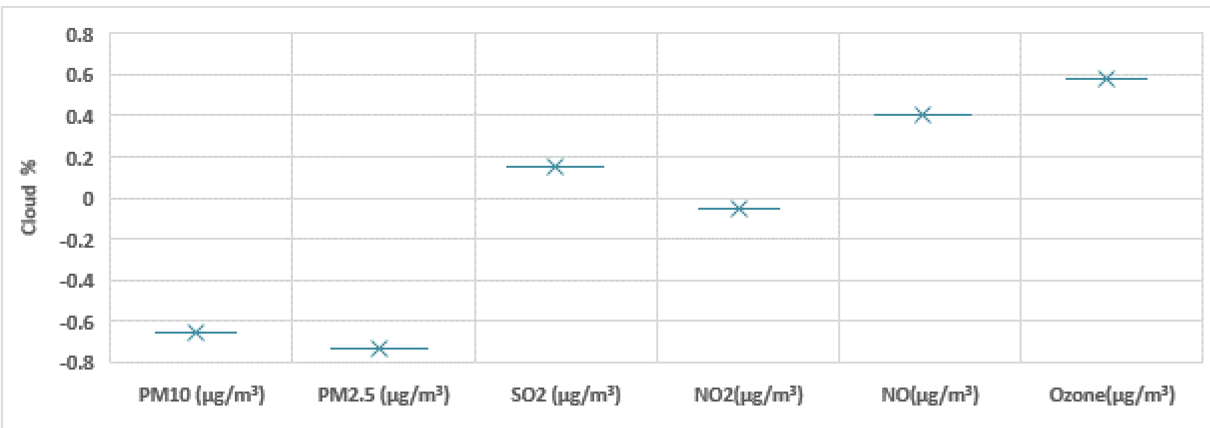
d.



e.



f.

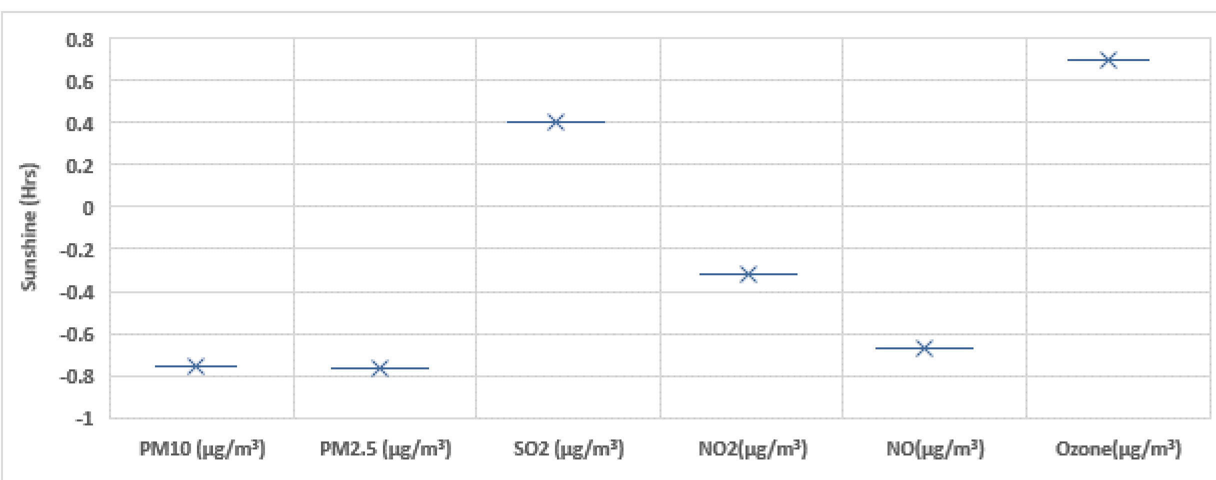


Fig 5: Correlation of ambient air pollutant with meteorological parameter

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The results (Fig.5) revealed that wind speed exhibited a positive association with Ozone (r=0.8099), followed by SO2 (r=0.7284), PM10 (r=0.7127), with PM 2.5 showing a negligible association (r=0.0183). No significant association was found with NO (r=0.051), whereas a highly negative correlation was observed with NO2 (r=-0.714). Air pressure showed a positive association with PM2.5 (r=0.8422), PM10 (r=0.8067), NO2 (r=0.7), NO (r=0.603), with a highly negative correlation found with O3 (r=-0.9834) and a negative correlation with SO2 (r=-0.3565). Cloud percentage exhibited a positive association with O3 (r=0.5788), NO (r=0.4), SO2 (r=0.1553), whereas a highly negative correlation was found with PM2.5 (r=-0.7333), PM10 (r=-0.6599), and NO2 (r=-0.0542). Relative humidity showed a positive association with O3 (r=0.8074), SO2 (r=0.8008), PM10 (r=0.2479), whereas a highly negative correlation was observed with NO (r=-0.3942), NO2 (r=-0.385), and PM2.5 (r=-0.284). Temperature exhibited a positive association with O3 (r=0.8873), whereas a highly negative correlation was found with PM10 (r=-0.6032), NO2 (r=-0.584), PM2.5 (r=-0.476), NO (r=-0.3601), and SO2 (r=-0.1303). Sunshine hours showed a positive association with Ozone (r=0.7) and SO2 (r=0.4) in the ambient air of Jail Road, while PM2.5 (r=-0.769), PM10 (r=-0.76), NO (r=-0.67), and NO2 (r=-0.32) exhibited negative correlations with sunshine hours.

The fluctuations in the temporal prevalence and coexistence trends of air pollutants are ascribed to intermediate gaseous reactions occurring in the ambient air, as revealed in the current study. A significant positive correlation was observed between PM10 and PM2.5 with NO (r = 0.80), followed by NO2 (r = 0.78) and SO2 (r = 0.25), while a negative correlation was noted with ozone (r = -0.45) based on the dataset analysis. Moreover, trend analysis of the temporal concentration range of PM10, PM2.5, NO, NO2, and SO2 showed a notable cyclic rise during the cold season, especially from November to February, and a decline in the hot season from April to August in the ambient air of Jail Road, Lahore.This behavior of air pollutants is influenced by meteorological factors. For instance, in summer, wind convection due to high temperatures causes vertically upward movement of pollutants, dispersing them in the air. The dilution effect of wind speed on pollutants rises initially and then tends to stabilize (Kgabi and Mokgwetsi, 2009). High wind speeds (>12 m/s) promote more dispersion and dilution, while a positive association of PM2.5 > PM10 > NO2 > NO > SO2 and negative correlation with O3 with air pressure was observed.

This is because under low-pressure circulation, mainly in summer, there are more rainy days and frequent changes in wind direction, aiding the diffusion and dilution of particulate matter. Conversely, high-pressure circulation brings more sunny days and stable weather conditions, causing particulate matter to stagnate near the surface. High relative humidity in the air causes agglomeration of PM2.5, mainly in winter. High sulfur content produces sulfuric acid when combined with fog droplets, exacerbating the formation of acidic particles (Rani et al., 2011). NOx concentrations are elevated during the wet season due to recurring thunderstorm flashes producing nitrogen oxide (Griffing, 1977). Temperature and sunshine hours are positively associated with O3 and highly negatively correlated with PM10 > NO2 > PM2.5 > NO > SO2. Higher heat deficit is associated with less turbulence, resulting in high concentrations of particulate matter, while low heat deficit is

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linked to high turbulence, causing lower levels of particulate matter in summer. High temperatures (>24°C) promote more dilution than dispersion, especially observed in summer, where wet ground due to precipitation traps more pollutants near their sources under strong temperature inversion conditions (Plocoste et al., 2018). Variation in meteorological factors at inter-month scale triggers different intermediate gaseous reactions in the ambient air, leading to the formation of particles smaller than 2.5 µm. These particles originate from secondarily formed aerosols, combustion particles, recondensed organic, and metal vapors.

Sulphur dioxide oxidizes in the atmosphere to form sulfuric acid, which can be neutralized by NH3 to form ammonium sulfate (Park et al., 2007). These secondary particles, dominant in fine particles produced mostly in winter, make the atmosphere more acidic by contributing to the formation of suspended tiny acid droplets. The higher concentration of ozone in summer is attributed to the oxidation of carbon monoxide, nitrogen dioxide, hydroxide, and VOCs triggered by photochemical reactions, resulting in elevated ground-level tropospheric ozone (Uzoigwe et al., 2013). High sunshine time, UV index, and temperature in summer trigger the high occurrence rate of photochemical reactions, leading to the formation of brownish oxidative air pollution (Derwent et al., 2016).

CONCLUSION

In summary, the recent investigations have unveiled that the winter peak mean concentrations of PM10 (307.76±54.9 µg/m3), PM2.5 (176±89 µg/m3), NO (250±35 µg/m3), and NO2 (127±07 µg/m3) exceeded significantly the standards set by Punjab Environmental Quality Standards (PEQS, 2016) and WHO-AQG (2021). Conversely, tropospheric ozone (O3) levels were notably higher during summer.

Ozone exhibited a strong positive correlation with temperature, wind speed, relative humidity, and sunshine hours, while showing an inverse relationship with air pressure. Conversely, NO, NO2, SO2, and PM2.5 demonstrated a positive correlation with air pressure and a negative correlation with temperature, sunshine, and wind speed, aligning with previous research by Czerwińska (2020) and Mohammadi et al. (2012).

Notably, approximately 60% of the Air Quality Index (AQI) values for PM2.5 exceeded the unhealthy threshold for sensitive groups during smoggy winters. Winter upwinds primarily originated from the northwest of Lahore, where industrial and agricultural activities were predominant sources of emissions. These findings underscore the seasonal variation in air pollution in Lahore, with winter characterized by reducive-type pollution due to elevated levels of NO, NO2, SO2, and PM2.5, resulting in acidic air conditions. In contrast, oxidative-type pollution prevails during summer due to the presence of tropospheric ozone since 2017, influenced significantly by local weather conditions affecting air pollutant prevalence and transport behavior. Therefore, it is imperative for the government to consider the seasonal dynamics of air pollutants in conjunction with emission control measures to mitigate smog-related challenges.

DECLARATION STATEMENT

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Author Contribution

***Rabia Shehzadi:** Methodology, writing original draft, data anaysis

Tahira Aziz Mughal: Investigation of draft

Prof. Dr. Shakeel Ahmad: Investigation of draft

ETHICS DECLARATIONS

Ethical approval

All authors have read ,understood and have compiled as applicable with the statement on "ethical responsibilities of authors" as found in the instructions for Authors and are aware that with minor exception, no changes can be made to authorship once the paper is submitted

Competing Interest

Authors have no competing interest

Data Declaration

The data sets analysed during the current study are available from the corresponding author on reasonable request

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