Introduction

The population of Lahore is 9 million, making it Pakistan’s second largest city [1]. There are 2.7 million vehicles along with 1,986 different industrial units in Lahore [1]. The ambient air pollution in the city predominantly originates from vehicular and industrial emissions [2].

The semi-arid climate of Lahore naturally favors the accumulation of pollutants. Solid aerosols are present in the samples of PM [3].

New housing schemes have not been found to fulfill the needs of sustainable development and transport sustainability. The city district government has failed to achieve its target of ambient air quality improvements under the 2001 devolution plan due to the absence of transport policy, alteration in land use policy, and deprived management and monitoring of air quality [4]. Furthermore, the city has been expanding due to migration from small cities of Punjab. Migration has been observed...
from Karachi and Peshawar as well, due to security reasons.

Diesel-fueled generators have been used extensively in industrial sectors (point sources) as well as in other sectors due to widespread power shortages in the country, which adds a lot to urban ambient air pollution [5]. The use of diesel fuel by mobile sources contributes a lot to particulate matter air pollution [6]. The sulfur contents are very high in diesel (0.5-1%) and furnace oil (1-3.5%) being used in Pakistan, whose fallout comes with higher sulfur dioxide pollution [7].

The environmental damage is associated with health issues. Currently, mobile sources have been found to promote high levels of tropospheric ozone and health concerns in urban areas [8]. The Organosulfates have been identified and quantified in fine particulate matter \(\text{PM}_{2.5}\) collected in Lahore, Pakistan, in 2007-08 [9]. Enhanced diastolic blood pressure has been found to be associated with long-term exposure to NO, and \(\text{PM}_{2.5}\) in those children who used to live at the same place since birth [10]. The \(\text{PM}_{2.5}\) levels have been exceeding the NEQS in four provincial as well as federal capitals of Pakistan [11].

In the fall season during October and November; burning of crop residues in eastern Pakistan and northwestern India increase the concentrations of \(\text{PM}_{2.5}\) in the atmosphere [12, 13]. Secondary inorganic PM in the form of sulfates and nitrates is formed by the oxidation of SO\(_2\) and NO\(_x\). However, the organic carbon fraction is formed due to oxidation of VOCs [14, 16]. This process is enhanced by ammonia [17]. The black carbon aerosols are present in 90% of \(\text{PM}_{2.5}\) in winter and contribute about 5-15% to overall \(\text{PM}_{2.5}\) in the ambient air [18, 19]. Black carbon has been found to be at much higher levels during foggy season. Black carbon has also been found to be trapped in aerosols during the foggy season, resulting in a lessening of solar radiation [20].

Other big cities in Punjab also have high pollution levels. Concentrations of CO, NO\(_x\), and SO\(_2\) have been found above NEQS levels in Faisalabad [21]. The traffic pollution has been found to be the most contributing factor to outdoor air pollution in most urban areas [22].

Brick kilns on the outskirts of Lahore are also a great point source of air pollution. A study of brick kilns in the Wahga and Batapur areas of Lahore revealed that the conventional Bull’s Trench Brick Kiln are being used in Lahore, which comprises no control measures to manage the air pollution. Modern brick manufacturing technologies such as vertical shaft brick kiln must be introduced to control the air pollution [23].

It is impossible to monitor the spatial and temporal variations in the atmosphere on the basis of a single monitoring site [24]. In a recent study on some metals in the vehicular exhaust emissions of rickshaws, it has been discovered that a significant boost has been found in Al, P, and Zn in the PM samples of four-stroke Rickshaws [25]. In another study in Beijing, perfluorinated compounds (PFCs) are found in ambient \(\text{PM}_{2.5}\), \(\text{PM}_{10}\), and TSP [26]. The environmental damage costs the country an annual loss of about Rs. 365 billion, of which the urban air pollution loss was approximately Rs. 65 billion in 2006 [27].

### Materials and Methods

Hourly air quality monitoring data for 2007-11 and 2014-15 were collected from the Provincial Environmental Protection Agency. The air quality monitoring stations remained almost out of work during 2012 and 2013 due to lack of budget to run them. Fix and mobile air quality monitoring stations had been used to monitor the six major pollutants along with meteorological parameters. The air quality monitoring stations contain an anemometer (KoshinDenkiKogyo Co., Ltd. Model KVS 501) combined wind vane, a solar radiation meter (Koshin Denki Kogyo Co., Ltd. Model SR-010), a thermohygrometer (Koshin Denki Kogyo Co., Ltd. Model ModelHT-010), and a data logging system (Horiba, Ltd. Model Special).

The six major air pollutants like ozone (O\(_3\)), carbon monoxide (CO), sulfur dioxide (SO\(_2\)), oxides of nitrogen (NO\(_x\), i.e., NO and NO\(_2\)), fine particulate matter (PM\(_{2.5}\)), and hydrocarbons (total hydrocarbons, non-methane hydrocarbons, and methane) were determined through analyzers described in Table 1.

The air quality index (AQI) was calculated according to “Eq.1” [28].

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>Analyzer</th>
<th>Range</th>
<th>Method</th>
<th>Detection Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO</td>
<td>Horiba Ltd; Model APMA-370</td>
<td>0~50 ppm</td>
<td>non-dispersive infrared ray method (ISO4224)</td>
<td>0.1ppm</td>
</tr>
<tr>
<td>NO/NO(_2) /NOx</td>
<td>Horiba Ltd; Model APNA-370</td>
<td>0~1 ppm</td>
<td>Chemiluminescence (ISO7996) method</td>
<td>0.5 ppb</td>
</tr>
<tr>
<td>Sulfur dioxide</td>
<td>Horiba Ltd; Model APSA-370</td>
<td>0~0.5 ppm</td>
<td>U.V. fluorescence method (ISO10498)</td>
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</tr>
<tr>
<td>Ozone</td>
<td>Horiba Ltd; Model APOA-370</td>
<td>0~1 ppm</td>
<td>UV photometry method</td>
<td>0.5 ppb</td>
</tr>
<tr>
<td>Hydrocarbon</td>
<td>Horiba Ltd; Model APHA-370</td>
<td>0~50 ppmC</td>
<td>Converter oven method</td>
<td>0.1 ppmC</td>
</tr>
<tr>
<td>PM(_{2.5})</td>
<td>Horiba Ltd; Model APDA-370</td>
<td>0~5 mg m(^{-3})</td>
<td>β-ray absorption method (ISO6349)</td>
<td></td>
</tr>
</tbody>
</table>
Lahore is located at 31°32’N 74°22’E at 217 m above sea level. The municipal area of Lahore is 332 km². Due to rapid urbanization, the area has been extended to 1,000 km². Two fixed air quality monitoring stations have been installed in Lahore to monitor air quality. One of the stations is installed on the second floor of the city hall building situated in the northern main commercial area of Lahore with a number of busy roads, markets, and dense population. The second station was installed in Quaid-i-Azam Township area, a southern residential area near Kotlakhpat industrial estate.

The city hall air quality monitoring station was selected for data analysis. The fixed air quality monitoring station installed at city hall on Lower Mall road in Lahore represents the ambient air quality of the main city of Lahore. The monitoring station was located about 8 m from the ground. Most of the main roads of Lahore are within a 1-3 km sphere of the station. The location of the two fixed Air Quality Monitoring Stations can be seen in Fig. 1.

The climate of Lahore can be distributed into five seasons: foggy winter (15 Nov-15 Feb) with low rainfall, low wind speed, and high inversion; spring (16 Feb-5 April) with low rainfall and moderate temperature (T); summer (15 April-June) with high temperature, high rainfall, low relative humidity (RH), and high dispersion effects; rainy monsoon (July-16 September) with high temperature, high relative humidity, and low pollution due to dispersion and washing effect; and dry autumn (16 September-14 November) with low wind speed and low RH [29].

June is the hottest month, with an average temperature of 33.9°C. The average temperature of January is 12.8°C, which makes it the coolest month of the year. The average annual temperature of Lahore is 24.3°C, which is fairly hot as annual average. Average monthly temperature range is 21.1°C. The average daily temperature variation is 15.5°C [29].

Minimum average sunshine has been observed in January with 6.9 hours day⁻¹. Overall annual average sunshine is 8.4 hours day⁻¹ [29].

Wind speed remains low almost throughout the year except some windy days in summer. Around 60% of the year remains calm and 33% of days see an average speed of 1-3 knots. Only 6% of the year experiences speeds of 4-6 knots. Wind direction remains mostly northwest during monsoon and summer and southeast during winter [29].

Relative Humidity (RH) remains low throughout the year except during monsoon season. The monthly average of relative humidity exceeds 60% during July, August, and September. Average relative humidity remains around 77% in the morning and 40% in the evening. The average monthly relative humidity ranges around 20% in May to 58% in August. Overall, the annual average relative humidity remains around 37.9%.

The climate of Lahore has observed extreme weather events in the near past. The highest ever recorded temperatures of the city were 48.3°C on 30 May 1944 and 48°C on 10 June 2007. The highest recorded rainfall was 221 mm, observed on 13 August 2008, and 4.5 mm hail was observed in Lahore on 26 February 2011 [29].
Results and Discussion

Ambient air quality data of Lahore for 2007-11 and 2014-15 has been analyzed to discern patterns and determine the sources of the six representative air pollutants. The hourly data for each pollutant collected was analyzed for average concentration, monthly mean pattern, and seasonal and diurnal variations.

Air Quality Index

The interpretation of AQI can be elaborated as clean, moderate, unhealthy, and very unhealthy. The Pakistani NEQS for O₃ for 24 hours has yet not been made available. The NEQS for O₃ for one hour have been revised from 180 to 130 and for PM₂.₅ for 24 hours have been revised from 40 to 35 since January 2013 [30]. So before January 2013, the index value would be calculated accordingly. A projected AQI is given in Table 2 [28].

AQI remains low (~74 to ~85) from June to August due to heavy rain, relatively high wind speed (~1.59 to ~1.85 monthly average), and dispersion due to high temperatures and high solar radiation. In summer, an improved air quality index also has been observed in northern China. [31].

The highest AQI (~132 to ~185) was observed from November to February due to inversion at low wind speed (< 1.5 m/s monthly average), low temperature (~15-21°C monthly average), and low solar radiation (~104-140 W m⁻² monthly averages) due to heavy fog during December and January. Another reason for the high AQI during fall can be due to burning crop residue in southwestern India and eastern Pakistan. The wind direction during winter remains mostly southeast, which can also be a reason for contributing to pollution in Lahore from a number of polluted steel industries in the northern part of Lahore and industrial clusters in Sheikhupura and Gujranwala. The steel industries are mostly located in Badami Bagh, Misry Shah, Daroghay Wala, and around the Band Road area in northern Lahore. Fig. 1 shows a map of Lahore.

Data Analysis

For data analysis, the data of daytime (07:00-15:00) has been taken for analysis of ozone and its precursors. The data of a sunny and clear day has been taken. The mean concentration of the ozone, other pollutants, and meteorological parameters are given in Table 3.

The day is dry and hot with low mean RH (30.66), high solar radiation (about 680 W m⁻²), and high mean temperature (around 38°C). Wind speed remained low (mean value = 1.72 m/sec) as a routine matter in semi-arid regions. NO remained almost nil (mean value = 1.93 µg m⁻³) during sunny hot days due to its conversion to NO₂ (mean value = 26.8 µg m⁻³) in the presence of high concentrations of O₃ (mean value = 122.50 µg m⁻³). Concentrations of CH₄ remained below (mean value = 2,210.61 ppb) its natural level (around 3,000 ppb) due to its consumption as a precursor of ozone. The mean value of PM₂.₅ (155.07 mg m⁻³) remained high due to a high amount of un-burnt carbon from vehicular exhaust emissions in the atmosphere.

Correlation Analysis

Table 4 shows the correlation of different air quality parameters. The following results are made according to statistical analysis of data in Table 4.

O₃ has a significant negative correlation with NO, NO₂, NOₓ, CH₄, CO, and RH (r-value > -0.5); and has significant positive correlation with T and solar radiation (r-value > 0.5). The level of tropospheric ozone is highly dependent on solar radiation and atmospheric temperature [32], while NO has significant positive correlation with NO₂, NOₓ, CH₄, CO, and RH (r-value > 0.5 for each); and has negative correlation with O₃, T, and solar radiation (r-value > -0.5 for each). NO concentration is almost negligible from 07:00-15:00 in the summers due to its conversion into NO₂ by reacting with abundant O₃ produced by different sources such as CO, NO₂, VOCs, and NMHCs in the presence of sunlight.

<table>
<thead>
<tr>
<th>Variable</th>
<th>NO</th>
<th>NO₂</th>
<th>NOₓ</th>
<th>CH₄</th>
<th>NMHC</th>
<th>CO</th>
<th>SO₂</th>
<th>O₃</th>
<th>PM₂.₅</th>
<th>Wind Speed</th>
<th>T</th>
<th>RH</th>
<th>Solar radiation</th>
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<tr>
<td>Unit</td>
<td>µg m⁻³</td>
<td>µg m⁻³</td>
<td>Ppb</td>
<td>Ppb</td>
<td>ppb</td>
<td>mg m⁻³</td>
<td>µg m⁻³</td>
<td>µg m⁻³</td>
<td>µg m⁻³</td>
<td>m/s</td>
<td>°C</td>
<td>%</td>
<td>W m⁻²</td>
</tr>
<tr>
<td>Mean Value</td>
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<td>28.52</td>
<td>16.14</td>
<td>2210.61</td>
<td>735.85</td>
<td>0.68</td>
<td>42.64</td>
<td>122.50</td>
<td>155.07</td>
<td>1.72</td>
<td>37.68</td>
<td>30.66</td>
<td>539.35</td>
</tr>
</tbody>
</table>
Urban Emission Patterns...

NO₂ has significant positive correlation with NO, NOₓ, CH₄, CO, and SO₂ (r-value > 0.5 for each), and has significant negative correlation with O₃, T, and solar radiation (r-value < -0.5). In daytime almost all the NO has been converted to NO₂ by reacting with O₃ in the presence of sunlight. The dominant sources of nitrogen oxides as far as vehicles are concerned are diesel and four-stroke engines [33].

NOₓ has a significant positive correlation with NO, NO₂, CH₄, CO, and SO₂ (r-value > 0.5 for each), and has a significant negative correlation with O₃ and solar radiation (r-value > -0.5). CNG engines are a main common source for the emission of CO and NO [33].

CH₄ has significant correlation with NO, NO₂, NOₓ, SO₂, and RH (r-value > 0.5 for each), and significant negative correlation with O₃, T, and solar radiation (r-value < -0.5).

NHMC has no significant correlation with any of the parameters.

CO has a significant positive correlation with NO, NO₂, NOₓ, CH₄, SO₂, and RH (r-value > 0.5 for each), and has a significant negative correlation with O₃ and T (r-value < -0.5). The correlation studies among NO, NO₂, NOₓ, CH₄, CO, and SO₂ suggest that the dominant sources of air pollution are direct or primary in nature. The major sources of CO are CNG, LPG, and petrol engines. Diesel engines generate a relatively very low amount of CO. Ambient CO emissions always remain within the permissible limit of 5 mg m⁻³ = 5000 µg m⁻³. Therefore, CO emissions may not be considered low in terms of µg m⁻³ units. The significant positive correlation between CO and NO (r = 0.72; p-value < 0.01) shows a common source for both. CNG engines are a main common source for the emission of CO and NO [33].

SO₂ has a significant positive correlation with NO, NO₂, NOₓ, CH₄, CO, PM₂.₅, WS, T, and solar radiation (r-value > 0.5 for each), and has significant negative correlation with O₃. The correlation of SO₂ with WS suggests that point sources can be a dominant source for SO₂ emissions. The common source for CO and SO₂ are LPG engines.

Table 4. Correlation analysis of ambient air variables of semi-arid region, Lahore.

<table>
<thead>
<tr>
<th></th>
<th>NO</th>
<th>NO₂</th>
<th>NOₓ</th>
<th>CH₄</th>
<th>NHMC</th>
<th>CO</th>
<th>SO₂</th>
<th>O₃</th>
<th>PM₂.₅</th>
<th>WS</th>
<th>T</th>
<th>RH</th>
<th>Solar radiation</th>
</tr>
</thead>
<tbody>
<tr>
<td>NO</td>
<td>Pearson Correlation</td>
<td>1</td>
<td>.946*</td>
<td>.741**</td>
<td>.953**</td>
<td>.416</td>
<td>.917**</td>
<td>.556</td>
<td>-.825**</td>
<td>.163</td>
<td>.058</td>
<td>-725'</td>
<td>.616'</td>
</tr>
<tr>
<td>NO₂</td>
<td>Pearson Correlation</td>
<td>.946*</td>
<td>1</td>
<td>.871**</td>
<td>.978**</td>
<td>.254</td>
<td>.912**</td>
<td>.571</td>
<td>-.675'</td>
<td>.200</td>
<td>-.084</td>
<td>-.634'</td>
<td>.496</td>
</tr>
<tr>
<td>NOₓ</td>
<td>Pearson Correlation</td>
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<td>.871**</td>
<td>1</td>
<td>.797**</td>
<td>.039</td>
<td>.734'</td>
<td>.363</td>
<td>-.520</td>
<td>.072</td>
<td>-.138</td>
<td>-.401</td>
<td>.249</td>
</tr>
<tr>
<td>CH₄</td>
<td>Pearson Correlation</td>
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<td>.978**</td>
<td>.797'</td>
<td>1</td>
<td>.214</td>
<td>.892**</td>
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<td>.094</td>
<td>-.003</td>
<td>-.710'</td>
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<td>CO</td>
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<td>.912*</td>
<td>.734'</td>
<td>.892**</td>
<td>.336</td>
<td>1</td>
<td>.809'*</td>
<td>.758**</td>
<td>.443</td>
<td>.224</td>
<td>.805''</td>
<td>.737''</td>
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<tr>
<td>SO₂</td>
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<td>.519</td>
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<td>.841''</td>
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<td>1</td>
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<td>-.635'</td>
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<td>-.160</td>
<td>.525</td>
<td>.487</td>
<td>-.088</td>
<td>.523</td>
<td>-.364</td>
</tr>
</tbody>
</table>

**Correlation is significant at the 0.01 level (2-tailed).  * Correlation is significant at the 0.05 level (2-tailed)
PM$_{2.5}$ has significant positive correlation only with SO$_2$ (r-value $> 0.5$). The correlation of PM$_{2.5}$ with SO$_2$ suggests that most of these pollutants originates with fresh emissions from mobile and point sources. Some amount of PM$_{10}$ may be produced by chemical conversion of SO$_2$ into particles. A negative correlation of PM$_{2.5}$ with T has already been reported [34]. Some researchers have reported the conversion of semi-volatile components from particle phase to gas phase at high temperatures [35-38].

Yasar has reported high smoke opacity for most diesel engines, which are a dominant source for PM$_{2.5}$ [33]. Diesel engines are a dominant source for SO$_2$ and PM$_{2.5}$ emissions, which explains the high correlation between PM$_{2.5}$ and SO$_2$.

RH has significant positive correlation with NO, CO, SO$_2$, and WS (r-value $> 0.5$), and significant negative correlation with O$_3$ and T (r-value $< -0.5$). In fact, RH has significant negative correlation with T and has very little correlation with other pollutants. The pollutants may have very minute correlations with WS and RH. In other words, it is difficult to explain the correlation of pollutants with WS and RH in the presence of many other factors as well.

In the winter, the excess amount of ammonia at low temperatures and high relative humidity upturns PM by producing nitrate particles [39, 40]. Temperature has a significant negative correlation with NO, NO$_2$, CH$_4$, SO$_2$, WS, and RH (r-value $< -0.5$), and has significant positive correlation with solar radiation and O$_3$ (r-value $> 0.5$) This explains the production of ozone in the presence of solar radiation at the cost of the precursors of O$_3$.

### Ratio Analysis

High ratios of CO/NO and low ratios of SO$_2$/NO indicate that mobile sources are the major source of NO$_x$ and point sources are the major source for SO$_2$ emissions. The production of NO$_x$ is associated with high temperatures during fossil fuel burning. Therefore, NO$_x$ is usually produced at high temperatures in four-stroke petrol and diesel engines. However, SO$_2$ is dominantly produced due to high sulfur content in fuel. High sulfur content (0.25-1%) is present in diesel available in Pakistan. Therefore, diesel engines are the major anthropogenic source of SO$_2$ emissions in Lahore [33]. As NO$_x$ is abundantly produced by both 4-stroke petrol engines as well as diesel engines at high temperature, the concentration of NO$_x$ usually remains high in Lahore city.

An emission inventory has been provided by [41, 42] for CO, SO$_2$, and NO$_x$. The data of ratio of CO/NO and CO/SO$_2$ is given in Table 5, which also provides the ratio analysis of CO by NO$_x$ and SO$_2$ by NO$_x$ provided by different studies, such as one in Denver, CO, US [43]; Boulder, CO, US [44]; Raleigh, NC, US [45]; and New Delhi, India [46]. The above studies show a similar trend of ratios of CO/NO and SO$_2$/NO as do in the current study.

### Analysis of Ozone Formation

Ozone is a secondary pollutant. The primary sources for ozone are CO, VOCs, CH$_4$, NO$_2$, and solar radiation. A large amount of O$_3$ has also been produced around high-voltage electric lines. Some countries also claim a high amount of O$_3$ due to trans-boundary movements. It has been observed that during summers, almost all the NO has been converted to NO$_2$ by reacting with O$_3$, being produced by different chemical reactions of CO, CH$_4$, VOCs, and NO$_x$ in the presence of sunlight. Therefore, NO concentrations remain almost nil in the presence of high solar radiation during the day in summers. A possible dynamic equilibrium between NO and NO$_2$ is given in “Eq. 2” [47]:

\[
\text{NO} + \text{O}_3 \leftrightarrow \text{NO}_2 + \text{O}_2 \quad (2)
\]

NO$_2$ reacts with oxygen in the presence of sunlight to produce O$_3$ and NO. As the NO concentration is almost nil in day-time in summers, it may be assumed that O$_3$ has been produced in abundant amounts by different primary sources to keep the reaction forward according to the Le Chatlier principle, i.e., almost all the NO has been converted to NO$_2$ due to an abundant amount of O$_3$ being produced by a number of primary sources in the presence of sunlight. Therefore, it can be assumed that O$_3$ concentration measured at day-time in summers (high solar radiations) is the O$_3$ that has been produced by sources other than NO$_2$ or NO$_x$ (as the amount of O$_3$
produced by NO₂ has been consumed by NO). Or it may be assumed that whenever the value of NO is negligible, the amount of O₃ produced would be that amount of O₃ that is produced by sources other than NO₂ or NOₓ.

Another assumption is that sources like VOCs, CO, and CH₄ convert NO to NO₂ and higher oxides of nitrogen. The NO₂ is further photo-lysed to produce O₃. In daytime the value of NO is negligible due to its conversion to NO₂. The value of NO₂ or NOₓ has been found to be as high as the O₃ value. Therefore, a significant positive correlation is observed between NO₂ and O₃ or between NOₓ and O₃ in daytime.

To assess the extent of dependence of Ozone on other variables, paired sample t test has been applied on data. The results of paired sample t test are given in Table 6.

The t value of all the precursors of ozone like NOₓ, CH₄, temperature, and solar radiation is non-zero. The p value of NO, NO₂, NOₓ, T, and solar radiation are less than or very close to 0.01 (99% confidence level), indicating their significant effect on ozone. For PM₂.₅, p-value is 0.13, indicating no significant dependence of Ozone on PM₂.₅. Although p values for wind speed and RH are close to 0.01, practically RH has no significant relation for ozone, and the dependence of ozone on wind speed depends on wind direction.

**Diurnal and Monthly Mean Pattern of Air Quality Parameters**

It has been observed that all the primary pollutants like CH₄, NMHC, CO, NO, NO₂, NOₓ, SO₂, and PM₂.₅ have positive correlations with each other and negative correlations with O₃. The peak value of O₃ has been observed in the daytime due to the presence of high solar radiation, especially in summers. In the absence or reduction of light at night, almost nil or minimum values of O₃ have been observed. The diurnal variations remain the same in every season and all months of the calendar. The value of O₃ has been observed as very high during the summer noon due to high solar radiation. Maximum pollution of primary pollutants has been observed from November to February due to low solar radiation and low photochemical reactions to produce O₃. Fig. 2 shows the diurnal variation of O₃ and other pollutants, while Fig. 3 shows the significant correlation of O₃ with temperature and solar radiation. In Fig. 3, CH₄ levels are divided by 100, NMHC are divided by 10, and CO levels are multiplied by 10 to better elaborate upon their monthly patterns.

**Seasonal Pattern of Ozone and other Air Quality Parameters**

There are five different seasons in Lahore. The two main seasons are winter and summer with extreme climatic conditions. As already discussed, O₃ has a significant correlation with temperature (r = 0.7; Table 3). The value of O₃ remains high during summers due to high solar radiation. The concentration of precursors of O₃ remains high during winter mainly due to low solar radains.

The main features of winter in Lahore are:
- Low wind speed,
- Low solar radiation/temperature
- Less precipitation

This favors accumulation and inversion of air pollutants. Therefore, the highest air pollution has been
found from November to February in Lahore as a semi-arid region. But concentrations of secondary O₃ pollutants remain low in winter due to low solar radiation.

Summer is composed of:
- Relatively high wind speed
- High solar radiation/temperature
- Monsoon rains during July and August

All these factors results in the dispersion and washout of air pollutants. But O₃ concentrations remain high during summers due to high solar radiation. Fig. 4 elaborates upon the monthly pattern of O₃ and other pollutants.

Conclusions

We have characterized the ambient air quality for criteria pollutants for Lahore, Pakistan. The annual average concentrations of PM₂.₅ and NO are exceeding the Pak-NEQS. The NEQS for PM₂.₅ needs to be relaxed for a semi-arid region as PM₂.₅ levels are exceeding strict NEQS of 35 µg m⁻³, even in rural areas around the city.

24 hours and annual Pak-NEQS have not been established for ozone, although its concentration remains too high during summers. Mobile sources are a major source of such high concentrations of NO. The hourly average concentrations of ozone exceed the Pak-NEQS primarily during summer. Carbon monoxide and sulfur dioxide are found to remain in compliance with the Pak-NEQS for the entire calendar year.

The monthly pattern of pollutants show that AQI remains high during winter due to relatively low washing effect (low rain), low wind speed, and high inversion. Moreover, the dominant wind direction from the southeast enables the polluting steel industry to contribute to pollution of Lahore in winter. But ozone levels remain low during winter due to low solar radiation. The diurnal trend of pollutants is similar to the monthly pattern, i.e., AQI remains low in the daytime at high T and solar radiation. The concentration of primary pollutants like NO, NO₂, NOₓ, CO, SO₂, CH₄, NMHC, and PM₁₅ remains low in the daytime due to their use as a precursor of O₃, dispersion effect, and many other factors. The ozone level remains high in the daytime (like in summers) due to high solar radiation and the presence of high concentrations of its precursors.

Ozone has positive correlation with T and solar radiation, and negative correlation with most pollutants like NO, NO₂, NOₓ, CO, and CH₄. Wind speed, T, and solar radiation have negative correlations with primary pollutants. A wide range of fluctuation in NO concentration has been observed in the presence and absence of solar radiation. Ozone in the presence of solar radiation has a reduction effect for most pollutants other than PM₁₅ and NMHC.

Correlation studies suggest that the dominant sources of the primary pollutants are fossil fuels, either from mobile sources or point sources. Four-stroke petrol engines are a common source for CO, NO, NO₂, and NOₓ, which are precursors of O₃. Diesel engines are a major common source for NOₓ, SO₂, and PM₁₅. There is a need to reduce sulfur contents in diesel being used in Pakistan. SO₂ emissions mostly remain in compliance with NEQS in Lahore, as most of the vehicles use petrol as fuel. As NOₓ are abundantly produced by diesel and four-stroke petrol engines, the concentration of NOₓ mostly remains high in Lahore. Ratio analysis showed that mobile sources are the major sources for NO and point sources are the major source for SO₂ emissions in the city hall area of Lahore.

Ozone is a dreadful pollutant for road traffic for arid and semi-arid areas in summer. There is a need to collect more data of its other primary precursors like VOCs as well.

The population of Lahore has been increasing at a very fast pace. There is a need to stop migration through the provision of health, education, employment, industrial, and fast transport facilities in other cities and remote areas as well.

There is also a need to provide better and more accessible public transport for all the housing societies of Lahore, to promote the use of public transport, and to lessen the use of private vehicles – especially cars.

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