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Spatial and temporal assessment of air particulate matter pollution in Faisalabad

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Abstract

Air pollution, particularly particulate matter (PM), poses significant health risks, especially in rapidly urbanizing and industrial cities. This study aims to assess the levels of $PM_{2.5}$ and PM_{10} across various locations in Faisalabad, compare them with national and international air quality standards, and evaluate their implications for public health. The data was collected from forty-nine (49) stations, including urban, industrial and residential areas, using the MicroDust Pro Real Time Aerosol Monitor. Most areas, including residential, commercial, and industrial zones, were observed to have $PM_{2.5}$ and PM_{10} levels above the World Health Organization (WHO) permissible limits. It was recorded that PM pollution was in the order of industrial > commercial > residential areas. The results revealed that PM concentrations frequently exceeded the World Health Organization's (WHO) 24-hour limits, with $PM_{2.5}$ ranging from 46.5 µg m^{-3} at University of Agriculture Faisalabad (UAF) Agronomy Gate (L1) to 90.28 µg m^{-3} at Laari Adda (L43), and PM_{10} ranging from 49.52 µg m^{-3} at Green View Road (L10) to 108.5 µg m^{-3} at Daewoo Terminal (L5). The Air Quality Index (AQI) for most sites fell within the "Unhealthy" or "Hazardous" categories, with values reaching 380.72 at Laari Adda (L43). Industrial areas, especially textile hubs, exhibited the highest particulate matter concentrations, while transport emissions also contributed substantially. The Air Quality Index classified most regions as "Very Unhealthy" or "Hazardous," underscoring serious public health risks. The study recommends the need to take prompt measures to decrease the amount of particulate matter with serious measures such as reinforcement of the laws controlling emissions by industries and traffic and the use of public health measures to prevent the effects of air pollution, especially to the vulnerable groups. Consequently, such information is essential for policymakers to develop proper air quality management in Faisalabad.

Keywords: Air pollution, Air Quality Index (AQI), Environmental monitoring, Faisalabad, Particulate matter ($PM_{2.5}$, PM_{10}), Urbanisation

Introduction

Air pollution, particularly the presence of particulate matter (PM), has become a serious environmental and public health concern worldwide. According to the World Health Organization (WHO), approximately 92% of the global population resides in areas where air pollution levels exceed safe limits, resulting in an alarming increase in health problems such as respiratory and cardiovascular diseases as well as premature deaths (WHO, 2018). In particular, small particles such as $PM_{2.5}$ and PM_{10} are hazardous; they are so small that they can make their way deep into the lungs and spill into the blood. It is linked with a variety of negative health outcomes, including asthma, lung cancer, and heart disease (Manisalidis *et al*., 2020). Air pollution is a contemporary issue, exacerbated by urbanisation, industrialisation, and increasing automotive emissions, and therefore a global threat to public health (Das *et al*., 2021).

Pollution has been globally primarily linked to urbanisation, industrialisation and the unprecedented emission of particulate matter (PM) from motor vehicles (Anjum *et al*., 2021). Faisalabad, Pakistan's third-most populous city, is grappling with air quality issues. The study also revealed that urban particulate matter was attributed to the mass share of other sectors, specifically the textile industry and vehicular emission (Zeeshan *et al*., 2024). Research has found that extremely high levels of $PM_{2.5}$ and PM_{10} were often close to or greatly exceeded national and international standards. The PM sources in the city were also determined to be emissions from cars and industries as well

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Table 1: Study monitoring sites and their locations in Faisalabad

Location ID	Coordinates (X, Y)	Location	Location ID	Coordinates (X, Y)	Location
		a) Residential			
1	73.04506, 31.26274	UAF Agronomy Gate	16	73.04642, 31.28598	Bawa Chak 120 JB
2	73.04572, 31.26711	Green view colony	17	73.04496, 31.29138	Dawood Textile Sgd road
3	73.05002, 31.26475	Islam Nagar	18	73.04371, 31.29685	Madina University
4	73.08889, 31.39643	Sarfraz colony	19	73.04202, 31.30276	Azhar Corporation
5	73.09323, 31.41788	Daewoo Terminal	20	73.04142, 31.30558	FDA city
6	73.07078, 31.45763	Lasani garden	21	73.05468, 31.42831	City Housing Society
7	73.50448, 31.24322	Sitara Sapna colony	22	73.06023, 31.27434	Noorpur
8	73.06672, 3146713	Ismail city	23	73.10418, 31.47105	Bilal Nagar
9	73.07881, 31.43429	Amban Wali Pulli	24	73.10485, 31.47582	121 JB
10	73.07229, 31.44609	Amban Wali Pulli	25	73.06376, 31.29192	Millat Town
11	73.07383, 31.44693	Int. Housing Society Green View Colony	26	73.06502, 31.30075	117 JB Dhanola
12	73.07590, 31.44721	UAF Housing Society	27	73.10580, 31.48259	Jalal town
13	73.07648, 31.45399	Amanat Home, Masjid Ismail Road	28	73.06502, 31.30075	Mustafabad
14	73.07538, 31.45607	2 Punj Pullian Road	29	73.05528, 31.26123	Hijwari town Sargodha Road
15	73.04993, 31.27438	Muslim town Sgd road	30	73.09185, 31.42603	Tariqabad
		b) Commercial areas			
31	73.04943, 31.26589	Ayesha Siddiqa Hospital Jail Road	38	73.09105, 31.44669	Crescent Girls' High School Lhr-Sheikhupura Road
32	73.09323, 31.41788	Daewoo Terminal	39	73.05806, 31.59271	Millat Chowk
33	73.07755, 31.44798	Akbarabad	40	73.06523, 31.27095	Misaq ul Mall
34	73.04919, 31.26948	Allied hospital	41	73.11952, 31.44941	Nishatabad
35	73.04888, 31.27702	Rathore hospital	42	73.09905, 31.46333	Green town
36	73.07005, 31.50772	Metro cash and carry	43	73.05643, 31.25723	Laari adda
37	73.08929, 31.44583	Sahil hospital			
		c) Industrial areas			
44	73.04719, 31.28315	Sitara textile Sgd road	47	73.35475, 31.51612	Masood Textile Mills (MTM)
45	73.07576, 31.47996	Rashid Textile	48	73.84453, 31.59414	Nishat Mills Ltd
46	73.04243, 31.30467	Crescent Textile	49	73.06285, 31.28533	Gokhowal Millat road

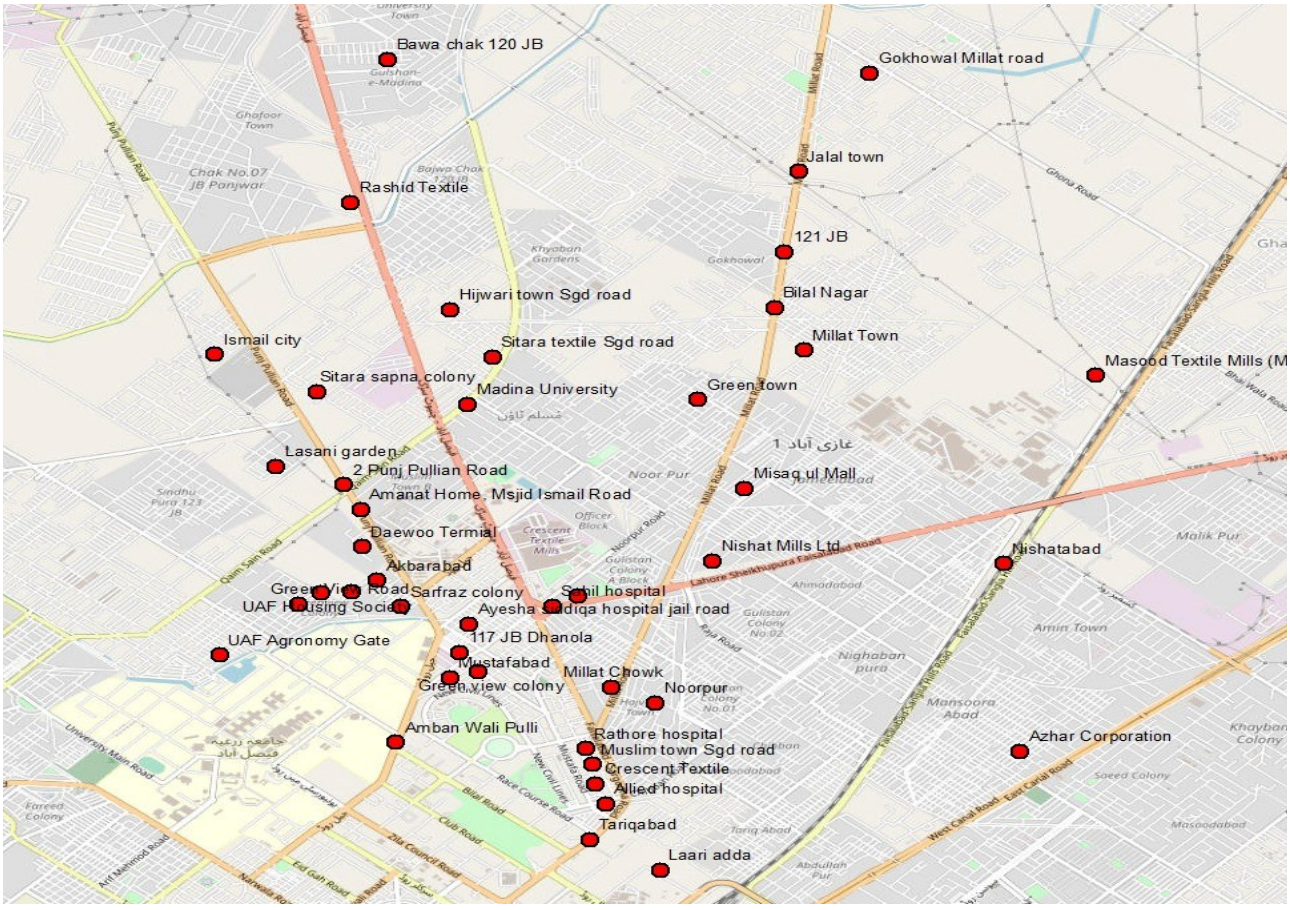


Figure 1: Map of study locations in Faisalabad

as dust resulting from construction. PM pollution poses numerous health and environmental risks, and the ongoing tracking and analysis of PM concentration in urban environments is critical to mitigating those risks. In recent studies, various approaches have been applied, such as measuring PM ($PM_{2.5}$ and PM_{10}) to understand their spatial distribution in different regions (Fan *et al*., 2021; Mamić *et al*., 2023). According to recent research, Faisalabad's air quality is getting worse, as PM levels in the city are several times higher than the thresholds established by the WHO (Mukherjee *et al*., 2022). Although various researchers have acknowledged the problem, no task has examined the native data for mapping the geographic distribution of such contaminants in the city.

This study evaluates $PM_{2.5}$ and PM_{10} concentrations across diverse land-use sites in Faisalabad to assess air pollution severity. The study identifies hotspots with elevated particulate levels, benchmarks them against national and global air quality standards, and assesses potential health risks. The findings are helpful for targeted interventions and policy strategies aimed at mitigating pollution-related impacts and protecting vulnerable populations.

Materials and Methods

Study area and Site selection

Faisalabad is the 3rd largest city of Pakistan. It experiences very high levels of industrial activity and rising vehicular traffic and a growing urban population making it the best suitable option for the current study. On a map, its latitude lies between 30 and 31.15 north and its longitude ranges from 73 to 74 degrees east. It has a mean annual rainfall of approximately 350 mm and feature an arid to semi-arid climate (Pasha *et al*., 2015) while Faisalabad lies 184 meters above sea level. Faisalabad's rapid industrial growth and increased traffic congestion have caused severe air pollution in the city. The monitoring sites of this study were chosen randomly based on a pre-survey. They were selected to be located in urban, industrial, and traffic areas, as well as residential and rural areas. The details of the monitoring sites and their locations are given in Table 1 and Figure 1.

The study area was representative of the location, providing meaningful and comprehensive data. To achieve this objective, the survey was conducted before monitoring the area. The selected sites represented urban, densely populated areas, motorways, industrial, railway crossings, bridges, rivers, and rural and agricultural areas. After the survey, the site was selected, which fulfils all the prerequisites for monitoring. The dust parameters ($PM_{2.5}$, PM_{10} and TSP) were monitored using the MicroDust Pro Real Time Aerosol Monitor (model HB327507, Casella CEL, United Kingdom) on a one-hour average basis at each sampling point. The Global Positioning System (GPS) gadget Etrex Gemin was used to record the coordinates of each location. The coordinates were then recorded in an Excel document, where the X coordinates (Latitude) and Y coordinates (Longitude) were methodically grouped with the relevant accuracy levels for each location. The collected data was then loaded into ArcGIS 10.8 software, where a base map was prepared.

Collection of particulate matter (PM)

PM samples were obtained using a high-volume air sampler (model CF-1001BRL, Hi-Q, USA) at each site in this study. Samples were collected using micro glass fibre filter sheets with a diameter of 47 mm. These filter sheets are chosen because of their inert character, good purity and ability to trap particles up to 0.01 m. The high-volume air sampler, outfitted with a protective covering and a high-speed motor operating as a blower, provided efficient PM sampling. The sampling was performed 10 meters from the road and 5 meters above ground level. The recovered filter papers were desiccated (45±5% relative humidity and 23±3°C temperature) for 24 hours in a desiccator to measure the PM mass. After the procedure, the filter papers containing PM were wrapped adequately in aluminium foil and delivered to the laboratory to extract PM for further studies (Method IO-2.1, US EPA, 2015).

Representative Color	Breakpoints of PM concentrations (μg m^{-3})			AQI Category	AQI
	$PM_{2.5}$	PM_{10}	TSP		
Green	0.0–12	0–54	0-104	Good	0–50
Yellow	12.1–35.4	55–1 54	105-264	Marginal (moderate)	51–1 00
Orange	35.5–55.4	155–254	265-364	Unhealthy for sensitive groups	101–1 50
Red	55.5–150.4	255–354	365-464	Poor (unhealthy)	151–200
Purple	150.5–250.4	355–424	465-524	Very poor (very unhealthy)	201–300
Maroon	250.5–350.4	425–504	525-604	Hazardous	301–400
Dark Maroon	350.5–500	505–604	605-704	Very hazardous	401–500
Blue	> 500	> 604	> 704	Very Critical	> 500

Figure 2: AQI categories against PM concentration ranges (Gurjar *et al*., 2008; US-EPA, 2012)

Quality assurance

Several quality control and quality assurance approaches were used to ensure the quality of the data acquired in this investigation. Such measures include monitoring and operational counterchecking, which are conducted according to the guidelines and procedures provided by the US Environmental Protection Agency (US-EPA, 2014). According to the Pakistan National Environmental Quality

Standards (Pak-NEQS), US-EPA and WHO ambient air quality standards (Figure 2), the permissible limits of ambient pollutants were also monitored and compared. This enabled the comparison of results against some standard or benchmark. Three types of blanks (filter paper blanks, reagent blanks, and field blanks) were used to control total suspended particulate (TSP) collection and minimise potential sources of error. The blanks acted as controls to eliminate any residual contamination that could interfere with sampling and/or the analytical methods.

To maintain accuracy in laboratory results, analytical reagent-grade chemicals and solvents were sourced from reputable companies, such as Merck (Darmstadt, Germany). The manufacturer's basic user guidelines or manuals were

Table 2: PM_{10}, AQI and category at residential areas

Location Name	ID	S1	S2	S3	S4	S5	Mean	Min	Max	SD	AQI	Category (Pak-EPA, 2010)
UAF Agronomy Gate	**L1**	76	68.6	66.3	65.3	66	68.44	65.3	76	4.40	136.88	UHS
Green view colony	**L2**	83	77.5	69.5	61	62.3	70.66	61	83	9.53	141.32	UHS
Islam Nagar	**L3**	94	79.5	69.6	65.7	65.1	74.78	65.1	94	12.19	149.56	UHS
Sarfraz colony	**L4**	77.5	83	47	51.2	52	62.14	47	83	16.75	124.28	UHS
Daewoo Terminal	**L5**	108.5	94.7	82	71.5	77.4	86.82	71.5	108.5	14.82	173.64	UN
Lasani garden	**L6**	67.9	77.9	66.1	59.7	61	66.52	59.7	77.9	7.22	133.04	UHS
Sitara sapna colony	**L7**	88	83	59.5	58	48.3	67.36	48.3	88	17.19	134.72	UHS
Ismail city	**L8**	84.4	79.5	55	49.4	51.2	63.9	49.4	84.4	16.69	127.8	UHS
Amban Wali Pulli	**L9**	87.4	67.9	61.3	62	62.8	68.28	61.3	87.4	10.99	136.56	UHS
Green View Road	**L10**	51	47	48	51.2	50.4	49.52	47	51.2	1.90	99.04	M
International Housing Society Green View Colony	**L11**	49.33	42.4	43	51	50.7	47.286	42.4	51	4.23	94.572	M
UAF Housing Society	**L12**	51.08	38.4	39.1	48.1	51	45.536	38.4	51.08	6.31	91.072	M
Amanat Home, Msjid Ismail Road	**L13**	54.89	45.1	46.1	62.3	61.6	53.998	45.1	62.3	8.20	107.996	UHS
2 Punj Pullian Road	**L14**	90.43	85	78	71.2	69.5	78.826	69.5	90.43	8.92	157.652	UN
Muslim town Sgd road	**L15**	90.71	84.1	77.4	85	79.4	83.322	77.4	90.71	5.20	166.644	UN
Bawa chak 120 JB	**L16**	101.89	112.5	95.6	85.9	79.4	95.058	79.4	112.5	13.04	190.116	UN
Dawood textile Sgd road	**L17**	118.4	90.3	82.3	81	79	90.2	79	118.4	16.33	180.4	UN
Madina University	**L18**	99.51	87.5	77.5	80.6	85.9	86.202	77.5	99.51	8.45	172.404	UN
Azhar Corporation	**L19**	41.5	50	52	78.5	72.2	58.84	41.5	78.5	15.73	117.68	UHS
FDA city	**L20**	60.48	61.3	59.8	61	62.9	61.096	59.8	62.9	1.15	122.192	UHS
City Housing society	**L21**	55.5	46.8	49.1	55	58.9	53.06	46.8	58.9	4.96	106.12	UHS
Noorpur	**L22**	47.11	34.4	46	52	39.9	43.882	34.4	52	6.82	87.764	M
Bilal Nagar	**L23**	56.98	62	48.6	51.1	46.7	53.076	46.7	62	6.31	106.152	UHS
121 JB	**L24**	99.41	89.9	88	75.3	55.9	81.702	55.9	99.41	16.78	163.404	UN
Millat Town	**L25**	67.9	55.5	67.5	72.1	69.9	66.58	55.5	72.1	6.45	133.16	UHS
117 JB Dhanola	**L26**	171	154.6	94	89.7	73.9	116.64	73.9	171	43.18	233.28	VUH
Jalal town	**L27**	90.54	86.6	86	78.9	77.9	83.988	77.9	90.54	5.40	167.976	UN
Mustafabad	**L28**	67.54	49.5	50	59.7	61	57.548	49.5	67.54	7.71	115.096	UHS
Hijwari Town Sgd road	**L29**	104.8	95.6	87	83.7	73.9	89	73.9	104.8	11.76	178	UN
Tariqabad	**L30**	75.1	69.5	79.5	77	69.5	74.12	69.5	79.5	4.49	148.24	UN

S: Sampling cycle; Min: Minimum; Max: Maximum; SD: Standard Deviation; AQI: Air Quality Index; VH: Very Healthy; M: Moderate; UH: Unhealthy; UHS: Unhealthy for sensitive group; Haz: Hazardous; VUH: Very unhealthy

Table 3: PM_{10}, AQI and category at commercial areas

Location Name	ID	S1	S2	S3	S4	S5	Mean	Min	Max	SD	AQI	Category (Pak-EPA, 2010)
Ayesha Siddiqa Hospital Jail Road	**L31**	105	93.9	81.1	75.3	76.4	86.34	75.3	105	12.8	172.7	UH
Daewoo Terminal	**L32**	108.5	94.7	82	71.5	77.4	86.82	71.5	108.5	14.8	173.6	UH
Akbarabad	**L33**	77.9	64.6	59.3	61	62.3	65.02	59.3	77.9	7.5	130	UHS
Allied hospital	**L34**	104.8	99.4	82.3	88.1	85.3	91.98	82.3	104.8	9.7	184	UHS
Rathore hospital	**L35**	78.9	49.6	51.4	56.9	61.2	59.61	49.6	78.98	11.8	119.2	UHS
Metro cash and carry	**L36**	81.0	66.8	58.6	59.7	61	65.42	58.6	81.03	9.3	130.9	UHS
Sahil hospital	**L37**	59.4	61	59.4	54	56.8	58.13	54	61	2.8	116.3	UHS
Crescent Girls High School Lhr-Sheikhupura Road	**L38**	42.8	38.5	43.3	55	51.3	46.19	38.5	55	6.7	92.39	M
Millat Chowk	**L39**	67.8	58.5	54.9	53.2	47.7	56.43	47.7	67.85	7.5	112.9	UHS
Misaq ul Mall	**L40**	95.3	66.6	60.1	61.6	62.3	69.19	60.1	95.39	14.8	138.4	UHS
Nishatabad	**L41**	78.8	55.4	60	59.7	48.5	60.49	48.5	78.85	11.3	121	UHS
Green town	**L42**	44.0	38	45.1	49.4	52.9	45.89	38	52.9	5.6	91.8	M
Laari adda	**L43**	164.8	119.3	101	89.6	81	111.14	81	164.8	33.2	222.3	VUH

S: Sampling cycle; Min: Minimum; Max: Maximum; SD: Standard Deviation; AQI: Air Quality Index; VH: Very Healthy; M: Moderate; UH: Unhealthy; UHS: Unhealthy for sensitive group; Haz: Hazardous; VUH: Very unhealthy.

followed during instrument operation and receptor model runs to maintain uniform processes and optimise overall data collection and analysis settings. The study aimed to ensure the accuracy, validity, and reliability of the data collected throughout the research process by employing these quality control and quality assurance techniques.

Statistical analysis

This study assessed $PM_{2.5}$, PM_{10} and the air quality index (AQI) at each sampling location. These measurements were taken every two weeks for 2.5 months. Statistix (Ver. 8.1) software was used for the statistical analysis. This software was used to compute statistical parameters, including means, standard deviations, analysis of variance (ANOVA), and minimum and maximum values. The map was created using GIS software.

Results

Particulate matter 10 (PM_{10}) (µg m^{-3})

PM_{10} and AQI at residential locations

At various locations, PM_{10} concentrations exceeded the WHO) 24-hour limit of 50 µg m^{-3}, placing them in the "Unhealthy for Sensitive Groups" or "Unhealthy" categories. At UAF Agronomy Gate (L1), the mean PM_{10} concentration was 68.44 µg m^{-3} with an AQI of 136.88, showing moderate variation with an SD of 4.40. Green View Colony (L2) had a mean of 70.66 µg m^{-3} and an AQI of 141.32, with a higher variability (SD of 9.53). Islam Nagar (L3) recorded a mean of 74.78 µg m^{-3} and an AQI of 149.56, exhibiting notable variation (SD of 12.19). Sarfraz Colony (L4) had a mean of 62.14 µg m^{-3}, AQI of 124.28, and a high SD of 16.75, indicating substantial fluctuation (Table 2). At Daewoo Terminal (L5), the mean was 86.82 µg m^{-3} with an AQI of 173.64, reflecting poor air quality and high variability (SD of 14.82). Lasani Garden (L6) had a mean of 66.52 µg m^{-3} and an AQI of 133.04, with moderate variability (SD of 7.22). Ismail City (L8) showed a mean of 63.9 µg m^{-3} and an AQI of 127.8, with significant fluctuation (SD of 16.69). Amabn Wali Pulli (L9) had a mean of 68.28 µg m^{-3}, an AQI of 136.56, and moderate variability (SD of 10.99).

Locations with lower fluctuations included Green View Road (L10), with a mean of 49.52 µg m^{-3}, AQI of 99.04, and very low variability (SD of 1.90) (Table 2). International Housing Society Green View (L11) had a mean of 47.29 µg m^{-3}, AQI of 94.57, and low variability (SD of 4.24). UAF Housing Society (L12) had a mean of 45.54 µg m^{-3}, AQI of 91.07, and moderate variability (SD of 6.31). Amanat Home, Masjid Ismail Road (L13) had a mean of 53.998 µg m^{-3}, AQI of 107.996, and moderate fluctuation (SD of 8.20). Punj Pullian Road (L14) recorded a mean of 78.826 µg m^{-3}, AQI of 157.65, and moderate variability (SD of 8.92). In comparison, Muslim Town Sgd Road (L15) had a mean of 83.322 µg m^{-3}, AQI of 166.64, and moderate variability (SD of 5.21).

Across the residential locations (Table 2), the range of PM_{10} concentrations varies from L7 to L10, reflecting varying pollution levels. Most locations exceed the WHO 24-hour PM_{10} limit of 50 µg m^{-3}, except for International Housing Society Green View (L11), which falls under the Moderate category. The mean PM_{10} concentrations generally fall into the "Unhealthy for Sensitive Groups" or "Unhealthy" categories, with L3 and L16 reaching the highest mean values. The AQI values consistently reflect poor air quality, with some locations, such as Daewoo Terminal (L5) and Bawa Chak 120 JB (L16), having exceptionally high AQI values, indicating very unhealthy air conditions. These results underscore the pressing need for air quality improvements in residential areas where particulate pollution regularly exceeds safe limits.

PM_{10} and AQI at commercial locations

Air quality measurements across commercial locations showed significant variability in PM_{10} concentrations and associated AQI levels, all of which exceeded the WHO 24-hour PM_{10} limit of 50 µg m^{-3}, thus categorising most locations as "Unhealthy for Sensitive Groups" or "Unhealthy." At Ayesha Siddiqa Hospital Jail Road (L31), the mean PM_{10} concentration was 86.34 µg m^{-3}, with an AQI of 172.7, reflecting "Unhealthy" air quality and moderate variability (SD of 12.78) (Table 3). Daewoo Terminal (L32) showed similar results, with a mean of 86.82 µg m^{-3} and an AQI of 173.64, indicating high variability (SD of 14.82).

Akbarabad (L33) had a mean PM_{10} concentration of 65.02 µg m^{-3} and an AQI of 130.04, categorising it as "Unhealthy for Sensitive Groups" with more stable PM_{10} levels (SD of 7.5). Allied Hospital (L34) displayed a wider range (82.3 µg m^3 to 104.81 µg m^{-3}), a mean of 91.98 µg m^{-3}, and an AQI of 183.96, indicating significant air quality concerns and moderate variability (SD of 9.66). Rathore Hospital (L35) showed a mean of 59.62 µg m^{-3}, with an AQI of 119.23, categorising it as "Unhealthy for Sensitive Groups" with moderate variability (SD of 11.75). Metro Cash and Carry (L36) had a mean of 65.43 µg m^{-3} and an AQI of 130.85, showing moderate variability (SD of 9.28) and placing it in the same category.

Sahil Hospital (L37) recorded a relatively low range (54 µg m^{-3} to 61 µg m^{-3}) and a mean of 58.14 µg m^{-3}, categorising it as "Unhealthy for Sensitive Groups" with minimal

variability (SD of 2.76). Crescent Girls High School (L38) had a mean PM_{10} concentration of 46.19 µg m^{-3} and an AQI of 92.39, placing it in the "Moderate" category with moderate variability (SD of 6.75). Millat Chowk (L39) recorded a mean of 56.43 µg m^{-3}, AQI of 112.86, and moderate variability (SD of 7.48), categorising it as "Unhealthy for Sensitive Groups." Misaq ul Mall (L40) had a mean of 69.20 µg m^{-3} and an AQI of 138.40, with high variability (SD of 14.84), indicating concerns for air quality.

Nishatabad (L41) showed a mean of 60.49 µg m^{-3}, with an AQI of 120.98 and moderate variability (SD of 11.27), placing it in the "Unhealthy for Sensitive Groups" category. L42 showed a mean of 45.9 µg m^{-3} and an AQI of 91.80, categorising it as "Moderate" with low variability (SD of 5.65). Laari Adda (L43) displayed the highest range (81 µg m^{-3} to 164.8 µg m^{-3}), with a mean of 111.14 µg m^{-3} and an AQI of 222.28, placing it in the "Hazardous" category with very high variability (SD of 33.25).

upon comparing all locations, it was observed that across the commercial locations, PM_{10} concentrations exceed the WHO 24-hour limit of 50 µg m^{-3} at all sites, placing most of the locations in the "Unhealthy for Sensitive Groups" or "Unhealthy" categories. The range of PM_{10} values varies significantly, with Laari Adda (L43) having the highest variation and the most severe pollution levels. Locations such as Crescent Girls High School, Lhr-Sheikhupura Road (L38) and Green Town (L42) have "Moderate" air quality, but even these locations experience PM_{10} levels above the recommended limits. The AQI values across all sites reflected poor air quality, and the SD showed varying degrees of air quality stability, with some locations exhibiting high variability. These results underscore the need for air quality management and mitigation measures, particularly in areas such as Laari Adda (L43), where pollution levels are particularly hazardous.

PM_{10} and AQI at industrial locations

The PM_{10} and AQI values across the industrial locations indicated considerable air quality concerns in these areas (Table 4). At Sitara Textile Sgd Road (L44), the range of PM_{10} values was 53 µg m^{-3} - 67.4 µg m^{-3}. This relatively narrow range showed slight fluctuation in PM_{10} levels at this location. Despite the slight variation, the mean PM_{10} concentration of 61.5 µg m^{-3} places the air quality in the "Unhealthy for Sensitive Groups" category, exceeding the WHO 24-hour standard limit of 50 µg m^{-3}. The SD of 5.7 µg m^{-3} indicates low variability in the PM_{10} concentrations across the sampling period, suggesting stable, albeit poor, air quality. The AQI value is 123.0, reinforcing that the air quality is unhealthy for sensitive individuals, including those with respiratory conditions.

Similarly, at Crescent Textile (L45), the range of PM_{10} values was 54.6 µg m^{-3} -70.5 µg m^{-3}, slightly higher than at Sitara Textile Sgd Road (L44). The mean PM_{10} concentration in this area was 61.6 µg m^{-3}. The SD of 7.6 µg m^{-3} indicated moderate variability in the PM_{10} concentrations, suggesting that the air quality fluctuates somewhat during the monitoring period. The AQI value of 123.1 indicated that air quality is unhealthy for sensitive groups at this location.

At Crescent Textile (L46), the range of PM_{10} values was significantly larger, with a spread of 61.2 µg m^{-3} - 81.5 µg m^{-3}. The mean PM_{10} concentration at this location was 70.7 µg m^{-3}, which again exceeds the WHO 24-hour limit of 50 µg m^{-3}. The SD of 8.6 µg m^{-3} suggested moderate variability in the PM_{10} levels, indicating fluctuations in air quality. The AQI value of 141.5 is higher than that of the previous locations, reflecting more serious pollution levels, and air quality at this location is categorised as unhealthy for sensitive groups.

At Masood Textile Mills (L47), it was observed that the range of PM_{10} values was the largest, with a spread of 64.3

Table: 4: PM_{10}, AQI and category at industrial areas

Location Name	ID	S1	S2	S3	S4	S5	Mean	Min	Max	SD	AQI	Category (Pak-EPA, 2010)
Sitara Textile Sgd road	**L44**	67.4	59	53	65	63.2	61.5	53.0	67.4	5.7	123.0	UHS
Rashid Textile	**L45**	70.45	58.4	54.6	69	55.4	61.6	54.6	70.5	7.6	123.1	UHS
Crescent Textile	**L46**	81.45	77.4	69.7	63.9	61.2	70.7	61.2	81.5	8.6	141.5	UHS
Masood Textile Mills (MTM)	**L47**	110.47	76.3	66	66.2	64.3	76.7	64.3	110.5	19.5	153.3	UH
Nishat Mills Ltd	**L48**	99.46	74	63	59.1	61	71.3	59.1	99.5	16.8	142.6	UHS
Gokhowal Millat road	**L49**	76.09	81.5	71.3	63	59.6	70.3	59.6	81.5	9.1	140.6	UHS
Sahil hospital	**L37**	59.4	61	59.4	54	56.8	58.13	54	61	2.8	116.3	UHS

S: Sampling cycle; Min: Minimum; Max: Maximum; SD: Standard Deviation; AQI: Air Quality Index; VH: Very Healthy; M: Moderate; UH: Unhealthy; UHS: Unhealthy for sensitive group; Haz: Hazardous; VUH: Very unhealthy.

µg m^{-3} to 110.5 µg m^{-3} indicating significant variation in particulate pollution levels at this location. The mean PM_{10} concentration is 76.7 µg m^{-3}, the highest of all industrial locations. The SD of 19.5 µg m^{-3} indicated high variability in the PM_{10} concentrations, meaning that the pollution levels fluctuate considerably throughout the monitoring period. The AQI value of 153.3 confirmed that the air quality falls into the "Unhealthy" category, indicating more severe pollution than other locations.

At Nishat Mills Ltd (L48), the concentration of PM_{10} ranged between 59-99.5 µg m^{-3}. It was observed that the mean of PM_{10} was 71.3 µg m^{-3} at this location, which exceeded the WHO limit (50 µg m^{-3}). The variation in PM_{10} concentration was moderate as indicated by an SD value of 16.8 µg m^{-3}. The

Table 5: $PM_{2.5}$, AQI and category at residential areas

Location Name	ID	S1	S2	S3	S4	S5	Mean	Min	Max	SD	AQI	Category (Pak-EPA, 2010)
UAF Agronomy Gate	**L1**	54.5	40	41.1	45.6	51.3	46.50	40.0	54.50	6.31	186.00	Unhealthy
Green View Colony	**L2**	71.13	34	41	49	52.3	49.49	34.0	71.13	14.04	197.94	Unhealthy
Islam Nagar	**L3**	66.01	56.6	55	62.4	60.3	60.06	55.0	66.01	4.43	240.25	Very unhealthy
Sarfraz Colony	**L4**	63.5	55	39.1	41	48.3	49.38	39.1	63.50	10.10	197.52	Unhealthy
Daewoo Terminal	**L5**	82.98	79	44.4	55.9	52	62.86	44.4	82.98	17.12	251.42	Very unhealthy
Lasani Garden	**L6**	67.76	54.2	47.2	43.8	49.6	52.51	43.8	67.76	9.33	210.05	Very unhealthy
Sitara Sapna Colony	**L7**	65.75	51	43.1	49.6	51	52.09	43.1	65.75	8.31	208.36	Very unhealthy
Ismail City	**L8**	65.7	33	45	51.3	50.7	49.14	33.0	65.70	11.82	196.56	Very unhealthy
Amban Wali Pulli	**L9**	89.11	76.6	59.9	62	59	69.32	59.0	89.11	13.17	277.29	Very unhealthy
Green View Road	**L10**	90.01	84	57	48	47.3	65.26	47.3	90.01	20.33	261.05	Very unhealthy
International Housing Society Green View Colony	**L11**	68.7	54.1	49.1	45.9	46.8	52.92	45.9	68.70	9.38	211.68	Very unhealthy
UAF Housing Society	**L12**	66.22	50.1	52	48.6	50.1	53.40	48.6	66.22	7.27	213.62	Very unhealthy
Amanat Home, Masjid Ismail Road	**L13**	90.01	89.5	72	54.9	55	72.28	54.9	90.01	17.4	289.13	Very unhealthy
2 Punj Pullian Road	**L14**	91.51	91.5	76	88	79.3	85.26	76.0	91.51	7.19	341.05	Hazardous
Muslim town Sgd road	**L15**	76.52	75.5	67.1	66	65.3	70.08	65.3	76.52	5.46	280.34	Very unhealthy
Bawa Chak 120 JB	**L16**	186	87	79.4	69.5	65.3	97.44	65.3	186.0	50.2	389.7	Hazardous
Dawood Textile Sgd road	**L17**	90.11	83.3	80	79.4	77	81.96	77.0	90.11	5.08	327.85	Hazardous
Madina University	**L18**	100.1	90.2	84.6	79	69.7	84.72	69.7	100.10	11.46	338.88	Hazardous
Azhar Corporation	**L19**	96.9	96.9	83.3	71.3	66.5	82.98	66.5	96.90	14.10	331.92	Hazardous
FDA City	**L20**	76	45	39.6	44.5	42.3	49.48	39.6	76.00	14.98	197.92	Unhealthy
City Housing Society	**L21**	62.1	39	42	49.6	50.4	48.62	39.0	62.10	8.98	194.48	Unhealthy
Noorpur	**L22**	72.65	65	61.7	61.2	58.8	63.87	58.8	72.65	5.38	255.48	Very unhealthy
Bilal Nagar	**L23**	54.7	46.7	43.1	44	52.6	48.22	43.1	54.70	5.18	192.88	Unhealthy
121 JB	**L24**	78.4	65.7	57.9	61	63.6	65.32	57.9	78.40	7.87	261.28	Very unhealthy
Millat Town	**L25**	98.05	85.3	80.1	75.6	77.7	83.35	75.6	98.05	8.98	333.40	Hazardous
117 JB Dhanola	**L26**	99.33	67.2	66.9	65	60.1	71.71	60.1	99.33	15.70	286.82	Very unhealthy
Jalal town	**L27**	69	46	50	63.1	60.6	57.74	46.0	69.00	9.51	230.96	Very unhealthy
Mustafabad	**L28**	90.7	67	69.5	71	72	74.04	67.0	90.70	9.50	296.16	Very unhealthy
Hijwari town Sgd road	**L29**	101.5	90	81	82.7	82	87.44	81.0	101.5	8.63	349.76	Hazardous
Tariqabad	**L30**	92	86	71	69	71	77.80	69.0	92.00	10.47	311.20	Hazardous

S: Sampling Cycle; Min: Minimum; Max: Maximum; SD: Standard Deviation; AQI: Air Quality Index.

Table 6: $PM_{2.5}$, AQI and category at commercial areas

Location Name	ID	S1	S2	S3	S4	S5	Mean	Min	Max	SD	AQI	Category (Pak-EPA, 2010)
Ayesha Siddiqa Hospital Jail Road	**L31**	70.75	64	61.1	60	62.3	62.206	60	64	1.68	254.52	Very unhealthy
Daewoo Terminal	**L32**	82.98	79	44.4	55.9	52	58.83	44.4	79	13.1	251.424	Very unhealthy
Akbarabad	**L33**	92.56	62	68	75	74.4	70.76	62	75	5.67	297.568	Very unhealthy
Allied hospital	**L34**	97.9	88.5	79.5	89.6	77.9	84.44	77.9	89.6	5.36	346.72	Hazardous
Rathore hospital	**L35**	80.05	81	66.5	54	53.2	64.33	53.2	81	11.40	267.8	Very unhealthy
Metro cash and carry	**L36**	74.31	54.1	48	44	46.7	49.24	44	54.1	4.37	213.688	Very unhealthy
Sahil hospital	**L37**	82.8	65.9	67.4	69.6	55	65.21	55	69.6	5.86	272.56	Very unhealthy
Crescent Girls High School Lhr-Sheikhupura Road	**L38**	73.01	66.3	56.8	54.7	44.9	56.37	44.9	66.3	7.75	236.568	Very unhealthy
Millat Chowk	**L39**	70.3	54.1	53	54	49.3	53.31	49.3	56.14	2.51	224.56	Very unhealthy
Misaq ul Mall	**L40**	66.34	49.4	52.4	55.8	53.9	53.41	49.4	55.8	2.63	222.272	Very unhealthy
Nishatabad	**L41**	73.1	73.7	66.8	65	62.3	67.2	62.3	73.7	4.24	272.72	Very unhealthy
Green town	**L42**	61.11	57	49	51	50	52.12	49	57	3.22	214.488	Very unhealthy
Laari adda	**L43**	119.7	100.3	93	82.6	80.3	90.28	80.3	100.3	8.52	380.72	Hazardous

S: Sampling Cycle; Min: Minimum; Max: Maximum; SD: Standard Deviation; AQI: Air Quality Index.

corresponding AQI value, 142.6, indicated that air at this location is "Unhealthy for Sensitive Groups."

Gokhowal Millat Road (L49), the concentration of PM_{10} ranged between 59.6 µg m^{-3} - 81.5 µg m^{-3}, with a mean concentration of 70.3 µg m^{-3}, which exceeds the WHO limit of 50 µg m^{-3}.PM_{10} concentration at this location fluctuated moderately, as indicated by SD value of 9.1 µg m^{-3} and an AQI value of 140.6, confirming that the air quality is unhealthy for sensitive individuals.

Across these industrial locations, PM10 levels consistently exceeded the WHO limit, with varying degrees of pollution severity. The AQI values confirmed that most locations fall into the "Unhealthy for Sensitive Groups" or "Unhealthy" categories, with Masood Textile Mills (L47) showing the most severe pollution.

Particulate matter 2.5 ($PM_{2.5}$) (µg m^{-3})

$PM_{2.5}$ and AQI at residential locations

The data regarding $PM_{2.5}$ and AQI at residential locations is presented in Table 5. At UAF Agronomy Gate (L1), the mean $PM_{2.5}$ concentration was 46.5 µg m^{-3} with an AQI of 186, placing it in the "Unhealthy for Sensitive Groups" category. Green View Colony (L2) showed a mean of 49.49 µg m^{-3} and an AQI of 197.94, indicating significant variation in $PM_{2.5}$ levels and placing it in the same category.

Islam Nagar (L3) had a mean $PM_{2.5}$ concentration of 60.06 µg m^{-3} and an AQI of 240.25, reflecting "Unhealthy" air quality. Sarfraz Colony (L4) exhibited moderate variation with a mean of 49.38 µg m^{-3} and an AQI of 197.52, categorising it as "Unhealthy for Sensitive Groups." Daewoo Terminal (L5) recorded a mean $PM_{2.5}$ concentration of 62.86 µg m^{-3} and an AQI of 251.42, placing it in the "Unhealthy" category, with high variability (SD of 17.12). Lasani Garden (L6) had a mean of 52.51 µg m^{-3} and an AQI of 210.05, while Sitara Sapna Colony (L7) showed a mean of 52.09 µg m^{-3} with an AQI of 208.36, both categorised as "Unhealthy for Sensitive Groups." Ismail City (L8) had a mean of 49.14 µg m^{-3} and an AQI of 196.56, with significant variation (SD of 11.82).

Amban Wali Pulli (L9) had a high mean of 69.32 µg m^{-3} and an AQI of 277.29, placing it in the "Very Unhealthy" category, with significant fluctuation in $PM_{2.5}$ levels. Green View Road (L10) recorded a mean of 65.26 µg m^{-3}, with an AQI of 261.05, categorising it as "Unhealthy." International Housing Society Green View (L11) had a mean of 52.92 µg m^{-3} and an AQI of 211.68, placing it in the "Unhealthy for Sensitive Groups" category. UAF Housing Society (L12) showed a mean $PM_{2.5}$ concentration of 53.40 µg m^{-3} and an AQI of 213.62, indicating "Unhealthy for Sensitive Groups" air quality. Amanat Home, Masjid Ismail Road (L13) had a mean of 72.28 µg m^{-3}, placing it in the "Unhealthy" category, with an AQI of 289.13, reflecting "Hazardous" air quality. 2 Punj Pullian Road (L14) showed a mean of 85.26 µg m^{-3} and an AQI of 341.05, also categorised as "Hazardous."

Muslim Town Sgd Road (L15) had a mean $PM_{2.5}$ concentration of 70.08 µg m^{-3} and an AQI of 280.34, indicating "Unhealthy" air quality. The residential locations showed widespread exceedance of the WHO $PM_{2.5}$ limit, with many areas categorised as "Unhealthy for Sensitive Groups" or "Unhealthy." Locations such as Bawa Chak 120 JB (L16) and Amanat Home, Masjid Ismail Road (L13) were classified as "Hazardous," highlighting the severe air pollution levels in these areas. The AQI values across these locations reflected high levels of particulate pollution, with varying degrees of air quality stability, and some locations exhibited significant fluctuations in pollution levels.

$PM_{2.5}$ and AQI at commercial locations

The $PM_{2.5}$ measurements in commercial areas revealed a significant variation in air quality conditions across different locations (Table 6). At Ayesha Siddiqa Hospital Jail Road (L31), the mean $PM_{2.5}$ concentration was 62.21 µg m^{-3}, with an AQI of 254.52, categorising the air quality as "Unhealthy." The 60 to 64 µg m^{-3} range indicated minimal fluctuations in air quality. Similarly, Daewoo Terminal (L32) had a mean of 58.83 µg m^{-3} and an AQI of 251.42, reflecting "Unhealthy" air quality with significant variation in $PM_{2.5}$ levels (44.4 to 79 µg m^{-3}).

Akbarabad (L33) had a higher mean concentration of 70.76 µg m^{-3}, with an AQI of 297.57, categorising the location as "Very Unhealthy." The 62 to 75 µg m^{-3} range indicated moderate fluctuations in $PM_{2.5}$ levels, while the SD of 5.67 suggested moderate variability. At Allied Hospital (L34), the $PM_{2.5}$ levels were the highest, with a mean of 84.44 µg m^{-3} and an AQI of 346.72, placing it in the "Hazardous" category. The range was from 77.9 µg m^{-3} to 89.6 µg m^{-3}, with low variability indicated by the SD of 5.37. Rathore Hospital (L35) had a mean $PM_{2.5}$ concentration of 64.33 µg m^{-3}, with an AQI of 267.80, categorising it as "Unhealthy" with significant fluctuation (SD of 11.40). Metro Cash and Carry (L36) recorded a mean of 49.24 µg m^{-3}, just above the WHO limit, and an AQI of 213.69, indicating "Unhealthy" air quality with moderate variability (SD of 7.53).

Millat Chowk (L39) had a mean $PM_{2.5}$ concentration of 53.31 µg m^{-3} and an AQI of 206.04, categorising the air quality as "Unhealthy" for sensitive individuals. L40 showed similar results, with a mean of 53.41 µg m^{-3} and an AQI of

205.18. Laari Adda (L43) was the most polluted commercial location, with a mean $PM_{2.5}$ concentration of 90.28 µg m^{-3} and the highest AQI of 380.72, reflecting "Hazardous" air quality. The range of 80.3 µg m^{-3} to 100.3 µg m^{-3}, along with an SD of 8.52, suggested considerable fluctuations in air quality at this location.

Table 7: $PM_{2.5}$, AQI and category at industrial areas

Location Name	ID	S1	S2	S3	S4	S5	Mean	Min	Max	SD	AQI	Category (Pak-EPA, 2010)
Sitara Textile Sgd road	**L44**	86.55	79.3	72.3	79.9	75.9	78.79	72.3	86.55	5.29	315.16	Hazardous
Rashid Textile	**L45**	89.5	89.6	75.7	69.9	59	76.74	59	89.6	13.14	306.96	Hazardous
Crescent Textile	**L46**	85.07	76	69	65	61.2	71.254	61.2	85.07	9.46	285.016	Very unhealthy
Masood Textile Mills (MTM)	**L47**	100.4	82	71.9	66.9	63.9	77.02	63.9	100.4	14.76	308.08	Hazardous
Nishat Mills Ltd	**L48**	81.5	79.4	60.8	56	55.9	66.72	55.9	81.5	12.7	266.88	Very unhealthy
Gokhowal Millat road	**L49**	82.53	67.4	60.6	59.4	61	66.186	59.4	82.53	9.65	264.744	Very unhealthy

In summary, most commercial locations exceed the WHO 24-hour $PM_{2.5}$ limit of 50 µg m^{-3}, with several places such as Ayesha Siddiqa Hospital Jail Road (L31), Daewoo Terminal (L32), and Allied Hospital (L34) having "Unhealthy" or "Hazardous" air quality. The AQI values consistently reflect poor air quality, and the SD values indicate varying degrees of air quality stability across the locations, with some areas showing high variability and others exhibiting more consistent pollution levels. These findings underscore the need for immediate measures to enhance air quality in commercial areas, where particulate pollution consistently exceeds safe limits.

$PM_{2.5}$ and AQI at industrial locations

The industrial locations revealed significant variations in $PM_{2.5}$ concentrations and AQI values (Table 7), indicating differing air quality conditions across these locations. At Sitara Textile Sgd Road (L44), the mean $PM_{2.5}$ concentration was the highest at 78.79 µg m^{-3}, with a range of 72.3 µg m^{-3} to 86.55 µg m^{-3} and an AQI of 315.16, reflecting "Hazardous" air quality. The SD of 5.30 indicated stable pollution levels at this location.

Rashid Textile (L45) had a mean of 76.74 µg m^{-3} and an AQI of 306.96, also categorised as "Hazardous." The range of $PM_{2.5}$ concentrations was 59 µg m^{-3} to 89.6 µg m^{-3}, with a high SD of 13.14, suggesting significant fluctuations in air quality. Crescent Textile (L46) had a slightly lower mean of 71.25 µg m^{-3}, an AQI of 285.02, and a moderate fluctuation in pollution levels (SD of 9.47), placing it in the "Very Unhealthy" category.

Masood Textile Mills (L47) recorded a mean of 77.02 µg m^{-3}, with a range from 69.3 µg m^{-3} to 100.4 µg m^{-3}, and an AQI of 308.08, reflecting "Hazardous" air quality. The SD of 14.77 indicated significant fluctuations in air quality. Nishat Mills Ltd (L48) had a mean of 66.72 µg m^{-3}, an AQI of 266.88, and moderate variability (SD of 12.71), categorising it as "Hazardous." Gokhowal Millat Road (L49) had a mean of 66.19 µg m^{-3}, an AQI of 264.74, and moderate fluctuation in pollution levels (SD of 9.65).

Across all industrial locations, the $PM_{2.5}$ concentrations ranged from 66.18 µg m^{-3} to 78.79 µg m^{-3}, with Sitara Textile Sgd Road (L44) having the highest $PM_{2.5}$ concentration and AQI. These findings underline the severity of air pollution in industrial areas, where $PM_{2.5}$ levels consistently exceed safe limits, emphasising the need for stronger air quality management strategies to mitigate these harmful conditions.

Discussion

The findings of the study indicated that Faisalabad had particular matter ($PM_{2.5}$ and PM_{10}) concentrations consistently exceed the permissible limits set by Pak-NEQS, WHO, and USEPA (USEPA, 2018) across all monitored locations. The study also found that none of the places surveyed met air quality standards. These results indicated that citizens of Faisalabad were widely exposed to high levels of air pollutants. Long-term high exposure to particulate matter (PM), particularly $PM_{2.5}$, has health impacts, especially respiratory and cardiovascular diseases (Guo *et al*., 2023). However, this study adds to the worrying levels of $PM_{2.5}$, which are hardest hit by the levels of air pollution exceeding national and international standards, posing grave threats to the health of populations.

Air quality classification and Health risks

The findings indicate that the 24-h threshold of $PM_{2.5}$ (25 µg m^{-3}) and PM_{10} (50 µg m^{-3}). Such as UAF Agronomy Gate (L1) and Islam Nagar (L3) residential areas showing high amounts of $PM_{2.5}$ concentrations were the 46.5 µg m^{-3} and 60.06 µg m^{-3}, respectively, which were classified using AQI (Air Quality Index) as "Unhealthy for Sensitive Groups". The same observations were made in commercial and industrial sites in the vicinity of Ayesha Siddiqa Hospital Jail Road (L31) and Sitara Textile Sgd Road (L44) in which

PM concentrations were also present under hazardous conditions (AQI ≥ 300). There data are following findings by Zeeshan *et al*. (2024) and Mukherjee *et al*. (2022), which observed that the air quality in Faisalabad regularly surpasses WHO limits, especially in regions influenced by industrial activities and vehicular emissions.

These results are consistent with the Air Quality Index (AQI), which is an important health measure of air pollution that gauges its potential impacts, a large percentage of which is classified as "Unhealthy" and "Hazardous" in many parts of Faisalabad, with AQI > 300 nm^3 in some areas in Faisalabad, especially more significant values observed in Laari Adda (L43) and Rashid Textile (L45). These exposure levels are of the high AQI reading category, which is correlated with significant health risks, such as aggravated asthma, bronchitis, heart diseases, and lung cancers (Deng *et al*., 2023). These results reflect global trends, with the level of delicate particulate matter. Low atmospheric pressure has been directly linked to early mortality and chronic lung disease (WHO, 2018).

Industrial and Vehicular contributions

According to the study, the high PM levels in Faisalabad are primarily attributed to industrial and vehicular emissions. Sitara Textile Sgd Road (L44), a highly industrialised area, showed the highest mean values for $PM_{2.5}$ with concentrations of 78.79 μg m^{-3} , which relates to 315.16 and puts it in "Hazardous". These results are consistent with similar earlier studies (Zeeshan *et al*., 2024), indicating that the textile industries dominating the economic sector in other industrial cities like Faisalabad are the major contributors to particulate pollution (Khan *et al*., 2024). A significant portion of the particulate burden in the air, particularly those resulting from the combustion of fossil and non-fossil fuels, originates from industrial emissions, such as dust from raw materials (Bhattu *et al*., 2024).

In addition, areas such as Daewoo Terminal (L5) and Green View Colony (L2) experience noticeable impacts on air quality due to automotive emissions. $PM_{2.5}$ and PM_{10} indicate that increased vehicular traffic was responsible for the deteriorated urban air quality (Das *et al*., 2021). Furthermore, not only in an urban environment but over many cities around the globe, we know that traffic density correlates with high levels of PM in ambient air, with emissions from traffic remaining a significant source of fine particles (Mead *et al*., 2013; Kelly and Fussell, 2015).

These findings also indicate the growing impact of industrialisation and urbanisation on air quality standards in Pakistan. On the contrary, city PM concentrations markedly increased because of rapid industrialisation, high urban population density and massive vehicle growth. A study by Pasha *et al*. (2015) regarding the air quality of Faisalabad also backs these findings, which suggest that the most relevant source of particulate pollution is industrial emissions, especially textiles and vehicle emissions. Construction and road dust are also mentioned as other contributors to PM levels (Das *et al*., 2021).

Spatial variability in air quality

The spatial distribution of $PM_{2.5}$ and PM_{10} concentrations across Faisalabad revealed significant variability in air quality, influenced by proximity to industrial, commercial, and residential areas (Javed *et al*., 2015). The suspended particulate matter (SPM) concentrations and bad AQI records from sites with high industrial activity (Masood Textile Mills (L47) and Nishat Mills Ltd (L48)) highlight the role of emissions from the industry in deteriorating local AQI. In the case of distance to sectors, it led to a more stringent setting of rules which allowed a better ambient air quality in Crescent Girls High School Lhr-Sheikhupura Road (L38) as compared to L1 (relative to other sites L38 showed moderate risk respiratory) but still exceeded the WHO reference limits for $PM_{2.5}$ and PM_{10}. Understanding this spatial variation is important for identifying areas that require air quality management and control strategies.

In addition, the PM measurements were also evaluated based on SDs, and it was demonstrated that the air quality response ranking differed according to location. Low variations were seen at Sgd Road (L44) (SD of 5.30) as expected, with stable but high pollution levels indicating steady industrial emissions. In contrast, individual locations, such as Rashid Textile (L45) or Masood Textile Mills (L47), showed higher variation in their pollution rates due to their larger SDs, which could be a result of varying production levels or traffic patterns.

Policy implications and Recommendations

Given the findings of this study, it is evident that Faisalabad's air pollution levels, particularly $PM_{2.5}$ and PM_{10} concentrations, pose significant public health risks. High air quality indices in industrial and residential regions indicated a dire need for air quality management policies. The Pak-NEQS and the WHO standards for particulate matter in sensitive areas must be strictly implemented. Adopting more demanding emissions standards for industry and vehicles, promoting pollution-control technologies, and better traffic management might also help reduce particulate pollution.

This study also emphasises the need for long-term air quality measurements in urban and industrial centres. This study explored the benefits of having real-time monitoring systems (like the one used in this study of urban ventilation) and how timely information can help managers in charge of many policies to mitigate pollution. Additionally, deploying further monitoring stations in rural and suburban areas may allow for a better comprehension of Faisalabad's spatial distribution of air pollution.

Most places with $PM_{2.5}$ exceeded the safety limits and covered an area of 1808277 km^2 of Faisalabad (approximately 44.19% of the creeping area in Faisalabad). Respondents and observing are trained through up-to-date data on PM up to 2023, which is scarce even though they live around this and are very far from these approaching responses. The concentrations of $PM_{2.5}$ and PM_{10} exceeded the thresholds set by the WHO. The results highlight the need for robust air quality management strategies to mitigate the excess burden of particulate pollution on health, especially in industrial and high-density urban areas. The findings add to the increasing literature on air quality in developing cities and underscore local data's value in guiding public health interventions and environmental policies.

Conclusion

This study assessed particulate matter ($PM_{2.5}$ and PM_{10}) concentrations and air quality across various locations in Faisalabad, revealing alarmingly high pollution levels that frequently exceed WHO guidelines. Measured values consistently exceed Pakistan's National Environmental Quality Standards and WHO guidelines, with Air Quality Index readings in "Very Unhealthy" to "Hazardous" categories during peak periods. These elevated particulate levels increase risks of respiratory and cardiovascular illness, especially among children, older adults, and individuals with preexisting conditions. Immediate interventions are warranted such as enforcing stricter emission limits on industry and vehicular sources, expanding green buffers, promoting cleaner transport, and implementing health advisories for vulnerable groups. By mapping pollution hotspots and identifying major contributors, this study provides policymakers with actionable evidence to prioritize resource allocation and assess the effectiveness of future air quality management initiatives.

References

Anjum, M.S., S.M. Ali, M.A. Subhani, M.N. Anwar, A.S. Nizami, U. Ashraf and M.F. Khokhar. 2021. An emerged challenge of air pollution and ever-increasing particulate matter in Pakistan: A critical review. *Journal of Hazardous Materials* 402: 123943.

Bhattu, D., S.N. Tripathi, H.S. Bhowmik, V. Moschos, C.P. Lee, M. Rauber, G. Salazar, G. Abbaszade, T. Cui, J.G. Slowik and A.S. Prévôt. 2024. Local incomplete combustion emissions define the $PM_{2.5}$ oxidative potential in Northern India. *Nature Communications* 15(1): 3517.

Das, A., M.P. Pathak, P. Patowary and S. Das. 2021. Introduction to lung physiology from a drug delivery perspective. p. 1-11. In: *Handbook of Lung Targeted Drug Delivery Systems*. Y. Pathak and N. Islam (eds.). CRC Press.

Deng, X., B. Zou, S. Li, J. Wu, C. Yao, M. Shen, J. Chen and S. Li. 2023. Disease specific air quality health index (AQHI) for spatiotemporal health risk assessment of multi-air pollutants. *Environmental Research* 231: 115943.

Fan, H., C. Zhao, Y. Yang and X. Yang. 2021. Spatitemporal variations of the $PM_{2.5}/PM_{10}$ ratios and its application to air pollution type classification in China. *Frontiers in Environmental Science* 9: 1-13.

Guo, J., G. Chai, X. Song, X. Hui, Z. Li, X. Feng and K. Yang. 2023. Long-term exposure to particulate matter on cardiovascular and respiratory diseases in low-and middle-income countries: A systematic review and meta-analysis. *Frontiers in Public Health* 11: 1134341.

Gurjar, B.R., T.M. Butler, M.G. Lawrence and J. Lelieveld. 2008. Evaluation of emissions and air quality in megacities. *Atmospheric Environment* 42: 1593-1606.

Javed, W., A.S. Wexler, G. Murtaza, H.R. Ahmad and S.M. Basra. 2015. Spatial, temporal and size distribution of particulate matter and its chemical constituents in Faisalabad, Pakistan. *Atmósfera* 28(2): 99-116.

Kelly, F.J. and J.C. Fussell. 2015. Air pollution and public health: Emerging hazards and improved understanding of risk. *Environmental Geochemistry and Health* 37(4): 631-649. https://doi.org/10.1007/s10653-015-9720-1

Khan, M., K. Muhmood, H.Z. Mahmood, I.H. Khaliq and S. Zaman. 2024. The health and economic burden of dust pollution in the textile industry of Faisalabad, Pakistan. *Journal of the Egyptian Public Health Association* 99(1): 3.

Mamić, L., M. Gašparović and G. Kaplan. 2023. Developing $PM_{2.5}$ and PM_{10} prediction models on a national and regional scale using open-source remote sensing data. *Environmental Monitoring and Assessment* 195(6): 644.

Manisalidis, I., E. Stavropoulou, A. Stavropoulos and E. Bezirtzoglou. 2020. Environmental and health impacts of air pollution: A review. *Frontiers in Public Health* 8: 1-14.

Mead, M.I., O.A.M. Popoola, G.B. Stewart, P. Landshoff, M. Calleja, M. Hayes, J.J. Baldovi, M.W. McLeod, T.F. Hodgson, J. Dicks and A. Lewis. 2013. The use of electrochemical sensors for monitoring urban air quality in low-cost, high-density networks. *Atmospheric Environment* 70: 186-203.

Method IO-3.1, US EPA. 1999. Selection, preparation and extraction of filter material. In: *Compendium of Methods for the Determination of Inorganic Compounds in Ambient Air*. US-EPA, Cincinnati, OH, USA.

Mukherjee, A., S. Mishra, S.B. Agrawal and M. Agrawal. 2022. Response of plants to atmospheric air pollution: An Asian perspective. p. 171-199. In: Asian Atmospheric Pollution. R.P. Singh (eds.). Elsevier.

Pakistan Environmental Protection Agency (Pak-EPA). 2010. National Environmental Quality Standards for Ambient Air. [online]: http://www.environment.gov.pk [Accessed 15/02/2025]

Pasha, M.F.K., H.M. Ahmad, M. Qasim and I. Javed. 2015. Performance evaluation of zinnia cultivars for morphological traits under the agro-climatic conditions of Faisalabad. *European Journal of Biotechnology and Bioscience* 3: 35-38.

United States Environmental Protection Agency (USEPA). 2018. Particulate Matter (PM) Basics. [online]: https://www.epa.gov/pm-pollution/particulate-matter-pm-basics [Accessed 17/02/2025]

US EPA. 2014. Air Quality Index (AQI): A Guide to Air Quality and Your Health. EPA-456/F-14-002. US Environmental Protection Agency Office of Air Quality Planning and Standards Outreach and Information Division, Research Triangle Park, NC, USA. [Accessed 18/04/2025]

US-EPA. 2012. Revised air quality standards for particle pollution and updates to the Air Quality Index (AQI). Office of Air Quality Planning and Standards, EPA 454/R99-010. [online]: http://www.epa.gov/pm/2012/decfsstandards.pdf [Accessed 11/03/2025]

US-EPA. 2015. NAAQS Table. [online]: http://www.epa.gov/criteria-air-pollutants/naaqs-table [Accessed 11/03/2025]

World Health Organization (WHO). 2018. Ambient (Outdoor) Air Pollution. [online]: https://www.who.int/news-room/fact-sheets/detail/ambient-(outdoor)-air-quality-and-health [Accessed 13/03/2025]

Zeeshan, N., G. Murtaza, H.R. Ahmad, A.N. Awan, M. Shahbaz and P. Freer-Smith. 2024. Particulate and gaseous air pollutants exceed WHO guideline values and have the potential to damage human health in Faisalabad, Metropolitan, Pakistan. *Environmental Monitoring and Assessment* 196(7): 659.