ASSESSING THE IMPACTS OF INDUSTRIAL GROWTH ON AIR QUALITY THROUGH GEOSPATIAL TECHNIQUES: A CASE STUDY OF LAHORE

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ABSTRACT: Air quality is the new focus in atmospheric sciences. The number of gases and pollutants in the air determines its air quality. The major source of these gases and pollutants in the atmosphere are many anthropogenic activities but this research is based on industries. The study area of this research is Lahore as it is the 2nd largest city of Pakistan and has a wide variety of polluting industries such as chemical, agriculture, technology, fuel, steel and iron, fashion, food-retail and construction. For this purpose, 10-meter satellite images Sentinel-5p and Sentinel 2A from EO Browser and USGS Earth Explorer, respectively, used to collect the air quality and LULC data. Following parameters were analysed: Aerosol Index (AI), CO, HCHO, O_3, NO_2 and CH_4. The data was then processed in ArcGIS 10.5 by using geo-spatial techniques such as Interpolation (IDW) and Weighted Sum. IDW was applied to determine the abundance of above parameters and Weighted Sum was applied to determine the UAQI of Lahore. Moreover, Point Density was applied on industrial data to check its influence on air quality. Results showed that the air quality of Lahore is affected badly in the areas where the ratio of industries is high. UAQI of Ganj Baksh and Gulberg lie in very bad category due to the incidence of numerous industries in these areas.

Key words: Air quality, Sentinel-5p, Urban Air Quality Index (UAQI), geo-spatial techniques.

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INTRODUCTION

Air quality, of course, is constantly changing. It varies from year to year or from one location to another. The quality of air depends on certain factors such as magnitude of emissions from individual sources, density of emission, topography and the state of the atmosphere (Godish & Fu, 2019). Climate change because of air contamination is the new focus in atmospheric science. Air quality issues originate by those pollutants whose time period in the atmosphere is long enough to travel another continent (Akimoto, 2003). Outside air pollution is a combination of pollutants originating from both natural and man-made sources (Ramsey *et al*., 2014). Sulphur dioxide, nitrogen dioxide, particulate matter, ozone and non-methane volatile organic carbons are considered the major air pollutants (Ozden *et al*., 2008). Pollution level has reduced in Western Europe and North America since the late 20th century but it is rising rapidly in developing countries of Asia (Loomis *et al*., 2013).

Unplanned urbanization, industrial and vehicular emissions and degradation of vegetation cover have resulted in the rise of air pollutants and emission sources (Tabinda *et al*., 2020). Industrialization is the conversion of agricultural resource-based economy toward an economy based on mass manufacturing. Rapid industrialization is an effective way to promote economy and to achieve modernization. However, it contributes to environmental issues. Heavy industries, power plants and transportation are the major contributor of nitrogen oxides. SO_2 emissions mainly come from energy-intensive industries and PM 10 pollutants mainly come from industrial dust, construction dust and automobile exhaust (Zhang *et al*., 2021). Refineries and petrochemical industries release many pollutants into the air which has become a reason of decline in air quality. Petrochemical areas around the world give us a wide picture of the contaminations and the way they affect air quality. VOCs, PM and GHGs are the main pollutants released by these sites. It emerges from the production process, pipelines, storage tanks, valves and waste zones. These industries are the significant source of hydrocarbons and creates a favourable environment for the formation of ozone (Ragothaman and Anderson, 2017).

Starting from the zero at the time of independence, Pakistan has made an exceptional progress in the sector of manufacturing. The share of the industrial sector has risen from 6.4 percent in 1949-50 to 18.3 percent in 2004-05 in GDP (Kemal, 2006). Pakistan, during the last decade, the rate of population, industrialization and urbanization is increasing which results in massive use of energy and greater emission of pollutants in the atmosphere. Particulate matter and nitrogen dioxide is emerging as the 2nd high risk pollutants in Pakistan. The government has taken some

steps to overcome air pollution in the form of Pakistan Clean Air Program but still the ambient air quality standards have not yet been established (Colbeck *et al*., 2010). Lahore is one of the 30th largest cities of the world and it is the second largest city of Pakistan where industrial units are the main emitter of sulfur dioxide, carbon monoxide and particulate matter. Air quality problem is one of the most difficult environmental problems currently faced by the city because of its impacts on human health (Ali and Athar, 2010). According to the study, the vehicular and industrial areas of Lahore were more severely polluted as compared to the residential commercial areas (Ashraf *et al*., 2013).

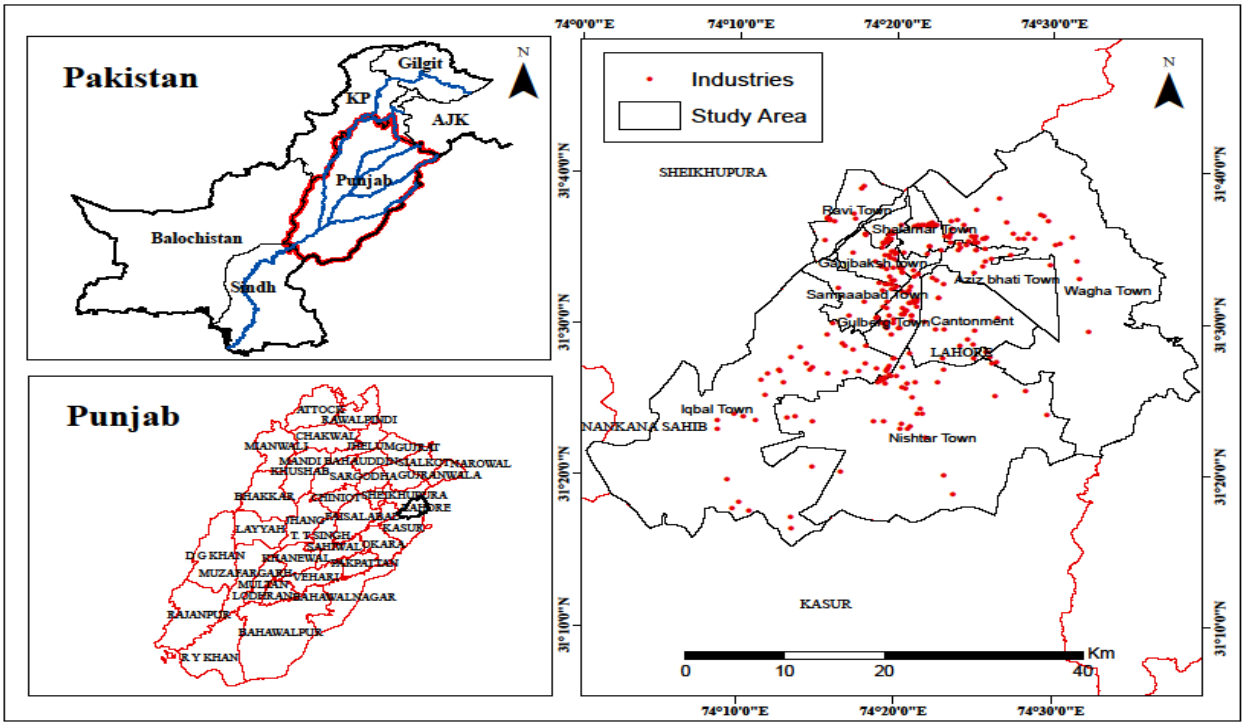

Figure 1. Study Area map of Lahore

The study area of this research is Lahore as shown in Figure 1. It is the provincial capital of Punjab which is located between 31°15′-31°45′ N and 74°01′-74°39′ E at an elevation of 217m above sea level. It is the second largest city in Pakistan which covers an area of 1772 square kilometer (Colbeck *et al*., 2019). It is surrounded by Wagha border, Kasur and Sheikhupura district (Saleem *et al*., 2020). According to the census report in 1998, the city population was 6.39 million which had increased to 11 million in 2017. The city comprises of one cantonment and nine towns namely: Aziz Bhatti Town, Ganj Baksh Town, Iqbal Town, Shalamar Town, Ravi Town, Wagha Town, Gulberg Town and Nishtar Town. The city is known by its historical significance because of the monuments and gardens from the Mughal era (Al-Rashid *et al*., 2020). It is a hub of cultural, educational and economical activities in Pakistan (Sajjad *et al*., 2009). The city is also considered the most developed city of Punjab because of its infrastructure and socioeconomic development (Bhatti *et al*., 2015).

The Weather conditions of Lahore touch extreme in both summers and winters. Summer continues from April to September, when temperature touches 40-48°C and winter continues from November to March, when temperature touches 0 °C. Highest rainfall is observed during the monsoon period otherwise the city remains dry. The city has one International Airport named Allama Iqbal International Airport which is also the 2nd largest civil airport in the country (Rana and Bhatti, 2018). Moreover, the city has dense network of transport and industries which is the leading cause of damage to urban environment and human health (Ashraf *et al*., 2013).

The current study aims to analyze the spatial air quality pattern of Lahore; to check the influence of industrial development on the air quality; and to identify towns in terms of air quality. For this purpose, following air quality parameters were discussed in this research i.e., Aerosol Index, methane, ozone, formaldehyde, nitrogen dioxide, carbon monoxide. To check the influence of industries on air quality, the following types of industries were also discussed in this research i.e., agriculture, chemical, steel and iron, technology, fashion, construction, fuel and food retail.

MATERIALS AND METHODS

Data sources: The data used in this research was collected from three different sources. First, Sentinel Hub EO Browser; second, USGS Earth Explorer; and third, Google Earth Pro. Satellite data of Air Quality was collected from Sentinel Hub EO Browser. It contains satellite data of numerous satellites. Sentinel-5P is a satellite that provides atmospheric data to be used for ozone monitoring, UV radiation, climate monitoring and forecasting and air quality. It has been providing data since April 2018 and onwards. It contains satellite data of aerosols, ozone, methane, formaldehyde, nitrogen dioxide, sulfur dioxide and clouds. Satellite images of aerosols index, ozone, methane, formaldehyde and nitrogen dioxide downloaded via the website EO Browser and used for measuring the air quality of Lahore in 2021.Table 1, shows the description of Sentinel-5p and Sentinel-2A data.

Sentinel-2A is a first twin polar-orbiting satellite of Sentinel-2 launched on 23 June 2015. It is a part of European fleet of satellites that are working for European Commission's Copernicus program. Their services address 6 thematic areas that is atmosphere, climate change, land, marine, security and emergency management. The MultiSpectral Imager (MSI) is the only optical instrument payload that Sentinel-2 satellites carry. Sentinel-2A image from USGS is used for Supervised Classification (Traganos and Reinartz, 2018). Industrial data was collected through Google Earth Pro. The random sampling technique was applied to locate the most polluting industries of Lahore as shown in Figure 2. These industries are agriculture, chemical, steel and iron, technology, fashion, construction, fuel and food retail.

Table 1. Description of spatial data.

Data Set Name	Resolution	Date
Sentinel-5p AER AI (Aerosol Index)	7 x 3.5km	17-10-2021
Sentinel-5p CH4 (Methane)	7 x 3.5km	21-10-2021
Sentinel-5p CO (Carbon monoxide)	7 x 3.5km	12-11-2021
Sentinel-5p HCHO (Formaldehyde)	7 x 3.5km	16-10-2021
Sentinel-5p NO2 (Nitrogen dioxide)	7 x 3.5km	19-10-2021
Sentinel-5p O3(Ozone)	7 x 3.5km	15-10-2021
Sentinel-2A	10, 20, 60m	28-12-2021

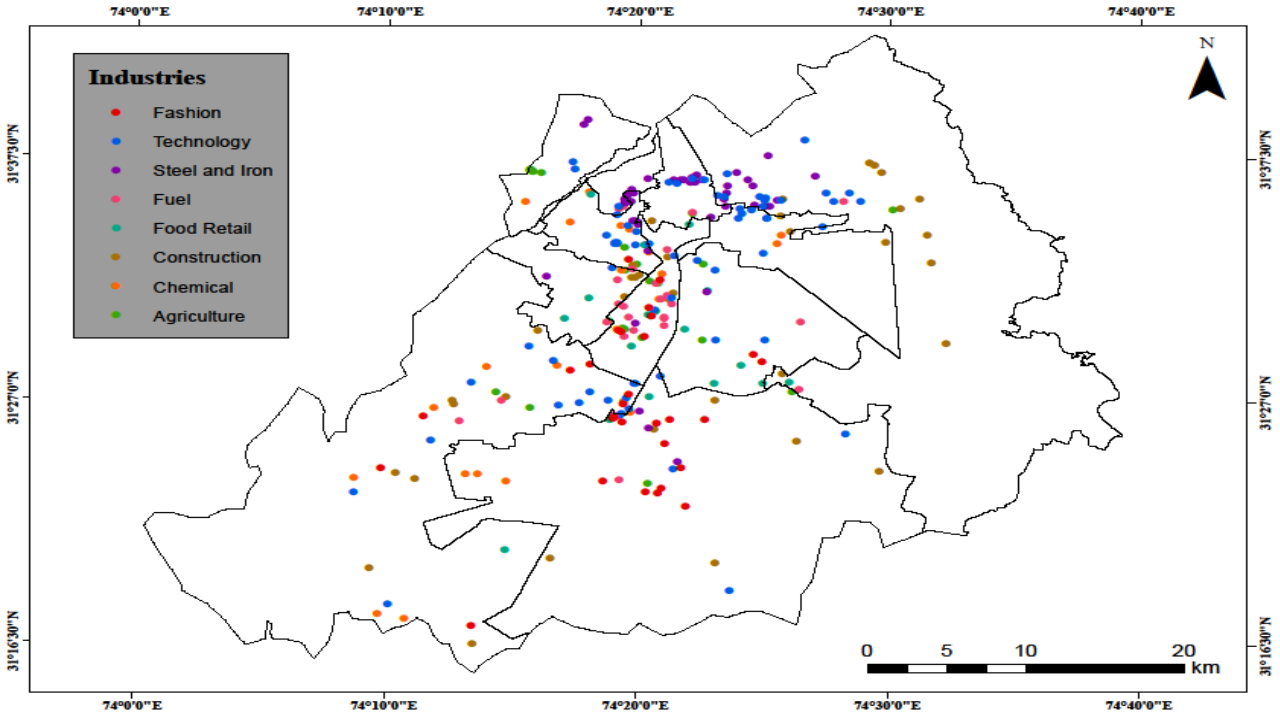

Figure 2 Location of Industries

Data Processing: The raw data was then processed in ArcGIS 10.5. First, satellite images (Sentinel-5p) were converted into point data using the tool Raster to Point. IDW interpolation was applied to obtain the spatial

pattern of carbon monoxide, methane, nitrogen dioxide, ozone, formaldehyde and aerosols index of Lahore. On the other side, point density was applied on industrial data to obtain the density of Fuel, Steel and Iron, Food Retail, Agriculture, Chemical, Technology, Fashion and Construction Industry of Lahore. Supervised image classification was applied on Sentinel-2A image for Land Use Land Cover (LULC) of Lahore of 2021. Weighted sum was applied using the following formula which combines all the rasters into single raster to obtain Urban Air Quality Index (UAQI) of Lahore.

Aerosols Index 340/380 = AIa
Aerosols Index 354/388 = AIb
Carbon monoxide = CO
Nitrogen dioxide = NO_2
Formaldehyde = HCHO
Methane = CH_4
Ozone = O_3
No. of Industries = Ix
Land Use Land Cover = LULC

$$\mathbf{UAQI = AIa+AIb+CO+NO_2+HCHO+CH_4+O_3+Ix+LULC}$$

RESULTS AND DISCUSSION

Aerosols Index (340/380 nm): Based on the results as shown in Figure 3, the highest and the lowest values of Aerosols Index (340/380 nm) recorded by Sentinel-5p on 17-10-2021 were 3.8 and 0.9 respectively. When these values were compared with the Table 2 (Source: Sentinel Hub), it can be seen that Lahore had satisfactory to poor levels of Aerosols Index in air. Satisfactory level observed in Ganj Baksh, Samnabad, Gulberg and Ravi town, moderate level observed in Cantonment, Iqbal and Nishtar and Shalamar town and poor level observed in Wagha and Ganj Baksh town.

Table 2 categorization of levels of AI in air.

Aerosols Index	Category
-1	Good
-0.25	Satisfactory
1.25	Moderate
2.75	Poor
4.25	Very poor
5	Severe

Aerosols Index (354/388 nm): Based on the results as shown in Figure 4, the highest and the lowest values of Aerosols Index (354/388 nm) recorded by Sentinel-5p on 17-10-2021 were 2.86 and 0.64 respectively. When these values were compared with the Table 2 (Source: Sentinel Hub), it can be seen that Lahore had satisfactory to poor levels of aerosols index in air. Satisfactory level observed in Ravi, Samnabad, Ganj Baksh and Gulberg town, moderate level observed in Cantonment, Nishtar, Iqbal and Shalamar town and poor level observed in Wagha and Aziz Bhatti town.

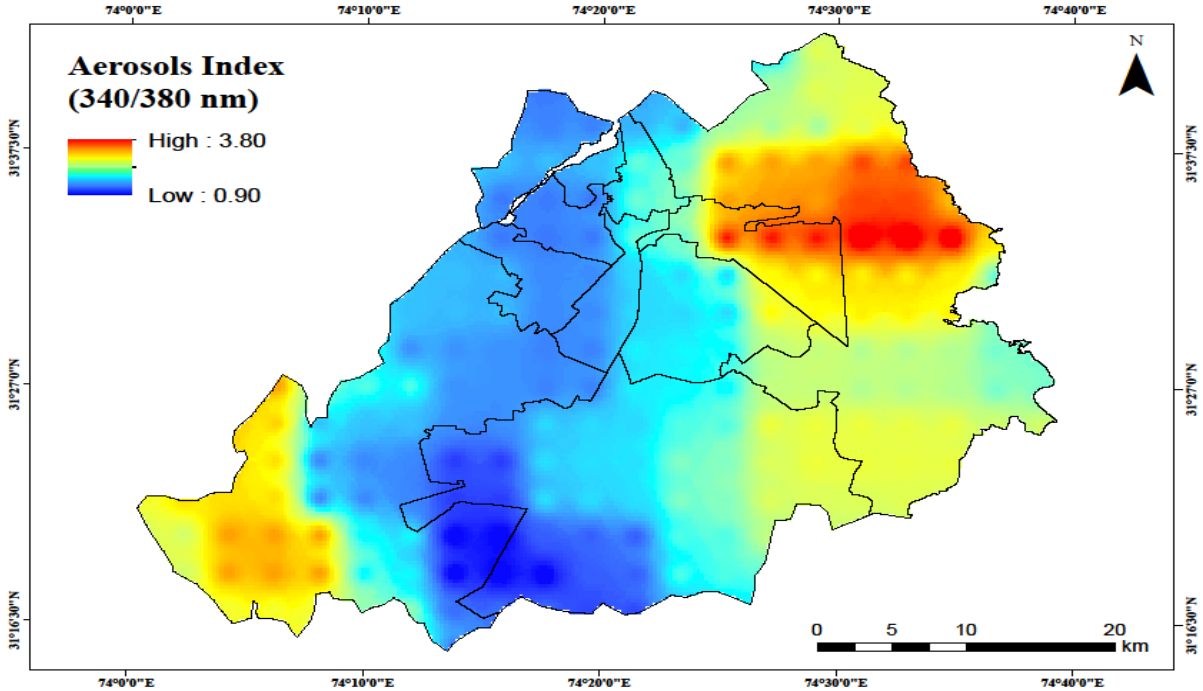

Figure 3 Spatial pattern of AI (340/380 nm) of Lahore

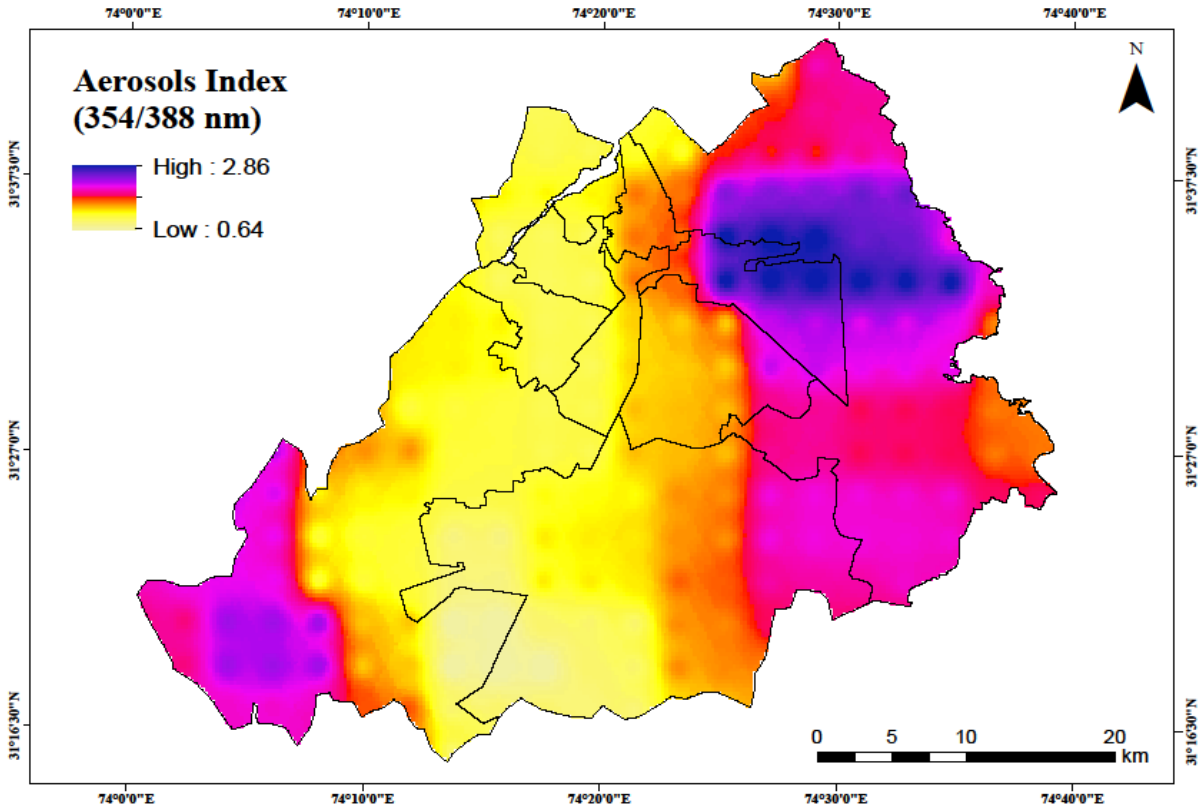

Figure 4. Spatial pattern of AI (354/388 nm) of Lahore

Carbon Monoxide: Based on the results as shown in Figure 5, the highest and lowest values of carbon monoxide recorded by Sentinel-5p on 12-11-2021 were 0.0679 and 0.03985 mol/m^2 respectively. When these values were compared with the Table 3 (Source: Sentinel Hub), it can be seen that Lahore had moderate to poor levels of carbon monoxide in air. Poor level observed in Wagha and Nishtar town while moderate level observed in Cantonment, Iqbal, Ravi, Shalamar, Aziz Bhatti, Samnabad, Gulberg and Ganj Baksh town.

Table 3 Categorization of levels of CO in air.

Carbon monoxide (mol/m^2)	Category
0.0	Good
0.0125	Satisfactory
0.0375	Moderate
0.0625	Poor
0.0875	Very poor
0.1	Severe

Formaldehyde: Based on the results as shown in Figure 6, the highest and the lowest values of formaldehyde recorded by Sentinel-5p on 16-10-2021 were 0.00086 and 0.00015 mol/m^2 respectively. When these values were compared with the Table 4 (Source: Sentinel Hub), it can be seen that Lahore had satisfactory to poor levels of formaldehyde in air. Cantonment, Nishtar, Iqbal and Wagha and Gulberg town had moderate to poor level of formaldehyde while satisfactory level observed in Ravi, Shalamar, Ganj Baksh, Samnabad, Aziz Bhatti and some part of Nishtar town.

Table 4 Categorization of levels of HCHO in air.

Formaldehyde (mol/m^2)	Category
0.0	Good
1.25E-4	Satisfactory
3.75E-4	Moderate
6.25E-4	Poor
8.75E-4	Very poor
1E-3	Severe

Methane: Based on the results as shown in Figure 7, the highest and the lowest values of methane recorded by Sentinel-5p on 21-10-2021 were 2127.99 and 1891.39 ppb. When these values were compared with the Table 5 (Source: Sentinel Hub), it can be seen that Lahore had poor to severe levels of methane in the air. Severe level observed in Wagha town, very poor level observed in Cantonment, Gulberg, Ganj Baksh and Ravi town and poor level observed in Nishtar, Iqbal, Samnabad and some part of Wagha town.

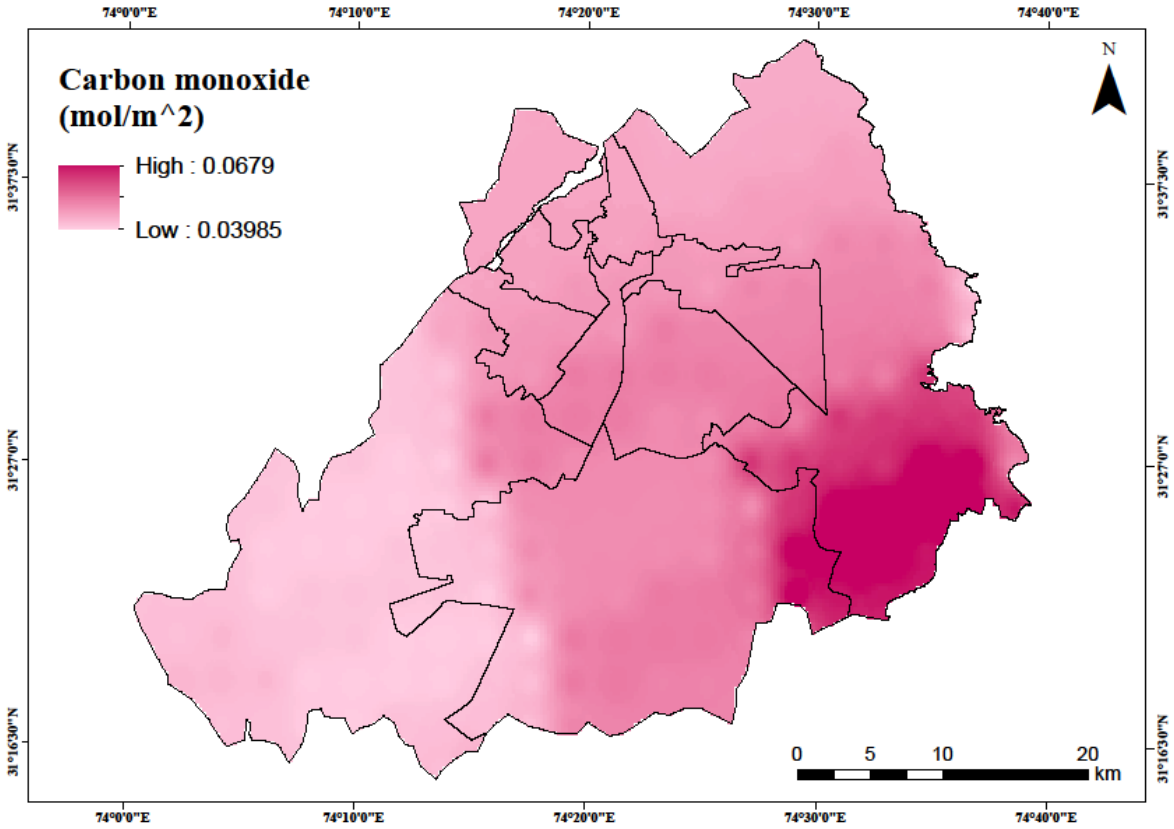

Figure 5 Spatial Pattern of CO (mol/m^2) of Lahore

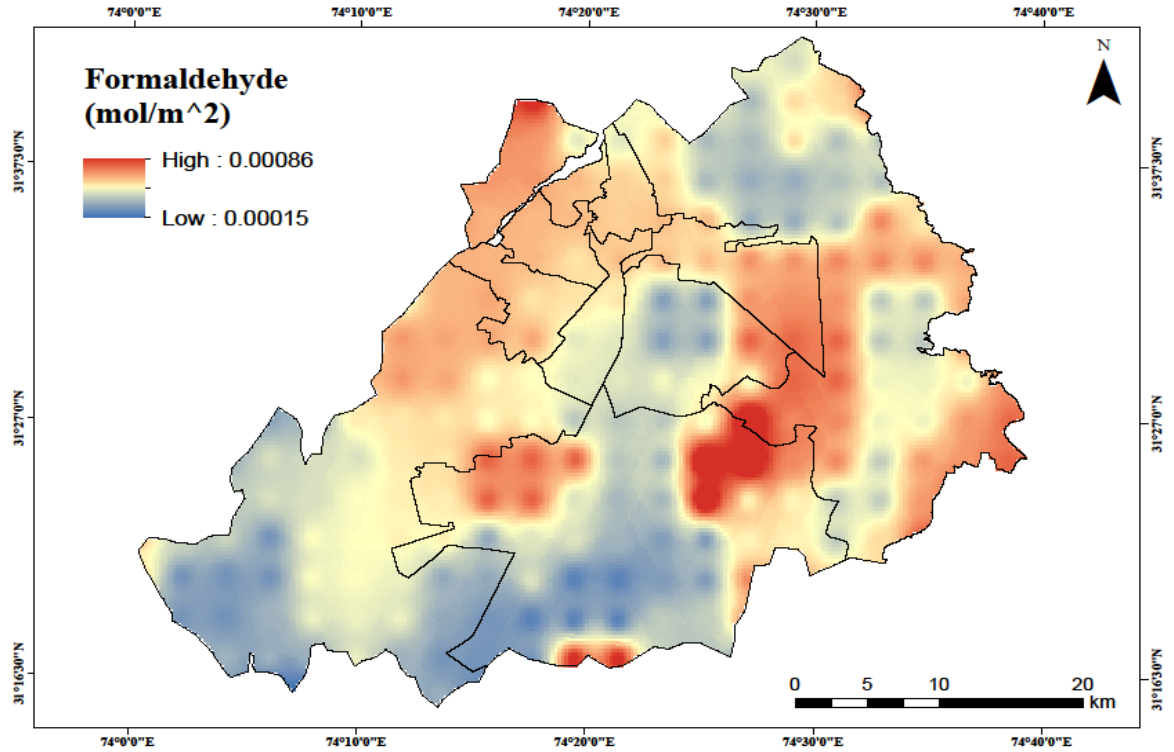

Figure 6 Spatial Pattern of HCHO (mol/m^2) of Lahore.

Table 5. Categorization of levels of CH_4 in air.

Methane (ppb)	Category
1600	Good
1650	Satisfactory
1750	Moderate
1850	Poor
1950	Very poor
2000	Severe

Nitrogen Dioxide: Based on the results as shown in Figure 8, the highest and the lowest values of nitrogen dioxide recorded by sentinel-5p on 19-10-2021 were 0.00033 and 0.000042 mol/m^2 respectively. When these values were compared with the Table 6 (Source: Sentinel Hub), it can be seen that Lahore had moderate to severe levels of nitrogen dioxide in air. Moderate to poor level observed Shalamar, Wagha, Aziz Bhatti and Iqbal town, very poor level observed in Nishtar town and severe level observed in Ganj Baksh, Gulberg, Samnabad and some areas of Ravi town.

Table 6. Categorization of levels of NO2 in air.

Nitrogen Dioxide (mol/m^2)	Category
0.0	Good
1.25E-5	Satisfactory
3.75E-5	Moderate
6.25E-5	Poor
8.75E-5	Very poor
1.0E-4	Severe

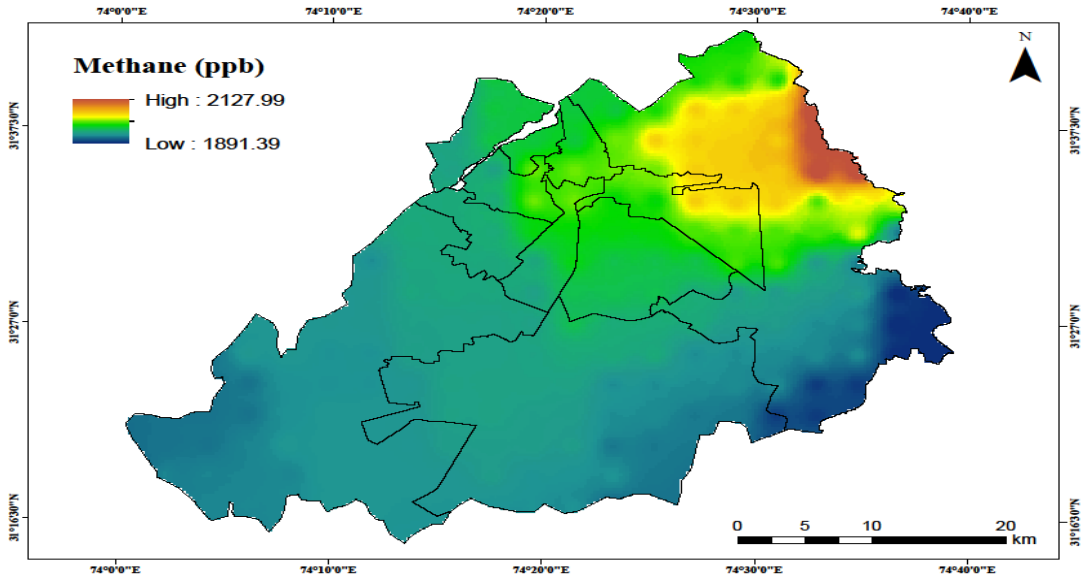

Figure 7 Spatial Pattern of CH_4 (ppb) of Lahore

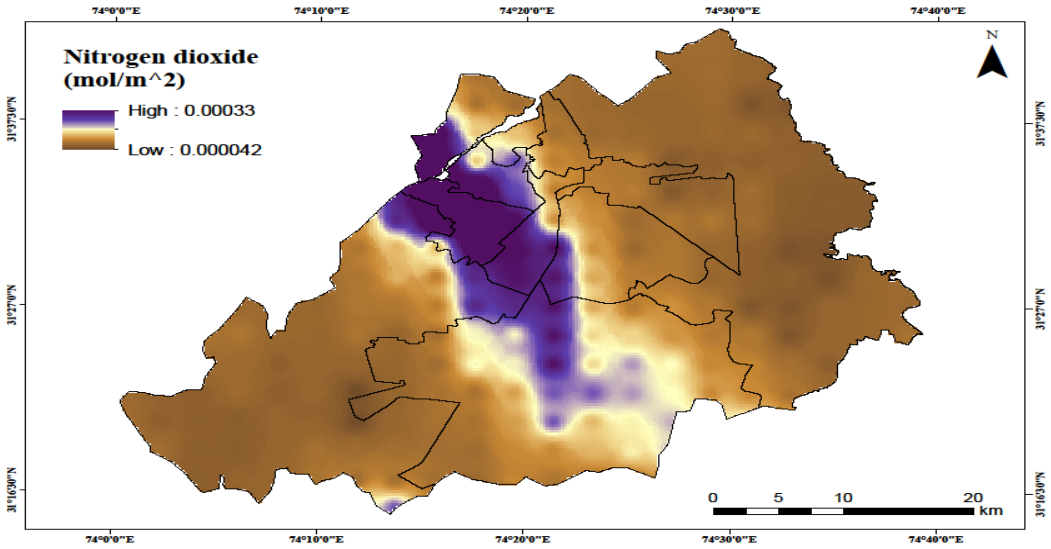

Figure 8 Spatial pattern of NO_2 (mol/m^2) of Lahore

Ozone: Based on the results as shown in Figure 9, the highest and the lowest values of ozone recorded by Sentinel-5p on 15-10-2021 were 0.1239 and 0.1196 mol/m^2 respectively. When these values were compared with the Table 7 (Source: Sentinel Hub), it can be seen that Lahore had satisfactory level of ozone in the air.

Table 7 Categorization of levels of O3 in air.

Ozone (mol/m^2)	Category
0.0	Good
0.045	Satisfactory
0.135	Moderate
0.225	Poor
0.315	Very poor
0.36	Severe

Urban Air Quality Index (UAQI): Based on the results as shown in Figure 10, Lahore had good to hazardous level of Urban Air Quality Index (UAQI). Table 8 shows the categorization of levels of AQI in air. Hazardous level observed in Cantonment, Gulberg, Ganj Baksh and Samnabad town while unhealthy to very unhealthy observed in Wagha, Nishtar, Iqbal, Shalamar and Ravi town. Centre of the Lahore is at high risk of pollutants because of the industrialization. Ganj Baksh, Gulberg, Samnabad, Shalamar and Ravi town are the centres of most of the polluting industries such as steel and iron, agriculture, chemical, food retail, technology and fuel industries as shown in Figure 2. These industries are located side by sides of others which makes the air more polluted. Wagha, Nishtar and Iqbal town recorded less contamination as compared to centre of Lahore because few industries are located there and they are randomly displaced.

Table 8. Categorization of levels of AQI in air.

Air Quality Index (AQI)	Category
0-50	Good
51-100	Moderate
101-150	Unhealthy for sensitive groups
151-200	Unhealthy
201-300	Very unhealthy
301+	Hazardous

(Source: Air Now)

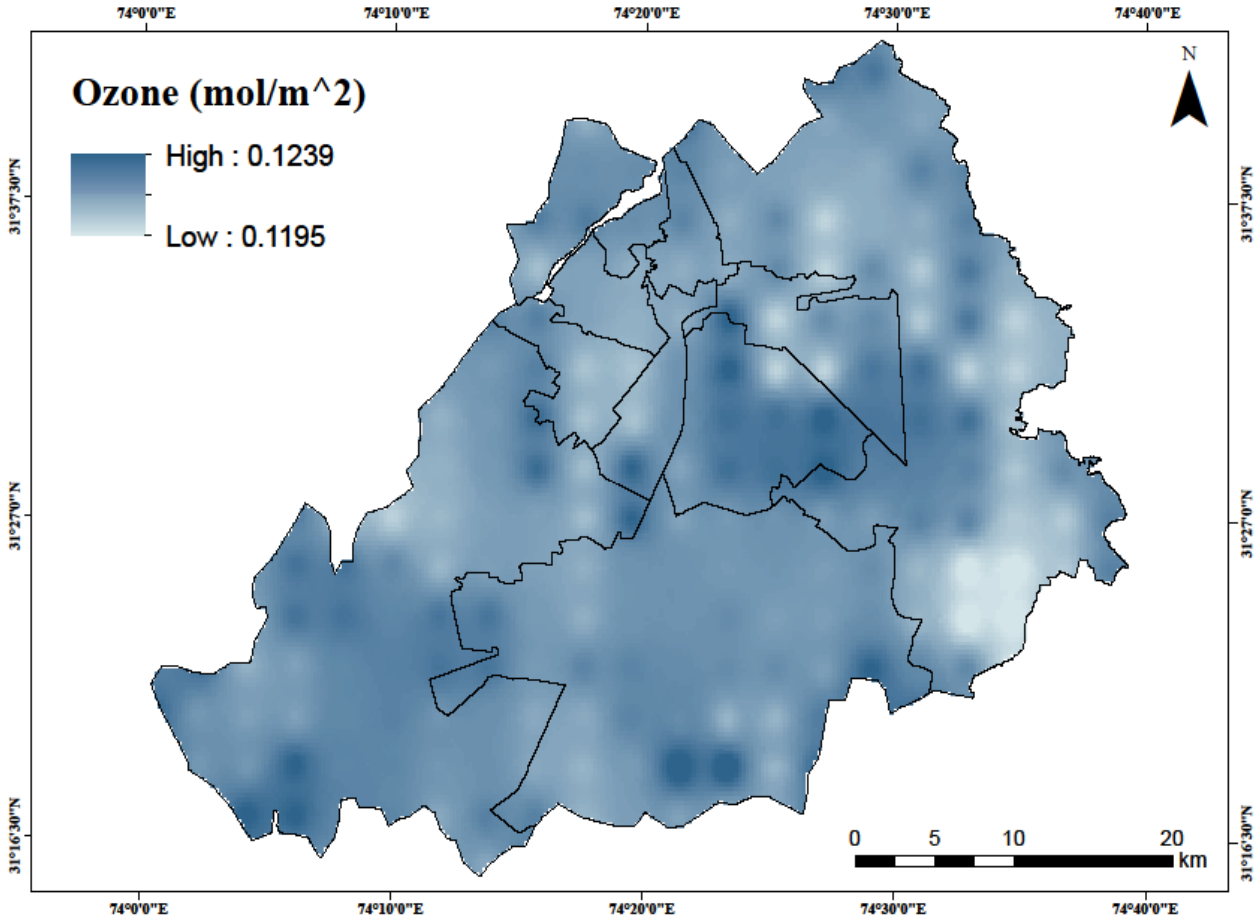

Figure 9 Spatial Pattern of O_3 (mol/m^2) of Lahore

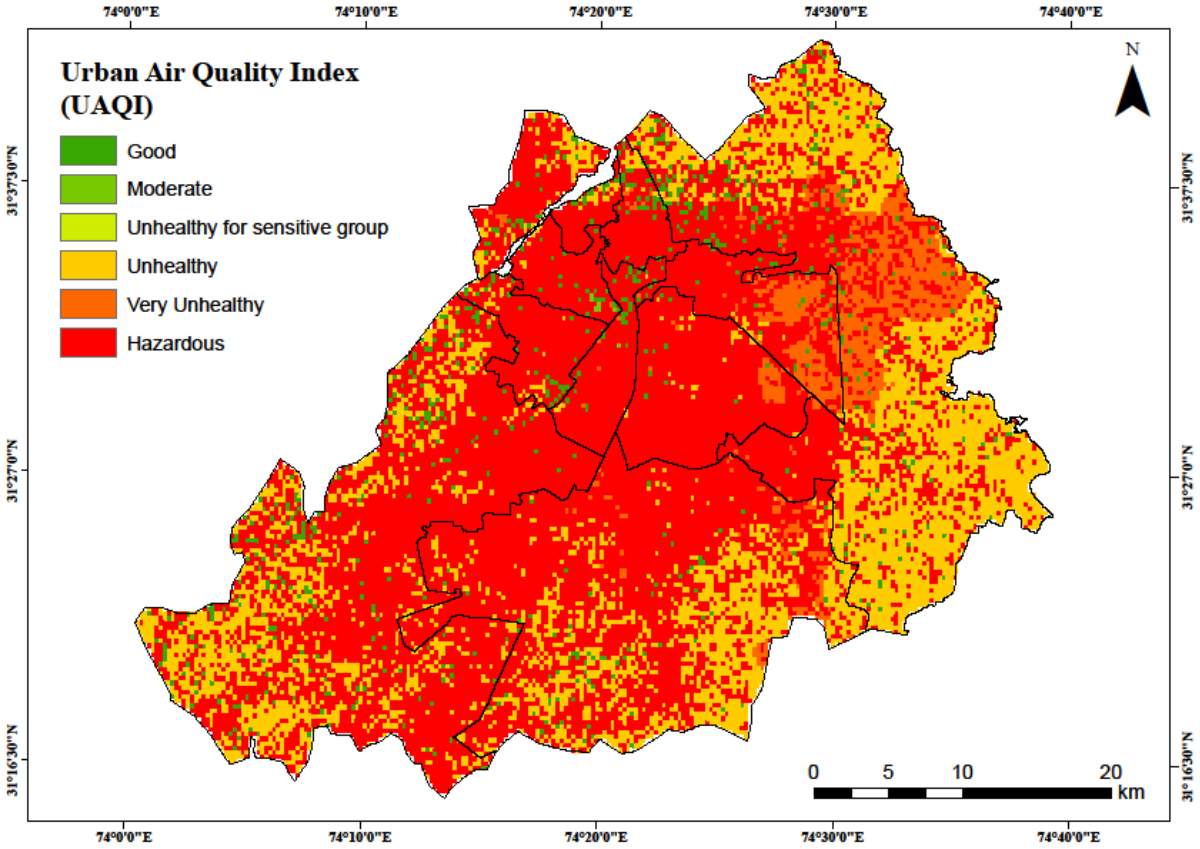

Figure 10 Spatial Pattern of UAQI of Lahore

Table 9 shows the mean values of each parameter with respect to towns.

TOWN	UAQI	CH_4 (ppb)	CO (mol/m^2)	O_3 (mol/m^2)	AI 340/380 nm	AI 354/388 nm	NO_2 (mol/m^2)	HCHO (mol/m^2)
Cantonment	556.9	1965.1	0.050	0.122	1.95	1.56	0.000102	0.00041
Iqbal Town	410.8	1931.6	0.042	0.122	1.92	1.47	0.000083	0.00039
Aziz Bhatti Town	435.2	1999.7	0.049	0.122	2.85	2.36	0.000069	0.00053
Nishtar Town	423.3	1933.4	0.049	0.122	1.74	1.34	0.000115	0.00042
Wagha Town	309.5	1977.1	0.053	0.122	2.60	2.05	0.000063	0.00046
Samnabad Town	543.7	1950.4	0.047	0.122	1.45	1.07	0.000248	0.00050
Gulberg Town	579.0	1964.3	0.049	0.122	1.60	1.22	0.000178	0.00044
Ganj Baksh town	569.2	1966.4	0.046	0.121	1.42	1.05	0.000197	0.00051
Shalamar Town	502.4	1980.8	0.046	0.122	1.86	1.45	0.000084	0.00048
Ravi Town	476.6	1958.2	0.045	0.122	1.49	1.12	0.000139	0.00054

Statistical Analysis: Industrial emissions are increasing rapidly in the less developed countries because of industrialization (Geng *et al*., 2016). Air quality of Lahore is also affected by industrialization. In order to find out the impacts of industries on air quality, the abundance of following parameters was analyzed in the air; NO_2, CH_4, HCHO, O_3, CO and AI. According to the results, NO_2 was found in moderate to severe level, methane was found in poor to severe level, HCHO and aerosols index was found in satisfactory to poor level while O_3 was in satisfactory level and CO was found in moderate to poor level. Later the results obtained from these parameters were used to determine the UAQI. It is observed that high concentration of pollutants was found at the industrial sites of Lahore. Greater no. of technology, steel and iron, fuel, agriculture, fashion, construction and chemical industries are located in Gulberg, Ganj Baksh, Ravi and Shalamar Town which is the reason that these towns had severe level of UAQI. These industries consume excessive amount of energy for daily activities. They get their energy either by burning of fossil fuel or by using cheap fuel. It is estimated that cement industry consumes 2% of worldwide energy consumption and emits 5% of global manmade carbon

dioxide emissions. (Chaurasia and Tiwari, 2016). As a result, excessive chemicals and gases are emitted into the air. Wagha, Iqbal and Nishtar Town have less no of industries, so these towns are less contaminated than other towns of Lahore.

Latest methodology and recent data were used to determine the impacts of industries on air quality. Spatial pattern of air quality is determined to analyze the areas in terms of air quality. The chances of errors in the data are minimal as satellite data is free from human errors. Although, if the yearly data of industries were available, the trend of industries could be measured and the result could have been more statistical. Moreover, there was no data of SO_2 on sentinel-5p so the abundance of SO2 could not be analyzed.

Conclusion and Recommendations: Air quality is being affected by the industrial emissions. Industries are the biggest source of harmful gases and pollutants in the air. The level of such gases and pollutants in the air is severe and it is harmful for the environment. According to the results, Lahore, which is a 2nd largest city of Pakistan, is facing unhealthy to severe level of Urban Air Quality Index (UAQI) because of these industrial emissions. Air Quality parameters such as carbon monoxide, formaldehyde and aerosols were found in poor level while methane and nitrogen dioxide were found in severe level. Only ozone was found in satisfactory level. The level of contamination in the air is directly proportional to the number of industries. Severe level of UAQI was found at the sites where great number of industries located. Gulberg and Ganj Baksh town are highly affected by air quality. Hence, it concludes that the air quality of Lahore is affected by the industrial development.

Industries are using low quality fuel for industrial activities which results in higher emissions, if high quality fuel is used then the emissions will be less. Air quality of mega cities can also be improved by the displacement of industries from cities to less densely populated areas.

Declarations

Ethical Approval: Not applicable

Competing interests: The authors declare that they have no competing interests.

Funding: Not applicable

Availability of data and materials: All the datasets and images used for supporting the article can be accessed on request from the corresponding author.

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