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A STUDY ON THE SEASONAL VARIABILITY OF AIR QUALITY IN LAHORE CITY

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By

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Abstract:

Concentrations of particulate matter directly affects the air quality and human health. Lahore has been among the list of most polluted cities in terms of air quality for past several years. This study focuses on the assessment of air quality in a densely populated area of Lahore with high traffic density, landfill site & informal process industry as the contributor to the air quality. A low cost locally built air quality monitor was utilized for the measurement purposes. Metrological parameters such as temperature and relative humidity & air pollutants such as CH_4, NH_3 & particulate matter ($PM_{1.0}$, $PM_{2.5}$ & PM_{10}) were measured. The data was collected for a period of one year from March 2022 to February 2023. Air quality indices were calculated and analyzed by using daily averages of $PM_{2.5}$ concentrations. The results were compared to the US AQI to find the number of breathable days.

Key Words:

Air Quality, Smog, Particulate matter, Air pollutants, AQI, Lahore, $PM_{2.5}$

Problem Statement

Air pollution is a critical environmental and public health issue which is faced by most of the world population today. World Health Organization (WHO)'s data show that almost all the global population breathe air having pollutant's levels exceeding WHO guideline limits[1]. Globally, the number of deaths each year caused by combined effects of outdoor and indoor air pollutants is 7 million. According to WHO, there were 236 thousand deaths reported due to air pollution in Pakistan in 2019[2]. The air quality of the atmosphere is closely linked to the earth's climate and ecosystem. The more there is imbalance in the earth climatic conditions, the higher the deviation of air quality from the acceptable conditions. Increasing urbanization and unplanned city expansions in the developing counties coupled with increasing energy demands and industrialization in the developed world, the air quality has deteriorated tremendously. In 2021, World Health Organization (WHO) has revised its guidance on exposure to critical air pollutant levels after a span of 15 years. It has made the requirements more

stringent. Trans-boundary air pollution due to climatic conditions and missing regulations have also contributed to overall poor air quality. Some air pollutants directly impact human health by causing various diseases, while some others, which are greenhouse gases, impact all forms of life indirectly through global warming and climate change. For this very reason, mitigating air pollution offers dual advantages; improving public health through reduced exposure to harmful pollutants and reducing GHG emissions resulting in climate change mitigation. The two lethal air pollutants linked to human illness are particulate matter ($PM_{2.5}$ PM_{10} $PM_{1.0}$) & ground level ozone.

Pakistan is the 5th most populous country in the world and it is an emerging economy in South Asia. The urban centers such as Lahore, Karachi and Peshawar are often seen among list of the top 10 most polluted cities of the world with Air Quality Index values reaching as high as 5 times the WHO safe limits[3]. The increasing levels of air pollution are associated with health issues. This has increased the stress on our already burdened health system. It has been reported that air pollution is the second leading risk factor and has resulted in 236 thousand premature deaths in year 2019. Major sources of air pollution in the country are vehicular emissions, urban fugitive dust, crop burning and industrial emission. Many industrial sectors are lacks awareness about the cleaner production and are ill equipped to control air emissions. Weak enforcement of law is also a major reason for unchecked air emissions from vehicles, manufacturing industries and agricultural fields. Lahore's story is no different. It is mega city with population exceeding 13 million. The Lahore Master Plan 2020 has become ineffective and all the current development is not part of any well thought of strategy. Lahore Master Plan 2050 has been under the design process for very long period now and is not finalized yet. This implies that there is very little chance of finding the reasoning for ongoing development projects in the city. First major episode of smog was observed in November 2016 in Lahore. Many people attribute this to the mega development project of Orange Line Metro Train. However, lack of credible historical air quality data is the reason one cannot test this hypothesis. The literature review has revealed that only a handful of researches has been undertaken on this issue in the last one decade. Environment protection department Punjab measures and publishes data at just two fixed points in the city[4]. Hence, this study was undertaken to fill the obvious and very wide measurement and data gap.

Methodology

WWF Pakistan through the EU Funded project titled "International Labor & Environmental Standards Application in Textile and Leather SMEs (ILES) has been working with different stakeholders to help identify, research and mitigate the adverse environmental impacts of anthropogenic activities. Since 2016, they have conducted environmental audits in more than 80 textile and leather enterprises. These audits have helped the organizations identify gaps in their chemical use, energy, water, fuel and solid waste management. Air pollution is a grave issue and Lahore's situation in the regard has been extremely alarming. Industries have an obligation to monitor their air & water effluents and keep them under the specified limits to avoid penalties from regulating bodies. Most progressive industrial units comply to the limits of pollutants as stipulated in the National Environmental Quality Standards. However, a large proportion of such units are found in non-compliance due to factors such as costs, capacity & weak governance. This contributes to high loads of pollution in water bodies and in the air. The quality testing of the water & waste water is not much expensive and its capacity already exists in the country in public and private sector laboratories. Same is the case with emission of air from the manufacturing industries. However, reliable & accurate assessment of ambient air quality is very expensive as most of the good quality monitors are not indigenous and even their operation and maintenance are to be outsourced from the manufacturer at a very high price.

Under the umbrella of ILES project of WWF Pakistan, a project was initiated to build low-cost air quality analyzers locally. The aim of the project was to establish and make good use of local knowledge and expertise in air quality monitoring & analysis. The project was awarded to Industrial Monitoring & Automation Lab (IMAL) based in Information Technology University (ITU) Lahore in 2020. One of the Air Quality Module developed by them was used for monitoring the ambient air quality in a densely populated area with presence of both point and non-point pollution sources. The working of the air quality module has been demonstrated through the figure below, with arrows depicting the flow of data. The module is fitted with various low-cost sensors. All the sensors were factory calibrated. However, the calibration was carried out in IMAL Lab using a primary standard before it was deployed at the site for measurement purpose. The module required 220V alternating current supply and a stable internet access through WIFI to export the data to the cloud storage.

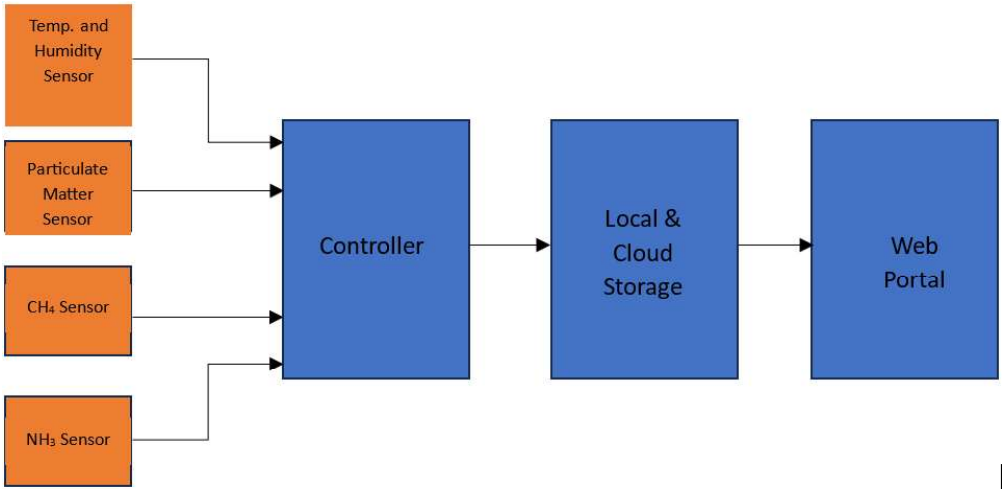


Figure-1: Schematics of the air quality monitor

Selection of Site:

Considering a range of variables, Daroghawala area in Lahore was chosen as the location for placing the air quality monitor. This area has high traffic density, high population density, formal and informal industrial sector (particularly steel manufacturing units), agricultural area & a scientific landfill site in the vicinity. All of these are well known contributors to the air quality and impact different forms of life including human beings. Figure-2 shows the GIS map of the area in Lahore where the Air Quality Module was deployed for the purpose of data acquisition.

Sampling Time & Data Acquisition:

The air quality monitor equipped with various sensors measured and recorded the data for a period from 1st March 2022 through 28th February 2023 i.e., 1 year period. Each sensor recorded the values at an interval of 1 minute. The data was logged and saved on both the cloud storage and in the memory card installed in the air quality monitor.

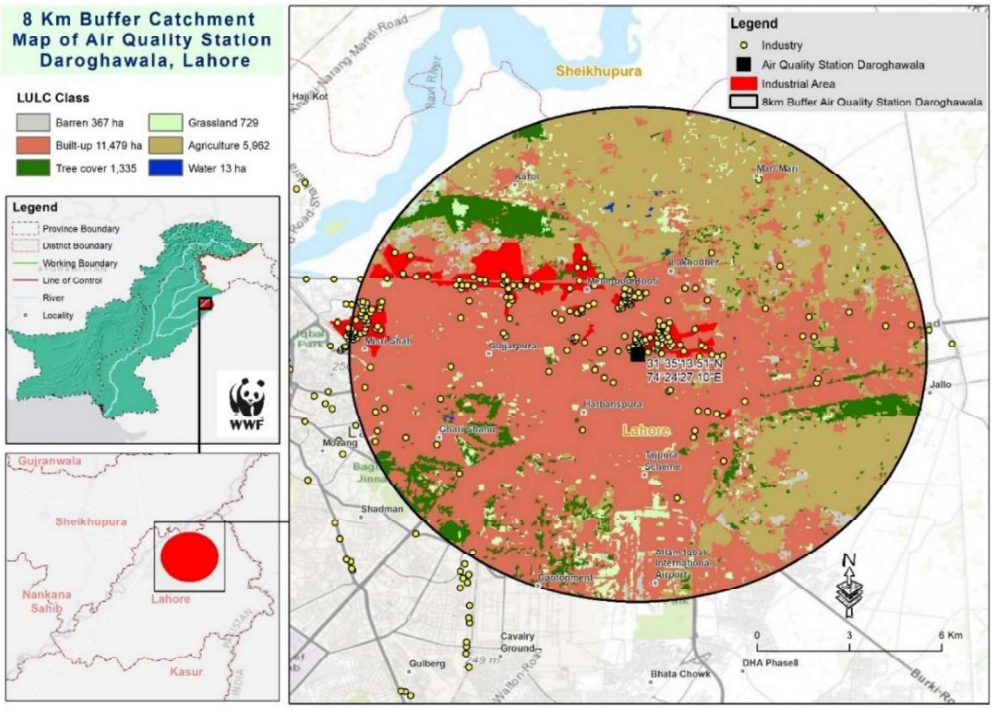


Figure-2: Geography around the location of air quality module

Data Analysis:

The data was exported in excel format and daily averages were calculated using the Pivot Table feature of the Microsoft Excel suite. The data was divided into four quarters for the sake of assessing the seasonal variations. The information is presented in Table-1.

Table-1: Classification of Data for Seasonal Variability Assessment

Quarter	Period	Season
1	Mar 2022 – May 2022	Spring & Summer
2	Jun 2022 – Aug 2022	Summer & Monsoon
3	Sep 2023 – Nov 2022	Autumn
4	Dec 2022 – Feb 2023	Winter

The daily average values of various parameters were plotted using a line chart. The abnormalities in the different parameters were observed. A data analysis & visualization software named Orange was used for the sake of visualization of the data. The analysis of the visualized data depicted

anomalies in the concentration of pollutants. There were some seasonal variations identified as various zones of concerns. Each zone is characterized by varying anomalies in the concentrations of different pollutants. The summary of the various zones and their respective time period is presented in the table:

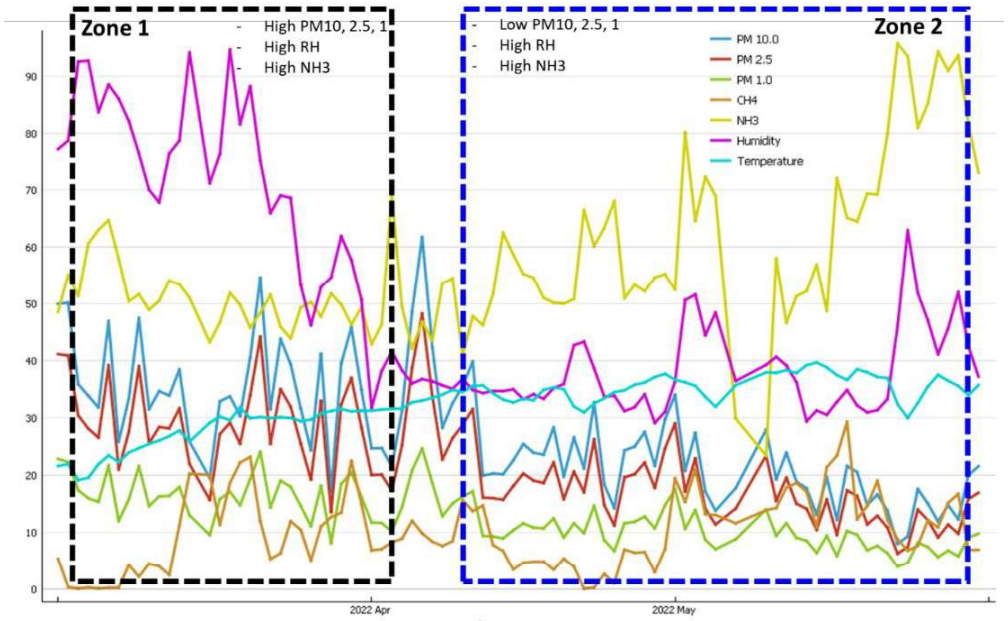
Table-2: Summary of identified zones of concern

Zone	Quarter	Period	Season
1	1	01 Mar 2022 – 07 Apr 2022	Spring / Summer
2	1	08 Apr 2022 – 31 May 2022	Summer
3	2	10 Jun 2022 – 28 Jul 2022	Summer/Monsoon
4	2	4 Aug 2022 – 31 Aug 2022	Monsoon
5	3	16 Oct 2022 – 30 Nov 2022	Autumn
6	4	01 Dec 2022 – 17 Feb 2023	Winter & Spring

Results and discussions:

a) Zone 1 – Spring/Summer Season:

High particulate matter (PM 1, 2.5 & 10) levels in the zone 1 along with relatively low temperatures has been observed during the March and early April period. This is attributed to the ability of the aerosols in the air to increase their mass concentration and particle number during low temperature period.



Quarter 1 – March 2022 – May 2022

Another key observation is high RH in the same period. This promotes the particle growth as the particles are hygroscopic in nature and high humidity accelerate this process. In turn, the particulate matter concentrations would increase.

High concentration of methane has been observed in the air. This can be attributed to the presence of a large landfill site in the vicinity. This Lakhodair landfill site received the waste from Lahore and adjoining areas. Landfill methane could have been contributing to higher levels of methane concentration. The temperature increase due to late spring and early summer accelerates the decomposition of the biodegradable waste in the landfill site.

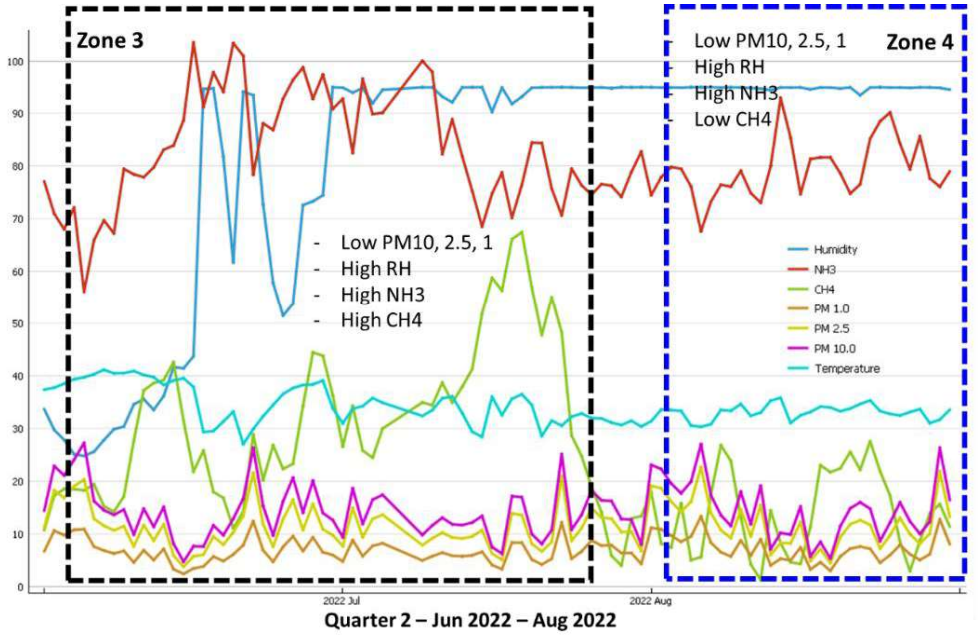
b) Zone 2 – Summer Season:

A decrease in the concentration of particulate matter has been observed as the temperature increases in this time period. When there is increase in temperature in summers, generally the wind speed increases due to convection currents which disperses the particulate matter. The relative humidity values decrease which reduces the particle portioning. As a result, we observe marked reduction in visible particulate matter concentrations & visible pollution.

There is a clear observation of the reduction in the concentration of particulate matter with decrease in relative humidity (RH). Increase in

temperature and decrease in humidity has a compounding effect on the concentration of particulate matter in the air. Temperature increases leads to convection currents in Lahore as it lies in the Punjab Plains. Due to mixing and dispersion effect, aerosols tend to scatter in the air. This is evident from the recording of lower concentrations through the particulate matter sensors.

Concentrations of the methane in this zone has increased even further due to higher atmospheric temperatures. The month of May is relatively hot and dry in Lahore which is ideal for decomposition of the organic matter present in the municipal solid waste.



c) Zone 3 – Summer / Monsoon Season:

Lahore receives large and heavy spells of rainfall in this period of July as it is a Monsoon season. High relative humidity has been recorded but in contrast to the zone 1 i.e., spring season, here the particulate matter concentrations are lower. This is because long spells of rain tend to settle the suspended particulate matter in the air leading to marked improvement is air quality. The rain particles take the dust & particulate matter along as they fall on the ground.

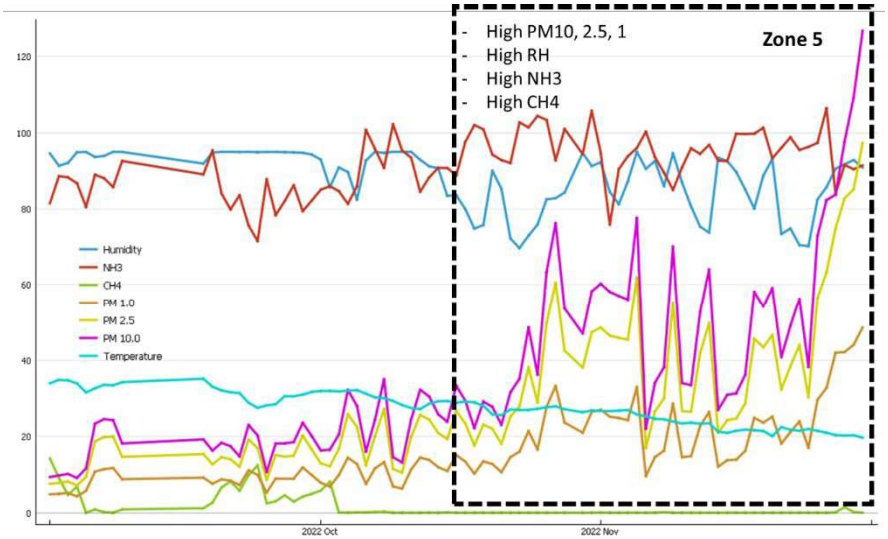
Methane concentrations are also quite high in this zone. This can be attributed to the rise in temperature and high moisture content due to Monsoon season. High temperature and moisture content accelerates the degradation of the biological waste in the municipal solid waste leading to

landfill emissions. Three spikes have been observed in the zone 3 with highest concentration of 68 ppb. Although methane does not have a direct impact on human health and crop production, it is a precursor to harmful air pollutant, tropospheric ozone.

Ammonia concentrations are found to be higher than usual in this zone 3. Major contributors are industrial emissions, agricultural & vehicular emission from the surrounding areas. The area has a great number of informal steel industries with little or no check on air emission. Mostly they burn low quality fuels. Ammonia has a significant role in NH_3 plays a significant role in the formation of atmospheric particulate matter.

d) Zone 4 – Monsoon Season:

Particulate matter concentrations show considerable variability. This can be linked to increased number of rainfall events in this month of August. Although the relative humidity is on higher side, the decrease in atmospheric concentrations of particulate matter is because of settlement of dust particles due to heavy downpours. Certain spikes observed in this zone could be because of the fugitive dust after the rainfall event that settles of the banks of the roads. Another reason for the spike in the particulate matter concentration could be the days with no rain and all other sources contributing to higher aerosol concentrations.



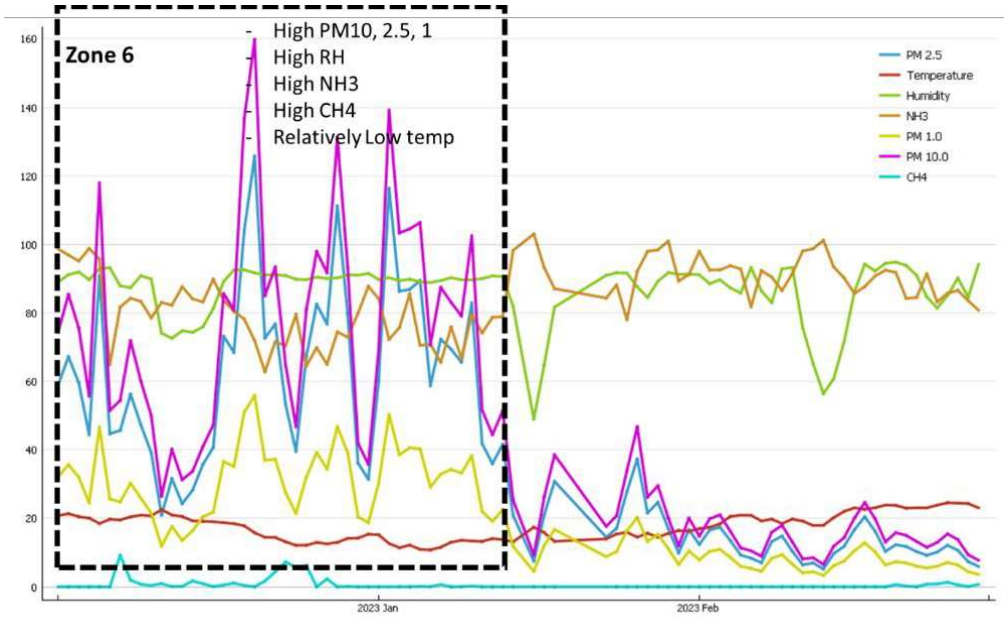
Quarter 3 – Sep 2022 – Nov 2022

e) Zone 5 – Autumn Season:

This zone is marked with abrupt increase in the concentrations of the particulate matter. The concentrations are nearly 2-3 times higher than in

the Monsoon period (zone 3 & 4). This period of the year is known for increase in the levels of smog and haze in the city. Increase in concentrations of particulate matter could be attributed to the dry period and decrease in wind speed and temperature inversion.

Ammonia concentrations are substantially higher in this period. The possible reasons for higher concentration of ammonia are agricultural emissions from nitrogenous fertilizers & industrial emissions.



Quarter 4 – Dec 2022 – Feb 2023

f) Zone 6 – Winter Season:

Particulate matter concentrations are 10-15 times higher than in March 2022. This zone spans the month of December & January 2023 and is marked with low temperature and fog including the higher concentrations of particulate matter. There is low supply of fuel gas to the industrial sector in the winter season because of high demand of the domestic users and the government prioritizes the domestic users. Hence the industry switches to alternate low quality fuel such as waste tires & coal. The burning of waste tires increases the emissions of particulate matter drastically.

Particulate Matter Concentrations - $PM_{2.5}$:

Based on the findings from our data, annual average exposure to $PM_{2.5}$ air pollutant was found to be roughly five times that of the WHO guideline limit while the PM_{10} exposure was two times the WHO limit. The population of the area is at high risk of air pollution and associated adverse health

impacts. Such high level of exposure for longer period of time has its implications on the burden of disease. Pakistan already has double burden of disease of non-communicable diseases including chronic respiratory diseases[5]. Air pollutants such as particulate matter has direct contribution in inflicting the respiratory diseases. The particulate matter in air with drop in temperature in winters leads to the formation of smog, which has become a serious public health concern. Breathing in smog with low exposure is known to cause Asthma and Bronchitis. The risk of lung cancer increases when the exposure is high.

Table-3: Comparison of the Particulate Matter Concentrations

Pollutant	**Averaging Time**	**WHO 2021**[6]	**PEQS 2016**[7]	**CHINA 2016**[8]	**Observed Values in Lahore, Pakistan Mar 2022 – Feb 2023**
$PM_{2.5}$, µg/m^3	Annual	5	15	35	25.41
	24-Hour[a]	15	35	75	Table 4
PM_{10}, µg/m^3	Annual	15	120	70	31.40
	24-Hour[a]	45	150	150	Table 4

µg = microgram

PEQS = Punjab Environmental Quality Standards, Pakistan

WHO = World Health Organization

[a] 99th percentile (i.e., 3–4 exceedance days per year)

Table-4: Daily averages of $PM_{2.5}$ & PM_{10} (Mar 2022-Feb 2023)

Date	**$PM_{2.5}$**	**PM_{10}**	**Date**	**$PM_{2.5}$**	**PM_{10}**	**Date**	**$PM_{2.5}$**	**PM_{10}**
	µg/m^3	µg/m^3		µg/m^3	µg/m^3		µg/m^3	µg/m^3
2022-03-01	41.14	49.97	**2022-04-18**	18.58	23.55	**2022-06-07**	11.55	14.51
2022-03-02	40.89	50.16	**2022-04-19**	22.22	28.35	**2022-06-08**	10.70	13.63
2022-03-03	30.43	35.88	**2022-04-20**	15.75	19.73	**2022-06-09**	11.47	14.63
2022-03-04	28.10	33.84	**2022-04-21**	20.58	26.55	**2022-06-10**	7.66	9.89
2022-03-05	26.53	31.79	**2022-04-22**	16.98	21.15	**2022-06-11**	11.66	14.80
2022-03-06	39.15	46.89	**2022-04-23**	26.21	32.69	**2022-06-12**	8.75	11.36
2022-03-07	20.96	25.78	**2022-04-24**	14.72	18.35	**2022-06-13**	11.85	15.12

Date	$PM_{2.5}$	PM_{10}	Date	$PM_{2.5}$	PM_{10}	Date	$PM_{2.5}$	PM_{10}
	$\mu g/m^3$	$\mu g/m^3$		$\mu g/m^3$	$\mu g/m^3$		$\mu g/m^3$	$\mu g/m^3$
2022-03-08	27.56	33.40	**2022-04-25**	11.15	14.21	**2022-06-14**	5.89	8.13
2022-03-09	38.97	47.48	**2022-04-26**	19.58	24.31	**2022-06-15**	3.79	4.75
2022-03-10	25.55	31.51	**2022-04-27**	20.14	24.96	**2022-06-16**	5.75	7.66
2022-03-11	28.40	34.66	**2022-04-28**	22.15	27.50	**2022-06-17**	6.08	7.62
2022-03-12	28.16	33.88	**2022-04-29**	17.75	21.60	**2022-06-18**	9.52	11.63
2022-03-13	31.66	38.45	**2022-04-30**	24.62	29.67	**2022-06-19**	7.98	9.78
2022-03-14	21.91	25.82	**2022-05-01**	29.03	34.01	**2022-06-20**	10.32	12.91
2022-03-16	15.64	19.47	**2022-05-02**	17.10	20.74	**2022-06-21**	13.42	16.73
2022-03-17	27.14	32.88	**2022-05-03**	22.89	27.33	**2022-06-22**	21.61	26.31
2022-03-18	29.15	33.74	**2022-05-04**	14.05	17.07	**2022-06-23**	11.81	15.29
2022-03-19	25.47	30.31	**2022-05-05**	11.32	13.74	**2022-06-24**	7.60	9.73
2022-03-20	33.94	40.54	**2022-05-07**	14.13	17.70	**2022-06-25**	12.82	16.19
2022-03-21	44.20	54.62	**2022-05-10**	23.39	27.91	**2022-06-26**	16.46	20.69
2022-03-22	25.46	31.54	**2022-05-11**	15.45	19.24	**2022-06-27**	10.75	14.07
2022-03-23	35.01	43.78	**2022-05-12**	19.51	23.89	**2022-06-28**	15.69	20.09
2022-03-24	31.92	39.36	**2022-05-13**	14.98	18.85	**2022-06-29**	10.90	13.99
2022-03-25	25.47	31.60	**2022-05-14**	14.06	17.66	**2022-06-30**	9.76	12.62
2022-03-26	19.20	24.34	**2022-05-15**	10.39	13.04	**2022-07-01**	7.70	9.41
2022-03-27	32.95	41.18	**2022-05-16**	15.70	19.60	**2022-07-02**	14.93	18.66
2022-03-28	13.51	17.01	**2022-05-17**	9.52	12.16	**2022-07-03**	9.41	11.89
2022-03-29	32.33	39.53	**2022-05-18**	17.29	21.56	**2022-07-04**	12.86	16.52

Date	$PM_{2.5}$	PM_{10}	Date	$PM_{2.5}$	PM_{10}	Date	$PM_{2.5}$	PM_{10}
	$\mu g/m^3$	$\mu g/m^3$		$\mu g/m^3$	$\mu g/m^3$		$\mu g/m^3$	$\mu g/m^3$
2022-03-30	36.97	45.82	**2022-05-19**	16.31	20.50	**2022-07-05**	13.66	17.43
2022-03-31	28.30	34.91	**2022-05-20**	11.36	14.72	**2022-07-09**	7.87	9.82
2022-04-01	19.99	24.64	**2022-05-21**	12.83	16.57	**2022-07-10**	9.19	11.63
2022-04-02	20.06	24.69	**2022-05-22**	10.76	13.74	**2022-07-11**	10.24	13.09
2022-04-03	17.23	21.49	**2022-05-23**	6.20	7.94	**2022-07-12**	9.34	11.84
2022-04-04	25.16	31.16	**2022-05-24**	7.36	9.24	**2022-07-13**	9.14	11.70
2022-04-05	38.65	48.54	**2022-05-25**	13.91	17.52	**2022-07-14**	9.54	12.16
2022-04-06	48.25	61.81	**2022-05-26**	12.09	14.97	**2022-07-15**	10.74	13.42
2022-04-07	33.83	42.43	**2022-05-27**	9.05	11.84	**2022-07-16**	6.28	7.52
2022-04-08	22.71	28.28	**2022-05-28**	11.30	14.72	**2022-07-17**	5.11	6.28
2022-04-09	26.42	32.56	**2022-05-29**	9.71	12.22	**2022-07-18**	13.91	17.17
2022-04-10	28.77	35.50	**2022-05-30**	15.79	19.96	**2022-07-19**	13.56	16.97
2022-04-11	31.51	39.85	**2022-05-31**	16.89	21.52	**2022-07-20**	8.14	10.00
2022-04-12	16.04	19.89	**2022-06-01**	11.29	14.44	**2022-07-21**	6.67	8.10
2022-04-13	15.93	20.26	**2022-06-02**	18.28	22.90	**2022-07-22**	8.52	10.75
2022-04-14	15.68	20.14	**2022-06-03**	16.86	21.11	**2022-07-23**	20.95	25.17
2022-04-15	18.05	22.52	**2022-06-04**	19.07	24.09	**2022-07-24**	8.69	10.82
2022-04-16	20.24	25.41	**2022-06-05**	20.32	27.29	**2022-07-25**	11.12	13.63
2022-07-26	14.89	18.26	**2022-09-19**	12.67	16.29	**2022-11-06**	16.95	22.07
2022-07-27	13.13	16.39	**2022-09-20**	14.55	18.33	**2022-11-07**	26.58	34.06
2022-07-28	12.90	16.26	**2022-09-21**	14.01	17.44	**2022-11-08**	29.96	38.15

Date	$PM_{2.5}$	PM_{10}	Date	$PM_{2.5}$	PM_{10}	Date	$PM_{2.5}$	PM_{10}
	$\mu g/m^3$	$\mu g/m^3$		$\mu g/m^3$	$\mu g/m^3$		$\mu g/m^3$	$\mu g/m^3$
2022-07-29	10.41	12.86	**2022-09-22**	12.04	14.75	**2022-11-09**	55.25	70.10
2022-07-30	10.46	12.72	**2022-09-23**	19.20	23.02	**2022-11-10**	26.65	33.96
2022-07-31	6.77	8.05	**2022-09-24**	16.95	20.26	**2022-11-11**	26.48	33.45
2022-08-01	19.15	23.13	**2022-09-25**	8.60	10.67	**2022-11-12**	41.74	52.64
2022-08-02	18.66	22.32	**2022-09-26**	15.12	18.13	**2022-11-13**	49.83	64.08
2022-08-03	16.18	19.60	**2022-09-27**	14.71	18.17	**2022-11-14**	20.97	27.00
2022-08-04	14.22	17.73	**2022-09-28**	14.97	18.51	**2022-11-15**	24.23	30.88
2022-08-05	16.15	19.96	**2022-09-29**	20.23	23.58	**2022-11-16**	24.71	31.31
2022-08-06	22.67	27.02	**2022-09-30**	16.56	20.08	**2022-11-17**	28.64	36.18
2022-08-07	13.98	17.34	**2022-10-01**	12.92	16.33	**2022-11-18**	45.64	58.15
2022-08-08	10.74	13.57	**2022-10-02**	12.18	16.53	**2022-11-19**	43.38	54.24
2022-08-09	9.21	11.53	**2022-10-03**	16.69	20.51	**2022-11-20**	46.63	59.14
2022-08-10	14.67	18.00	**2022-10-04**	25.81	32.22	**2022-11-21**	32.33	40.81
2022-08-11	9.56	11.86	**2022-10-05**	22.52	28.02	**2022-11-22**	38.41	49.04
2022-08-12	15.47	19.15	**2022-10-06**	12.40	16.04	**2022-11-23**	43.93	56.25
2022-08-13	6.02	7.12	**2022-10-07**	20.10	24.36	**2022-11-24**	30.28	38.23
2022-08-14	8.30	10.19	**2022-10-08**	27.18	35.00	**2022-11-25**	56.53	72.88
2022-08-15	8.22	9.90	**2022-10-09**	11.45	14.57	**2022-11-26**	63.36	82.31
2022-08-16	12.25	15.21	**2022-10-10**	10.52	13.18	**2022-11-27**	74.86	83.76
2022-08-17	4.90	5.75	**2022-10-11**	19.82	24.44	**2022-11-28**	82.80	97.71
2022-08-18	7.13	8.50	**2022-10-12**	25.63	32.24	**2022-11-29**	85.13	109.27

Date	$PM_{2.5}$	PM_{10}	Date	$PM_{2.5}$	PM_{10}	Date	$PM_{2.5}$	PM_{10}
	$\mu g/m^3$	$\mu g/m^3$		$\mu g/m^3$	$\mu g/m^3$		$\mu g/m^3$	$\mu g/m^3$
2022-08-19	4.48	5.36	**2022-10-13**	24.43	30.45	**2022-11-30**	97.33	126.82
2022-08-20	9.40	11.46	**2022-10-14**	20.90	25.81	**2022-12-01**	59.03	74.40
2022-08-21	11.86	14.86	**2022-10-15**	19.33	23.86	**2022-12-02**	67.26	85.41
2022-08-22	12.62	16.02	**2022-10-16**	26.70	33.30	**2022-12-03**	59.58	75.61
2022-08-23	11.72	14.80	**2022-10-17**	23.41	29.35	**2022-12-04**	44.53	55.85
2022-08-24	7.23	8.66	**2022-10-18**	17.63	22.18	**2022-12-05**	90.86	117.94
2022-08-25	9.74	12.18	**2022-10-19**	23.09	29.13	**2022-12-06**	44.76	51.54
2022-08-26	13.04	16.00	**2022-10-20**	22.00	27.75	**2022-12-07**	45.70	54.49
2022-08-27	9.99	12.41	**2022-10-21**	18.07	23.05	**2022-12-08**	56.30	71.93
2022-08-28	8.14	10.03	**2022-10-22**	25.25	31.58	**2022-12-09**	47.30	60.11
2022-08-29	10.09	12.35	**2022-10-23**	27.92	35.15	**2022-12-10**	39.23	50.06
2022-08-30	21.83	26.31	**2022-10-24**	38.16	48.60	**2022-12-11**	20.90	26.48
2022-08-31	13.24	16.46	**2022-10-25**	28.83	36.24	**2022-12-12**	31.60	40.17
2022-09-01	7.56	9.35	**2022-10-26**	49.77	63.40	**2022-12-13**	24.29	31.27
2022-09-02	7.80	9.76	**2022-10-27**	60.57	76.24	**2022-12-14**	28.23	33.77
2022-09-03	8.18	10.17	**2022-10-28**	42.49	53.63	**2022-12-15**	35.77	41.01
2022-09-04	7.13	9.11	**2022-10-30**	38.06	47.03	**2022-12-16**	40.73	47.30
2022-09-05	9.35	11.65	**2022-10-31**	47.36	58.29	**2022-12-17**	73.26	85.68
2022-09-06	18.73	23.34	**2022-11-01**	48.58	60.29	**2022-12-18**	68.53	80.96
2022-09-07	19.83	24.54	**2022-11-02**	46.47	58.16	**2022-12-19**	104.04	136.74
2022-09-08	19.94	24.26	**2022-11-03**	45.87	57.09	**2022-12-20**	125.75	159.71

Date	$PM_{2.5}$	PM_{10}	Date	$PM_{2.5}$	PM_{10}	Date	$PM_{2.5}$	PM_{10}
	$\mu g/m^3$	$\mu g/m^3$		$\mu g/m^3$	$\mu g/m^3$		$\mu g/m^3$	$\mu g/m^3$
2022-09-09	14.63	18.16	**2022-11-04**	45.41	56.12	**2022-12-21**	72.68	85.09
2022-09-18	15.37	19.21	**2022-11-05**	61.96	77.57	**2022-12-22**	76.79	93.46
2022-12-23	53.29	64.78	**2023-01-29**	17.07	20.14			
2022-12-24	39.57	46.78	**2023-01-30**	9.87	11.97			
2022-12-25	67.37	80.98	**2023-01-31**	16.67	20.09			
2022-12-26	82.59	97.92	**2023-02-01**	12.34	14.80			
2022-12-27	76.76	91.75	**2023-02-02**	16.57	19.87			
2022-12-28	111.15	131.15	**2023-02-03**	17.42	21.01			
2022-12-29	79.67	93.35	**2023-02-04**	13.50	16.21			
2022-12-30	36.13	41.97	**2023-02-05**	9.27	11.37			
2022-12-31	31.45	35.76	**2023-02-06**	8.37	10.51			
2023-01-01	60.21	69.49	**2023-02-07**	7.03	8.94			
2023-01-02	116.43	139.16	**2023-02-08**	13.17	15.91			
2023-01-03	86.35	103.37	**2023-02-09**	14.85	17.97			
2023-01-04	86.90	104.54	**2023-02-10**	10.39	13.08			
2023-01-05	89.51	106.39	**2023-02-11**	6.40	8.13			
2023-01-06	58.79	70.71	**2023-02-12**	6.96	8.49			
2023-01-07	72.34	87.46	**2023-02-13**	5.19	6.54			
2023-01-08	69.45	83.13	**2023-02-14**	9.68	11.85			
2023-01-09	65.64	79.13	**2023-02-15**	11.82	14.35			
2023-01-10	82.88	102.47	**2023-02-16**	16.67	20.06			

Date	$PM_{2.5}$	PM_{10}	Date	$PM_{2.5}$	PM_{10}	Date	$PM_{2.5}$	PM_{10}
	µg/m^3	µg/m^3		µg/m^3	µg/m^3		µg/m^3	µg/m^3
2023-01-11	41.82	51.66	**2023-02-17**	20.44	24.65			
2023-01-12	35.98	44.44	**2023-02-18**	16.26	19.88			
2023-01-13	41.71	51.51	**2023-02-19**	10.34	13.13			
2023-01-14	20.84	25.30	**2023-02-20**	12.29	15.82			
2023-01-16	7.47	9.30	**2023-02-21**	11.77	15.01			
2023-01-17	21.05	26.26	**2023-02-22**	10.30	13.26			
2023-01-18	30.82	38.54	**2023-02-23**	9.20	11.52			
2023-01-23	14.48	17.67	**2023-02-24**	10.15	12.96			
2023-01-24	17.06	20.76	**2023-02-25**	12.11	15.46			
2023-01-25	27.74	33.93	**2023-02-26**	10.66	13.78			
2023-01-26	37.35	46.74	**2023-02-27**	7.34	9.36			
2023-01-27	21.57	26.21	**2023-02-28**	5.93	7.75			
2023-01-28	24.70	29.54						

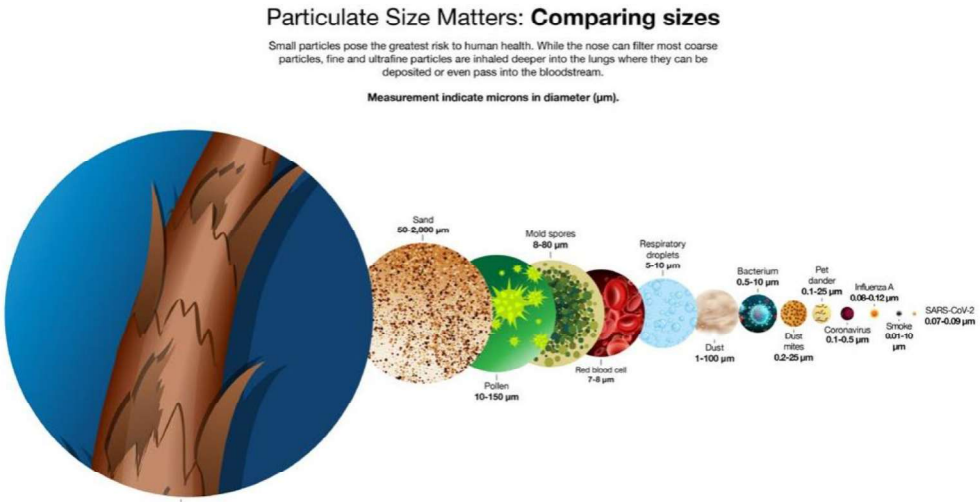


Figure-3: Understanding the PM2.5 size [3]

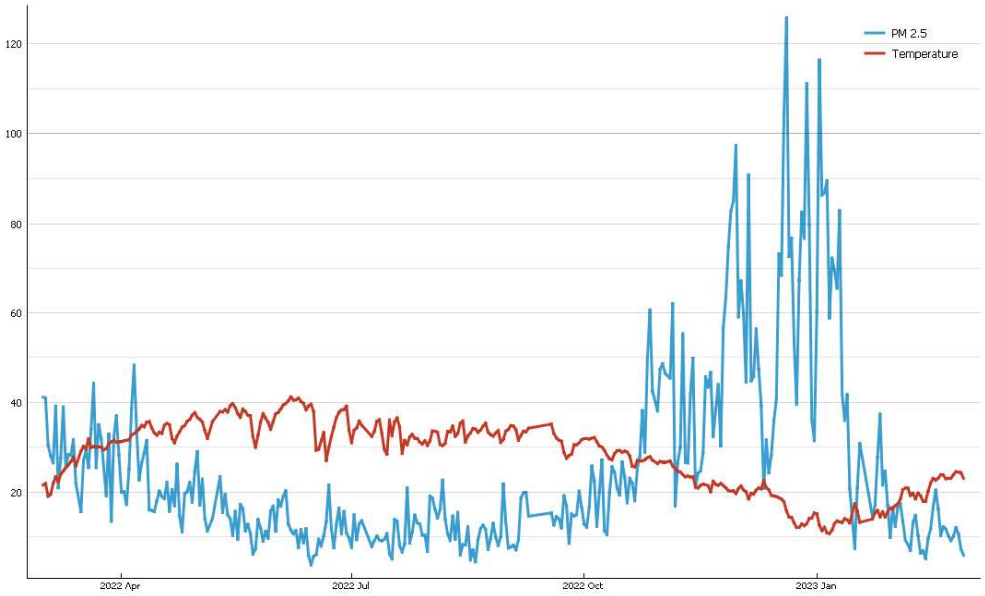


Figure-4: Temperature vs $PM_{2.5}$ concentrations

Table-5 shows the summary of number of days in the study year where $PM_{2.5}$ concentrations have exceeded the annual average daily exposure upper limit. The number of days on which $PM_{2.5}$ concentrations have exceeded WHO safe limit is 207 while it is 74 when it has exceeded PEQS. Out of the 74 days where $PM_{2.5}$ concentrations have exceeded PEQS, 65 were in the period from Oct 2022 through Jan 2023.

In peak summer months of May & June, daily averages of $PM_{2.5}$ concentrations have dropped significantly as compared to late spring. This can be attributed to the rise in temperature and convection currents which lead to dispersion of the pollutants.

In July & August, the $PM_{2.5}$ concentrations are well within limits. This could be directly correlated to the number of heavy rainfalls in the city. In September with significant decline in rainfall, the air pollutants start to aggregate and ambient temperatures start dropping. This leads to gradual increase in pollutant buildup in the atmosphere. Subsequently, the period from October through December is the worst as reflected in Figure-3 & Table-5.

PM 2.5 daily averages in December 2022 were found to be more than 5 times the WHO limit. This is the peak season of smog as the temperature drops and there is almost no rain coupled with low wind speed. It is an established fact that low temperature promotes gas to particle portioning which increases the particle number and mass concentration. The same trend is observed in the month of January 2023.

However, there is a sudden drop in pollutant concentrations in the late January which culminates to even low pollutant concentrations in February 2023. This is clearly visible in Figure-3 & Table-5. The reason for the sudden improvement might be the rise in temperature & wind speed. High temperature & wind speed prevents the pollutant build up in air and aggregation[9].

Table-5: Monthly Breakup of poor air quality days in Lahore vs Average Rainfall

Month	**No. of days with Daily Average $PM_{2.5}$ > 15 µg/m^3**	**Average Rainfall in Lahore (mm)**
Mar-22	29	5.4
Apr-22	28	0
May-22	11	6.4
Jun-22	7	88.7
Jul-22	1	208.2
Aug-22	7	239.9
Sep-22	9	27.4

Month	No. of days with Daily Average $PM_{2.5}$ > 15 µg/m^3	Average Rainfall in Lahore (mm)
Oct-22	25	5.4
Nov-22	30	1.9
Dec-22	31	1
Jan-23	23	5.2
Feb-23	5	8

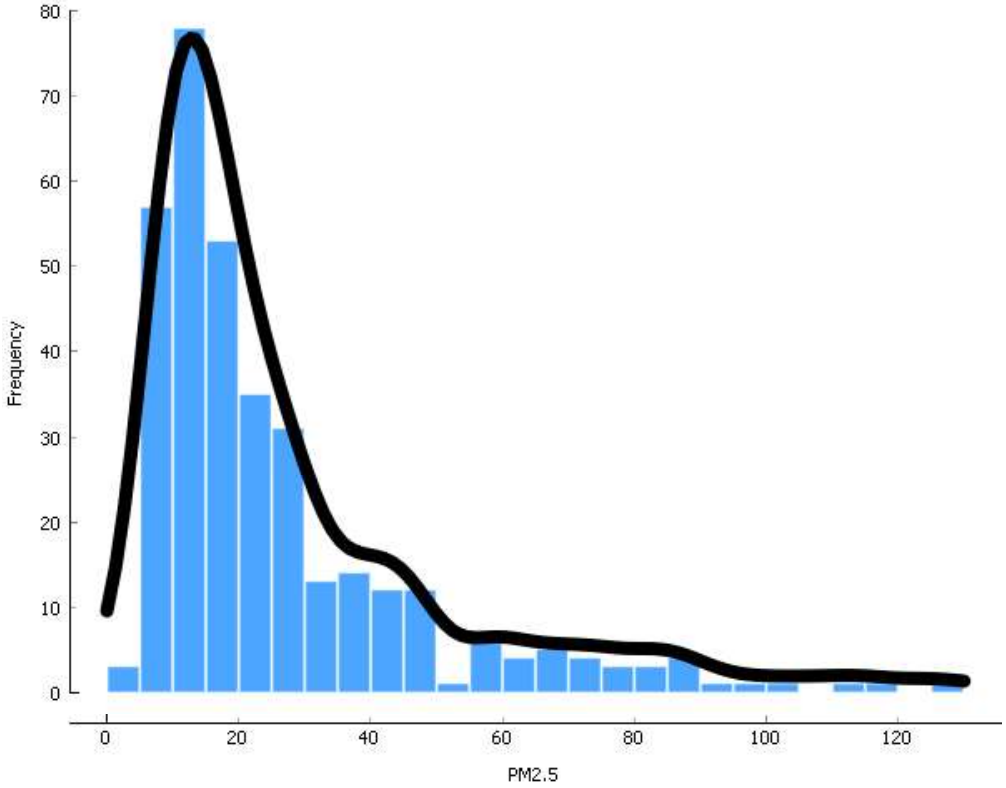


Figure-5: Frequency distribution of $PM_{2.5}$ Concentration for Mar 2022 - Feb 2023

Air Quality Index (AQI):

Air quality index is a measure of the pollutant concentration in the ambient air. The higher the index value, the poor the air quality and vice versa. Various countries have used various pollutant concentrations to report the AQI. Table-5 presents the summary of comparison of air quality index as

defined by Punjab Environmental Quality Standards (PEQS) Pakistan, US EPA & China. Surprisingly, the PEQS values up to AQI 200, which correspond to same pollutant concentration level as US EPA AQI, are marked satisfactory. This implies that as per PEQS, AQI 200 or below is not a concern at all.

Table-6: Comparison of Air Quality Index

PEQS[10]		**US EPA**[11]		**CHINA**[8]	
AQI	*Health Impact*	*AQI*	*Health Impact*	*AQI*	*Health Impact*
0-100	Good	0-50	Good	0-50	Optimal
101-200	Satisfactory	51-100	Moderate	50-100	Good
201-300	Moderately Polluted	101-150	Unhealthy for sensitive groups	100-200	Light Pollution
301-400	Poor	151-200	Unhealthy	200-300	Moderate Pollution
400-500	Very Poor	201-300	Very Unhealthy	300-400	High Pollution
500+	Extremely Poor	300+	Hazardous	400-500	Severe Pollution

US AQI Level		PM2.5 (µg/m³)	Health Recommendation (for 24 hour exposure)
Good	0-50	0-12.0	Air quality is satisfactory and poses little or no risk.
Moderate	51-100	12.1-35.4	Sensitive individuals should avoid outdoor activity as they may experience respiratory symptoms.
Unhealthy for Sensitive Groups	101-150	35.5-55.4	General public and sensitive individuals in particular are at risk to experience irritation and respiratory problems.
Unhealthy	151-200	55.5-150.4	Increased likelihood of adverse effects and aggravation to the heart and lungs among general public.
Very Unhealthy	201-300	150.5-250.4	General public will be noticeably affected. Sensitive groups should restrict outdoor activities.
Hazardous	301+	250.5+	General public at high risk of experiencing strong irritations and adverse health effects. Should avoid outdoor activities.

Table-6: US AQI, $PM_{2.5}$ & associated health recommendations[11]

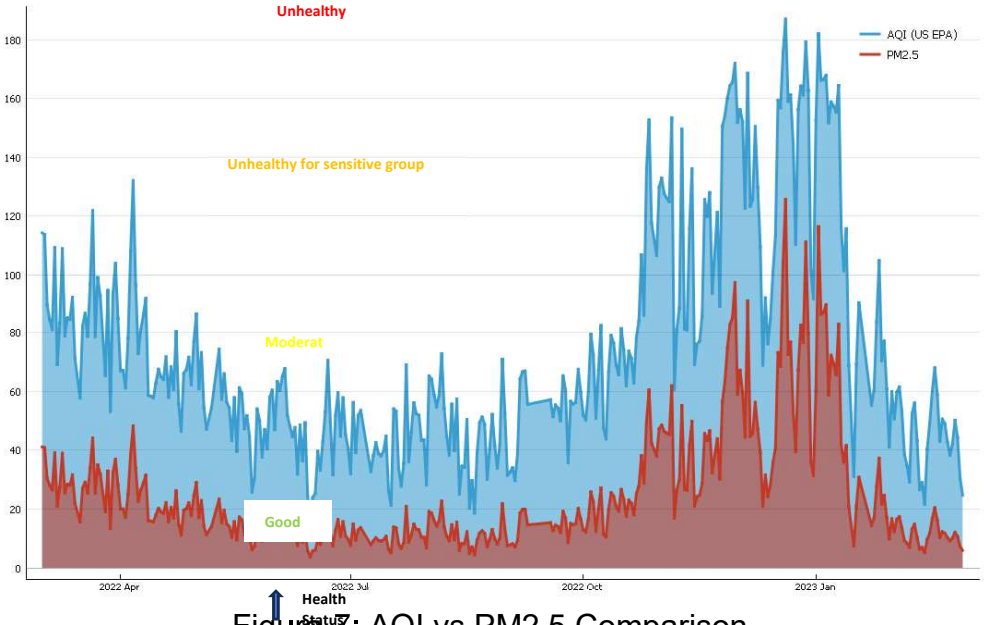


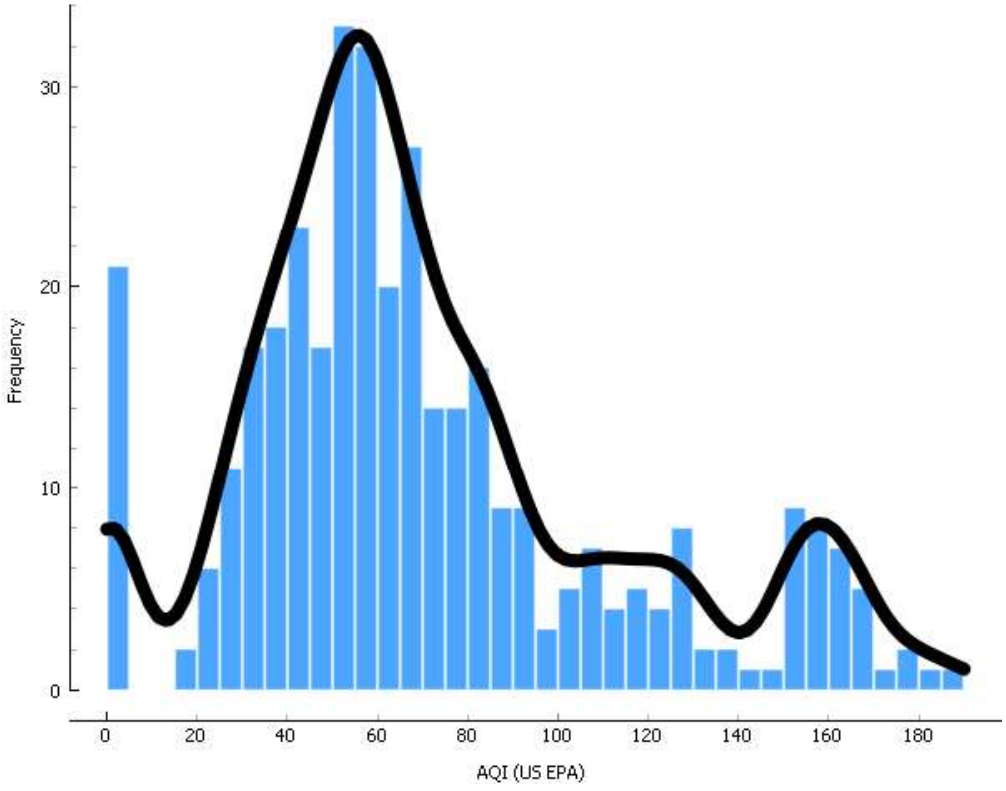
Figure-7: AQI vs PM2.5 Comparison

As clearly evident from Figure-6, the US EPA AQI values indicate that the AQI was good on only less than one-third of the days in one year period from Mar 2022 through Feb 2023. It is only through the Monsoon period that the AQI remained below 50, which implies good air quality days also called

breathable days. On the PEQS AQI yardstick, the air quality is either good or the air pollution is at satisfactory level.

Table-7: Classification of days with regard to AQI

US EPA AQI	No. of days	Health Implication	PEQS AQI	No. of days	Health Impact
0-50	94	Good	0-100	271	Good
51-100	169	Moderate	101-200	72	Satisfactory
101-150	38	Unhealthy for sensitive groups	201-300	0	Moderately Polluted
151-200	32	Unhealthy	301-400	0	Poor
201-300	0	Very Unhealthy	400-500	0	Very Poor
301 & above	0	Hazardous	500+	0	Extremely Poor



Conclusion:

For most part of the year, the daily average of $PM_{2.5}$ concentration have exceeded the WHO and Punjab Environmental Quality Standards. This implies that air pollution is a year-round issue and should not be dealt with, only in the smog period. The levels of air pollutants were found many times higher than WHO & PEQS limits. This implies that the urban population of Lahore has been experiencing higher levels of harmful air pollutants for most part of the year. Hence, there could be higher health risk to the population. There is a stark contrast in the air pollution levels observed in the various seasons. Autmn and Winter season has the highest concentrations of particulate matter. The same is true for spring season. However, the pollutant concentrations are above safe limits but not significantly higher than safe limit as opposed to what is usually observed in smog period. Meteorological parameters such as temperature, humidity and wind speed may either improve or worsen the air quality. A significant drop in pollutant concentrations was observed in the rainy season of monsoon i.e., July and August. It will be worthy to note that there was only one day in July 2022 when the daily average $PM_{2.5}$ concentration exceeded the WHO exposure limits. This suggests that rain is the only instrument that brings respite to the otherwise unfortunate population of the city who are exposed to critically higher levels of pollutant concentrations which, in turn, poses lethal health challenges. If no timely action is taken by the concerned authorities for effective air quality management through policies and action, the burden of disease might increase manyfold in the near future.

Way Forward:

There is a dire and urgent need to invest in and deploy more low-cost air quality sensors to increase the availability of the reliable and accurate data. This will help in the informed decision making. The data & research work should be promoted through private sector financing to understand the root cause of the issue and to identify and implement cost effective solutions. Chemical analysis of the particulate matter and gaseous pollutants in the air will help in the source appointment. There should be public-private partnership to introduce pollution control measures, particularly for the informal industry. The vehicular emission measurement and control is inevitable for managing the ever-increasing issue of air pollution and smog in urban centers like Lahore. No study has been undertaken for source appointment of various air pollutants present in the ambient air. This clearly shows our criminal negligence towards this grave issue. Multi-disciplinary research initiatives must be undertaken involving professionals from fields

such as environmental engineering, automobile engineering, medicine and urban planning.

Significant health benefits can be achieved by reducing population's exposure to air pollution. Addressing air pollution through policy actions in energy, transport, waste management, agriculture and urban planning can also uncover additional co-benefits for health, climate mitigation and sustainable economic development.

EXPLANATORY NOTES

Particulate Matter

A complex mixture of microscopic solid particles and liquid droplets suspended in the atmosphere is referred to as particulate matter (PM). These particles can have a major effect on the environment and human health. They differ in size, composition, and origin. The size of the particles determines the classification of PM because smaller particles can enter the respiratory system more deeply and have more noticeable health effects. PM10 and PM2.5, which stand for particles with aerodynamic diameters of 10 micrometers and 2.5 micrometers or less, respectively, are the two main classifications.

PM_{10}:

- Includes particles with diameters 10 micrometers or smaller.
- Sources of PM_{10} include dust from construction sites, unpaved roads, agricultural activities, and industrial processes.

$PM_{2.5}$:

- Contains particles with diameters 2.5 micrometers or smaller.
- Common sources include combustion processes from vehicles, power plants, wildfires, and certain industrial activities.
- $PM_{2.5}$ particles can penetrate deep into the lungs and pose greater health risks due to their smaller size.

$PM_{0.1}$:

- $PM_{0.1}$ refers to particulate matter with an aerodynamic diameter of 0.1 micrometers or smaller. It falls within the category of ultrafine particles.
- Common sources include combustion processes, industrial emissions, and other human activities.

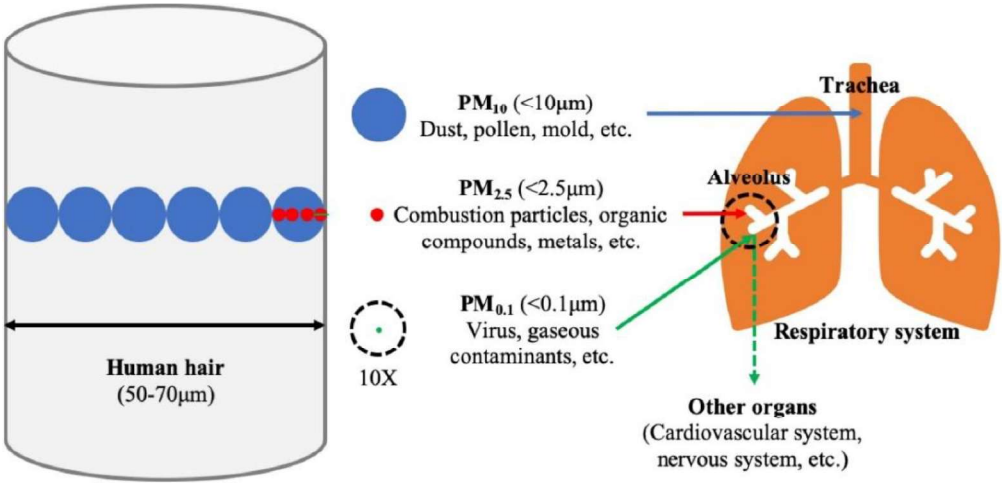


Figure-1: Impact of Particulate Matter on respiratory system.

Smog

Smog is a specific type of air pollution. It is a combination of harmful pollutants (often appearing relatively low to the ground as a yellow-brown haze) that are introduced into the atmosphere by both natural and human induced processes. It was first described over 5 decades ago as a mixture of smoke and fog, hence the name "smog", but today it has a more specific definition and composition.

Smog is made up of many chemicals including nitrogen oxides (NO_x), sulphur dioxide (SO_x), carbon monoxide (CO), and volatile organic compounds (VOCs), but the two main components of smog are particulate matter (PM) and ground-level ozone (O_3).

There are two main types of smog

Classical Smog (London Smog or Sulfurous Smog):

Composition: This type of smog is characterized by high concentrations of sulfur dioxide (SO_2) and particulate matter.

Formation: It occurs in areas with a high concentration of coal-burning industries. During the winter, temperature inversions trap the pollutants near the ground, leading to the formation of smog.

Effects: Classical smog can cause respiratory problems, eye irritation, and contribute to the deterioration of buildings and monuments.

Photochemical Smog:

Composition: Photochemical smog is primarily composed of ground-level ozone (O_3), nitrogen oxides (NO_x), volatile organic compounds (VOCs), and other reactive organic gases.

Formation: It forms in sunny conditions when pollutants from vehicle emissions, industrial activities, and other sources react in the presence of sunlight. This type of smog is common in urban areas with high traffic.

Effects: Photochemical smog can irritate the respiratory system, cause eye irritation, and contribute to the formation of respiratory issues. Ground-level ozone, a major component, is known to be a potent respiratory irritant.

Air Quality Index (AQI)

The Air Quality Index (AQI) is a numerical scale used to communicate information about the quality of air in a specific location. It provides a simple way for the public to understand how air pollution levels might affect their health. The AQI is often calculated based on the concentrations of several major air pollutants, and it is categorized into different levels or color-coded bands to convey the potential health implications. The pollutants commonly included in AQI calculations are ground-level ozone, particulate matter (PM_{10} and $PM_{2.5}$), sulfur dioxide (SO_2), nitrogen dioxide (NO_2), and carbon monoxide (CO).

Here are the general characterizations of the AQI scale:

Table-1: Characterization of AQI scale

AQI Values	Levels of Health Concern	Colors
0-50	Good	Green
51-100	Moderate	Yellow
101-150	Unhealthy for sensitive groups	Orange
151-200	Unhealthy	Red
201-300	Very Unhealthy	Purple
301-500	Hazardous	Maroon

Point and Non-point Pollution Sources

Point Source Pollution:

Definition: Point source pollution refers to contaminants discharged or released from a single identifiable location or specific point. These sources typically have a distinct and well-defined discharge point, such as a pipe, ditch, or outfall.

Examples: Industrial discharges, wastewater treatment plant effluents, mining operations, power plants, oil refineries, and discharges from specific factories or facilities are common examples of point sources.

Non-point Source Pollution:

Definition: Non-point source pollution refers to diffuse sources of pollutants that are not released from a single, identifiable location. Instead, these pollutants come from multiple, widespread activities across a landscape and are carried into water bodies by runoff.

Examples: Agricultural runoff carrying fertilizers and pesticides, urban runoff containing pollutants from roads and construction sites, forestry practices, grazing livestock, septic systems and atmospheric deposition are examples of non-point source pollution.

Source Apportionment Study

A source apportionment study is an investigation that aims to identify and quantify the contributions of various sources to a specific air pollution issue. This involves determining the proportion of pollutants originating from different anthropogenic (human-made) and natural sources. Source apportionment studies use various techniques, such as air quality modeling, chemical analysis of pollutants, and statistical methods, to attribute pollution to specific emission sources. This information is valuable for policymakers to develop targeted strategies for pollution control and management.

Contribution of Fugitive Dust in Air Pollution

Fugitive dust refers to particulate matter that becomes airborne and is not emitted directly from a stack or duct. It is often the result of various human activities, natural processes, or disturbances that disturb soil, create dust, and release particulate matter into the air.

Sources of Fugitive Dust: Common sources of fugitive dust include construction activities, mining operations, agricultural practices, unpaved roads**,** wind erosion, and landfills etc.

Environmental and Health Impacts:

1. **Air Quality Degradation**

Fugitive dust can contribute to elevated levels of particulate matter in the air, impacting overall air quality.

2. **Respiratory and Cardiovascular Health**

Inhalation of fine particles from fugitive dust can have adverse effects on respiratory and cardiovascular health, particularly for vulnerable populations.

3. **Visibility Reduction**

Fugitive dust can reduce visibility, impacting transportation safety and the scenic quality of an area.

4. **Ecosystem Effects**

Deposition of dust on vegetation and ecosystems can affect plant health and soil fertility.

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