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Original Research

Physicochemical and Particulate Matter ($PM_{2.5}$, PM_{10}) Analysis of Air from Residential Areas: *In-vitro* Cytotoxicity Analysis of Particulates Against Red Blood Cells (RBCs)

Fatima Irshad[1], Khawar Sultan[1], Qamar uz Zaman[1], Arslan Sohail[1], Abid Ali[2], Mazhar Abbas[3], Samiah H. Al-Mijalli[4], Munawar Iqbal[5], Naveed Ahmad[6], Arif Nazir[7]***

[1]Department of Environmental Sciences, The University of Lahore, Lahore, Pakistan
[2]Department of Allied Health Sciences, The University of Chenab, Gujrat, Pakistan
[3]Department of Basic Sciences, University of Veterinary and Animal Sciences, Lahore (Jhang-Campus), Pakistan
[4]Department of Biology, College of Sciences, Princess Nourah bint Abdulrahman University, P.O. Box 84428, Riyadh 11671, Saudi Arabia
[5]School of Chemistry, University of the Punjab, Lahore, Pakistan
[6]Department of Chemistry, Division of Science and Technology, University of Education, Lahore, Pakistan
[7]Department of Chemistry, The University of Lahore, Lahore, Pakistan

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Abstract

Urban area air pollution has become a source of serious health impacts on city dwellers. The main purpose of this research is to investigate the major ambient air pollutants ($PM_{2.5}$, PM_{10}, TVOC, and HCHO). Data was collected (n = 50) using a portable air quality instrument during the spring season and spatial distribution analysis was carried out using GIS software to identify the hotspots. A significant number of locations were found to be higher in measured pollutant levels as compared to WHO and PEQS guidelines limits of PM_{10} and $PM_{2.5}$. The highest values of PM_{10} and $PM_{2.5}$ were measured along the main roads. The highest values of TVOC and HCHO were measured to be at locations around the drain carrying effluent. The exposure risk found at field sampling sites of TVOC was higher versus HCHO. The *in vitro* cytotoxicity assay of $PM_{2.5}$ and PM_{10} was performed against red blood cells (RBCs), the findings revealing a significant toxicity to the RBCs. This research work is significant to document because the concerned authority takes action to mitigate the major air pollutants by controlling transportation and covering the drain side by the plantation.

Keywords: air quality, pollutants, particulate matter, residential areas, plantation

*e-mail: arif.nazir@chem.uol.edu.pk
**e-mail: abidali@ahs.uchenab.edu.pk

Introduction

A gaseous particle that at high abundance levels poses a threat to the property, human life, and the environment is considered air pollution. Contaminants can come from both natural and man-made origins. The most harmful contaminants are atmospheric particulate matter (PM) and the gasiform contaminants volatile organic compounds (containing benzene), formaldehyde (HCHO), carbon monoxide (CO), nitrogen dioxide (NO_2), and sulfur dioxide (SO_2) [1-4].

Asian countries (Bangladesh, Pakistan, India, and Nepal) had been included among the leading 10 countries with the highest $PM_{2.5}$ levels [5]. Over the previous two decades, the concentrations of major pollutants in the atmosphere including SO_2, O_3, and NOx have also increased dramatically in Pakistan [6, 7]. Lahore seems to be the most contaminated city in the country of Pakistan, rising at a level of 4% each year. That is a significant potential hazard associated with the heavily contaminated Hudiara Drain, where roughly 600 industries discharge the effluent [8].

The detection of 4 major contaminants in the atmosphere near the residential areas named $PM_{2.5}$, PM_{10}, total volatile organic compounds (TVOCs), and formaldehyde (HCHO) is important [9]. There are two main types of particulate matter which include $PM_{2.5}$ and PM_{10}. Because it may reflect and absorb specific wavelengths from daylight, PM_{10} is also causing poor vision [10]. $PM_{2.5}$ is now a prominent contaminant in urban air and has received great consideration because of its negative impacts on public health and climate change. The compounds with a greater vapor pressure but limited solubility in water are referred to as total volatile organic compounds (TVOC) and are mostly generated through anthropogenic sources within metropolitan regions [11]. The quantities of VOC in indoor areas are almost always considerably greater than in outside ones. This would be impacted by the condition of construction products, as well as individual actions [12]. Formaldehyde is utilized in home items and the manufacturing of construction products. As a result of regular metabolic activities, humans can generate minor concentrations of formaldehyde as well. Average rates from 5 to 15 parts per billion are common within central and northern Europe, as well as the United States [13].

These pollutants are triggered by naturally produced events which include sandstorms in vast areas of open terrain and forest fires in dry weather [14]. Furthermore, anthropogenic factors seem to be the most significant contributors to atmospheric contamination nowadays [15]. It's mostly caused by fossil fuel usage and industrial facilities, modern farming, illegal dumping, and the transportation sector, and may result in chronic health conditions in humans [16]. These contaminants have a poisonous impact on the pH of the soil and decrease photosynthetic activity [17]. This research aims to investigate and understand changes in atmospheric pollutants in the study area with a particular focus on the residential areas and local drains.

Materials and Methods

Study Area

Lahore, a city with a significant population in Pakistan, is situated within latitudes 31°15′ to 31°45′ as well as longitudes 74°01′ to 74°39′, spanning a considerable region. It is the provincial capital of the vast municipality known as Punjab. However, the region faces pressing challenges due to busy transportation, industrial activity, and resulting poor air quality, adversely impacting both human health and the urban environment [18]. Lahore's climate is subtropical, featuring five distinct seasons: hot summers, foggy winters, pleasant springs, dry autumns, and monsoon rains [19]. The urban population in the Lahore district constitutes 82 percent of the total, leaving the remaining percentage residing in rural areas [20]. The escalating concern over various health risks, particularly polluted air, has become a critical issue for Lahore's residents, necessitating immediate attention as the city continues to grow and evolve.

Sampling

In this study, we utilized a portable air quality sampling device, specifically the IGERESS air sensor, renowned for its versatile capabilities in detecting $PM_{2.5}$, Total Volatile Organic Compounds (TVOC), PM_{10}, and formaldehyde (HCHO). Before each field sampling campaign, the instrument underwent precise calibration. A notable feature of this tool is its alert system, designed to activate when pollutant concentrations exceed predefined thresholds. Ambient air sampling commenced at the outset of March, coinciding with the arrival of the spring season. A detailed sampling map was essential for pinpointing each field ID or specific sampling location. This task required employing an air pollution field data sheet and a reliable pen to meticulously record readings and other pertinent data. The initial step involved reaching each designated sampling site with care.

Upon arrival at a site, the device was held above the ground surface (~ 1 meter) for the measurements. Subsequently, recorded pollutant values were meticulously transcribed onto the datasheet. Each sampling interval lasted roughly 15 to 30 minutes. Occasionally, the instrument emitted discernible beep alerts, signifying that pollution levels had exceeded predefined standard thresholds. A total of 50 samples were meticulously gathered within a 200-meter radius. The sampling locations included a diverse range, such as residential areas, the Hudiara drain, industrial facilities, a university campus, banking institutions, supermarkets, restaurants, roads, and sports facilities.

In-vitro Cytotoxicity Evaluation

Cytotoxicity of airborne particulate matter, diameter ($PM_{2.5}$), and PM_{10} was measured against in-vitro red blood cells (RBCs) with slight modification [1]. In this method, fresh human blood (4 mL) was collected, and using phosphate buffer saline and centrifugation, the red blood cells (RBCs) were purified and suspended in phosphate buffer saline (PBS~7.4.) and cell count 7.068 x 108 cells/mL was maintained for hemolytic/cytotoxicity assay. The air sample was collected using an IGERESS air sensor (portable air quality sampling device), a piece of filter paper containing different particulate ($PM_{2.5}$ and PM_{10}) was dissolved in 1 mL ultrapure water, vortex the Eppendorf and then filter the contents. The filtrate containing dissolved particulate is used for *in-vitro* cytotoxicity study. A 50 µL sample containing suspended particulate was treated with 175 µL red blood cells (RBCs) suspended in phosphate buffer saline. The entire reaction mixture was incubated for 30 minutes at 37°C. After the initial 10 minutes of incubation, agitation was introduced. Subsequently, the tubes were transferred to an ice bath for 5 minutes and then subjected to centrifugation at 1310×g for 5 minutes. Following centrifugation, 100 µL of the supernatant was carefully extracted from each tube and diluted with 900 µL of chilled PBS. To minimize mechanical blood lysis, all Eppendorf tubes were consistently kept on ice after dilution. A 200 µL aliquot from each Eppendorf was dispensed into separate wells of a 96-well plate. In each assay, 0.1% Triton X-100 served as the positive control, while phosphate-buffered saline (PBS) was employed as the negative control. The absorbance readings were recorded at 576 nm using a BioTek µ Quant microplate reader (BioTek, Winooski, VT, USA). The percentage of red blood cell (RBC) lysis was determined using the relationship depicted in Equation (1).

$$\text{Lysis of RBCs (\%)} = \frac{\text{Absorbance of sample}}{\text{Absorbance of Triton (X−100)}} \times 100 \quad (1)$$

Data Analysis

Both MS Excel and GIS (Geographic Information System) software were used in analyzing environmental data, specifically the concentrations of pollutants at different sampling points [21]. On the other hand, GIS software is highlighted for its ability to create detailed maps, drawing from various data sources such as digitized information, databases, aerial photography, GPS testing, scanned data, and remote sensing data [20].

Results and Discussion

Air Quality ($PM_{2.5}$, PM_{10}, TVOC, and HCHO)

Table 1 shows data regarding observed and measured parameters in the study areas The minimum value of PM_{10} was 19 µg/m³ and it was located in two areas, which are the University of Lahore and Hudiara Drain. The maximum value of PM_{10} was 228 µg/m³ and it was located at Lahore Ring Road. The average value of PM_{10} was 95.48 µg/m³ and the Standard Deviation value of PM_{10} was 63.65604 µg/m³. Querol et al. [22] reported PM_{10} levels (annual mean) ranging from 19 to 24 µg/m³ at regional background sites in the selected European cities with slightly higher levels ranging from 37 to 53 µg/m³ at kerbside sites. The minimum value of $PM_{2.5}$ was 17 µg/m³ and it was located in two areas, which are the University of Lahore and Hudiara Drain. The maximum value of $PM_{2.5}$ was 199 µg/m³ and it was located at Lahore Ring Road. The average value of $PM_{2.5}$ was 82.92 µg/m³ and the Standard Deviation value of $PM_{2.5}$ was 54.98973559 µg/m³. Zhang and Cao [23] carried out a long-term study of $PM_{2.5}$ levels of one-year monitoring in 190 cities in China to be 61 µg/m³ on average. The minimum value of TVOC was 0.003 mg/m³ and it was located at Wyeth CHS. The maximum value of TVOC was 9.659 mg/m³ and it was located at Hudiara Drain. The average value of TVOC was 1.24174 mg/m³ and the Standard Deviation value of TVOC was 2.066653717 mg/m³. Varshney and Padhy [24] reported the TVOC levels in the ambient environment of the Urban Environment of Delhi to vary from 3 to 42 ppmv registering a wide temporal and seasonal variation. The minimum value of HCHO was 0 and it was located at Khayaban-e-Amin Society. The maximum value of HCHO was 0.476 mg/m³ and it was located at Hudiara Drain. The average value of HCHO was 0.0514 mg/m³ and the Standard Deviation value of HCHO was 0.080245796 mg/m³. Neamtiu et al. [25] determined the mean values of indoor and outdoor formaldehyde levels in the major cities of Romania in the range of 0.014-0.035 mg/m³.

Spatial distribution maps of measured pollutants are shown in Fig. 1 (a-d). Fig. 1(a) presents the spatial distribution map depicting PM_{10} levels in the Lahore region, situated in the Punjab province. In this PM_{10} map, a noticeable trend emerged, with higher concentrations observed on the eastern side compared to the western side. The university area and drain region exhibited the lowest values, benefiting from a cleaner environment and refreshing breezes. In contrast, the highest values were evident along roadways, attributed to heavy transportation, dusty roads, various shops, and vehicular traffic. The World Health Organization (WHO) set a stringent air quality standard of 45 µg/m³. However, the sampling results surpassed this limit, with 30 samples breaching the WHO standard, while 20 samples remained below it. Similarly, the air quality standard set by the Punjab Environmental Protection Agency (PEQS) was 150 µg/m³. Notably, 17 samples exceeded the PEQS standard, whereas 33 samples adhered to it. Areas with sample values exceeding both the WHO and PEQS standards pose higher health risks in comparison to regions where sample values fall below these standards. Ahvaz, a city in Iran, experiences

Table 1. Field data showing various observed and measured parameters in the study area.

Sr. No.	Field ID	Location	Class	Longitude	Latitude	PM_{10} (µg/m³)	$PM_{2.5}$ (µg/m³)	TVOC (mg/m³)	HCHO (mg/m³)	Humidity (%)	Temp. (ºC)	Wind Speed (km/h)
1	MR1	Restaurant	RT	74.24305	31.39078	38	36	0.155	0.004	31	28	18
2	UOL2	University of Lahore	UN	74.24098	31.3906	19	17	0.077	0.006	31	28	18
3	SF3	Sapphire Factory	FT	74.24034	31.39001	25	20	0.31	0.007	31	28	18
4	HD4	Hudiara Drain	DR	74.24033	31.38842	19	17	0.421	0.223	31	28	18
5	JM5	Jamia Masjid	MS	74.25093	31.38139	34	30	0.044	0.001	36	27	24
6	WS6	Wyeth CHS	HS	74.25033	31.37811	25	22	0.003	0.016	36	27	24
7	WS7	Wyeth CHS	HS	74.24924	31.37765	24	21	0.043	0.034	36	27	24
8	WS8	Wyeth CHS	HS	74.24349	31.38389	40	35	0.446	0.058	36	27	24
9	CF9	Coca-cola Factoy	FT	74.23645	31.38406	33	29	0.187	0.04	42	26	11
10	SR10	Restaurant	RT	74.23378	31.38399	32	28	0.111	0.035	43	26	11
11	HD11	Hudiara Drain	DR	74.23053	31.38934	49	42	9.659	0.476	46	26	11
12	HD12	Hudiara Drain	DR	74.24298	31.38912	141	126	2.303	0.056	44	26	11
13	HD13	Hudiara Drain	DR	74.24675	31.38771	124	109	3.854	0.221	46	25	11
14	PA14	Pine Ave	HS	74.25142	31.38516	87	72	0.782	0.077	46	25	11
15	PA15	Pine Ave	HS	74.25024	31.38835	44	38	0.669	0.012	43	25	23
16	PA16	Pine Ave	HS	74.24887	31.39182	49	45	0.786	0.006	43	25	23
17	YR17	Yasir broast Restaurant	RT	74.25466	31.39223	171	147	7.526	0.011	44	25	23
18	SB18	Soneri Bank	BK	74.25889	31.39139	37	32	3.64	0.059	46	24	11
19	KS19	Khayaban-e-Amin Society	HS	74.26046	31.38882	67	59	1.882	0.062	46	24	11
20	KS20	Khayaban-e-Amin Society	HS	74.26047	31.3864	122	107	0.8	0.075	46	24	11
21	KS21	Khayaban-e-Amin Society	HS	74.26026	31.38301	74	65	3.309	0.169	46	24	11
22	KS22	Khayaban-e-Amin Society	HS	74.26016	31.38065	87	73	7.655	0.012	48	24	11
23	KS23	Khayaban-e-Amin Society	HS	74.25986	31.37542	71	61	2.909	0.008	50	23	11
24	KS24	Khayaban-e-Amin Society	HS	74.25969	31.3719	44	38	2.075	0.005	50	23	11
25	PA25	Pine Ave	HS	74.25318	31.38105	156	139	0.19	0.008	77	15	0
26	PA26	Pine Ave	HS	74.25372	31.37964	158	136	0.247	0.046	77	15	0

Table 1. Continued.

27	PA27	Pine Ave	HS	74.25542	31.37631	174	150	0.293	0.047	77	16	0
28	RR28	Lahore Ring Road	RD	74.25779	31.37153	150	130	0.221	0.042	77	16	0
29	RR29	Lahore Ring Road	RD	74.26416	31.36871	145	127	0.207	0.045	77	16	0
30	RR30	Lahore Ring Road	RD	74.25307	31.36947	163	139	0.219	0.04	75	16	5
31	RR31	Lahore Ring Road	RD	74.24883	31.3699	163	140	0.965	0.04	75	16	5
32	RR32	Lahore Ring Road	RD	74.24015	31.37011	175	152	1.22	0.042	75	16	5
33	RR33	Lahore Ring Road	RD	74.23481	31.36965	228	199	2.944	0.041	72	17	5
34	EP34	Edenabad Park	PR	74.24923	31.37584	25	23	0.286	0.006	38	27	0
35	ES35	Edenabad Society	HS	74.24868	31.37417	26	23	0.402	0.011	38	27	0
36	FS36	Fazaia Housing Society	HS	74.24365	31.37313	26	22	0.305	0.02	38	27	0
37	FS37	Fazaia Housing Society	HS	74.24072	31.37271	20	18	0.613	0.025	38	26	0
38	FS38	Fazaia Housing Society	HS	74.23717	31.37575	37	33	0.786	0.022	40	26	18
39	FS39	Fazaia Housing	HS	74.24346	31.37658	25	22	0.251	0.021	40	26	18
40	CM40	Supper Mart	MK	74.25257	31.37542	33	30	0.715	0.013	40	26	11
41	KS41	Khayaban-e-Amin	HS	74.26059	31.37431	146	127	0.092	0	76	17	8
42	KS42	Khayaban-e-Amin	HS	74.2676	31.37085	157	134	0.04	0.005	76	17	8
43	KS43	Khayaban-e-Amin	HS	74.27041	31.3741	140	121	0.06	0.003	76	17	8
44	CS44	Cricket Stadium	SP	74.25896	31.38068	162	139	0.183	0.019	76	17	8
45	HD45	Hudiara Drain	DR	74.25803	31.38288	164	144	0.219	0.07	76	17	8
46	HD46	Hudiara Drain	DR	74.26296	31.38217	161	136	0.251	0.049	76	17	8
47	KS47	Khayaban-e-Amin	HS	74.26313	31.38041	172	146	0.368	0.023	76	17	8
48	KS48	Khayaban-e-Amin	HS	74.26663	31.38131	167	144	0.537	0.051	76	17	8
49	KS49	Khayaban-e-Amin	HS	74.26754	31.3779	169	150	0.229	0.02	76	17	8
50	KS50	Khayaban-e-Amin	HS	74.27047	31.38203	176	153	0.598	0.188	76	17	8
Minimum						19	17	0.003	0	31	15	0
Maximum						228	199	9.659	0.476	77	28	24
Average						95.48	82.92	1.24174	0.0514	54.22	22.26	10.54
Standard Deviation						63.016	54.437	2.046	0.079	17.537	4.690	7.368

the highest average yearly PM_{10} concentration, reaching 372 μg/m³. This has profound consequences on human health, radiation, agriculture, aviation, tourism, and the overall dust-related concerns in Ahvaz [26]. The investigation's findings from 2018 revealed an average yearly PM_{10} level of 110 μg/m³ and a peak of 1447 μg/m³, significantly exceeding WHO recommendations by 7.3 and 32.2 times, respectively. Such high levels may result in a notable increase in cardiovascular and respiratory morbidity cases [27].

The $PM_{2.5}$ distribution map in Fig. 1b) highlights levels in the study area. This $PM_{2.5}$ map reveals a distinct trend in both the east and southwest directions. The lowest values persistently appear in the university and drain area, benefiting from a cleaner environment, reduced pollution, and a refreshing breeze. Conversely, the highest values are consistently observed near roadways, attributed to heavy transportation, dusty roads, varied shops, and vehicular traffic. The measured values surpassed the allowable limit, with 50 samples exceeding the WHO standard of 15 μg/m³. Similarly, the air quality standard set by the Punjab Environmental Protection Agency (PEQS) is 35 μg/m³. Notably, 34 samples exceeded the PEQS standard, while 16 samples adhered to it. Areas with sample values exceeding both the WHO and PEQS standards pose a higher health risk compared to regions where 43 samples fall within the standard limits. Shijiazhuang in China faces severe pollution due to its unique geographical and climatic circumstances, coupled with

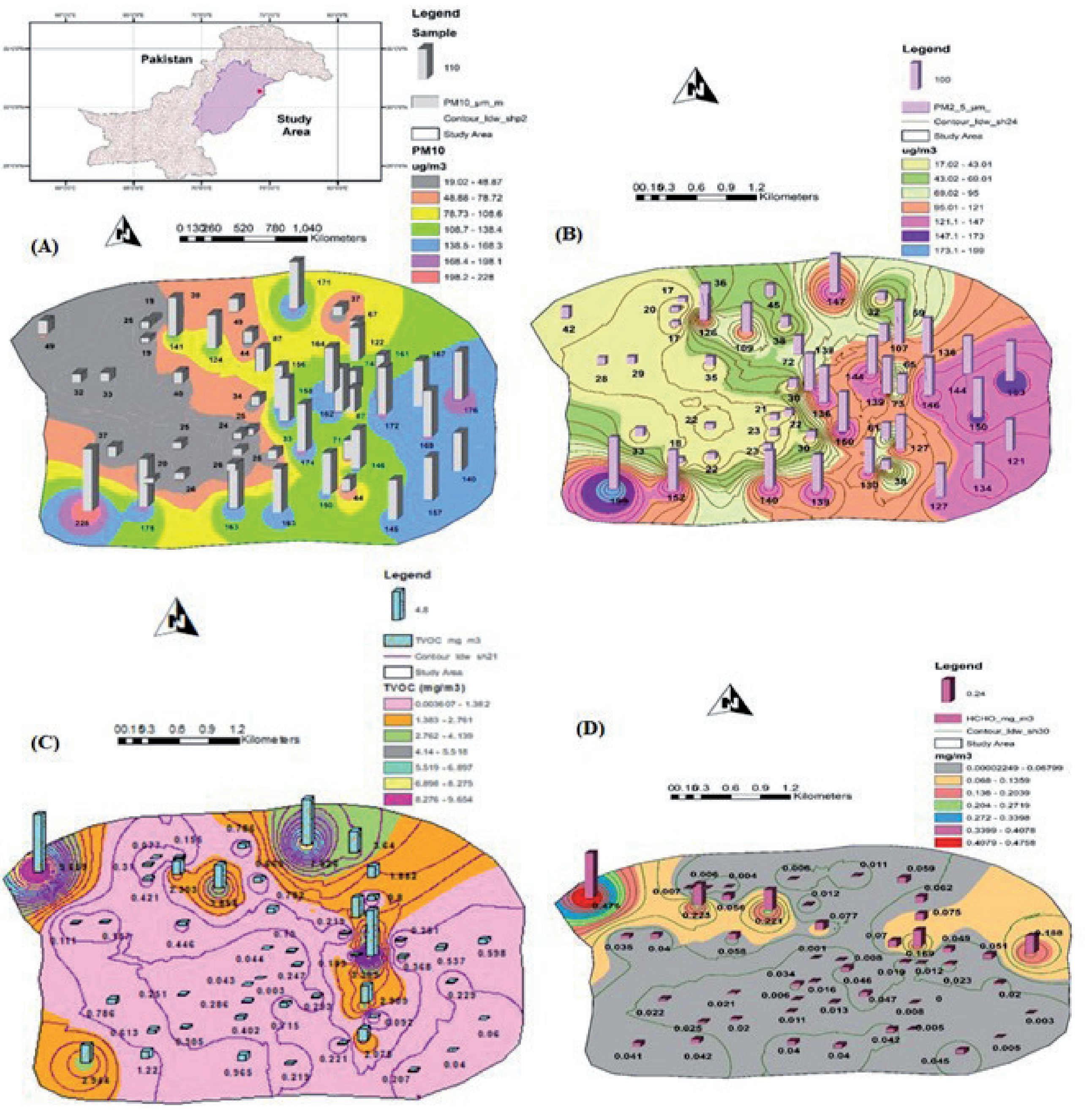

Fig. 1. Distribution maps (a-d) showing levels of measured air pollutants in the study area.

rapid development [28]. This research investigates $PM_{2.5}$ levels during the pre-lockdown, lockdown, and unlocking phases across 10 significant cities in Maharashtra. Our findings reveal that $PM_{2.5}$ levels were notably high during the pre-lockdown phase (January to March), sharply decreasing during the lockdown phase. Subsequently, during the unlocking phase, levels rebounded, exceeding the pre-lockdown levels due to the resumption of outdoor activities. In response to these unlocking circumstances, levels returned to their prior position and rose by 70% compared to the lockdown period.

Fig. 1c) displays the spatial distribution map of TVOC levels across Lahore, within Punjab province. This map reveals a notable trend, with higher concentrations detected in the northwest direction, contrasting with the southeast direction. The lowest values are consistently found in residential areas, benefiting from a clean environment, reduced pollution, and favorable atmospheric conditions. Conversely, the highest values are concentrated near drainage areas, attributed to the strong odor from drain effluents and the dense fume emissions. The air quality standard set by the Hong Kong Special Administrative Region (SAR) government for TVOC is less than 0.6 mg/m^3. However, the sampling results indicate that 20 samples exceeded this limit, while 30 samples remained within it. This presents a significant health risk, leading to potentially serious health issues. China reports elevated TVOC concentrations in urban and suburban regions, notably in cities such as Beijing, Tianjin, and Shanghai, which exhibit the highest TVOC levels. Key sources of atmospheric VOCs in China encompass vehicle emissions, industrial processes, solvent usage, fossil fuel combustion, fuel evaporation, rubber manufacturing, LPG utilization, petroleum industry, and coal burning [29, 30]. Additionally, in India, an investigation highlights the impact of lockdown measures on VOC levels in the Punjab metropolitan region. Findings indicate a substantial decrease in overall TVOC levels across all reporting areas before, during, and after the pandemic. When compared to the years preceding the lockdown, the average TVOC concentration dropped by 43% across all monitored stations. During the outbreak, Patiala recorded a higher air pollution ratio (2970 mg/m^3), potentially attributed to automobile emissions [31].

Fig. 1d) illustrates the spatial distribution map of HCHO levels in Lahore. The lowest value is observed in residential areas, benefiting from fresh air, a clean atmosphere, and abundant greenery. Conversely, the highest value is concentrated in the drain area, attributed to the foul smell, heavy effluents, and chemicals emitted from the drain. The air quality standard set by the Hong Kong Special Administrative Region (SAR) government for HCHO is below 0.1 mg/m^3. However, the sampling results reveal that 5 samples exceeded this limit, while the remaining 45 samples remained within it [32]. This suggests a low health risk exposure due to the minimal number of samples surpassing the limit. Primary HCHO contributes significantly to atmospheric HCHO concentrations, accounting for up to 50% regularly during the night and up to 80% in the morning [33]. Beyond its negative impact on human health, formaldehyde plays a crucial role in secondary organic aerosols and tropospheric ozone. Furthermore, HCHO exhibited a comparable trend with elevated levels during both dry and rainy seasons for each of the three population categories. The findings underscore the need for mitigation measures to counteract the adverse effects on individuals affected by HCHO emissions [34].

Fig. 2 (a and b) showed scatter plots that depict the relationships among four pollutants: PM_{10}, $PM_{2.5}$, TVOC, and HCHO. In essence, the respective correlation equations provide valuable insights into the connections between these pollutants. While the first two pollutants, PM_{10} and $PM_{2.5}$, exhibit highly predictable and strongly correlated behavior, the correlation between TVOC and HCHO is much less pronounced, indicating a more complex and potentially non-linear interaction between these two pollutants.

The outcomes of the Principal Component Analysis (PCA, Fig. 2c) indicated the presence of two distinct groups within the measured parameters. These groups are categorized as follows: one group comprises Total Volatile Organic Compounds (TVOCs) and Formaldehyde (HCHO), while the other centers around Particulate Matters (PMs). The PCA analysis highlights the significance of two principal components, namely PC1 and PC2. PC1 encapsulates a substantial 59% of the overall data variability, while PC2 contributes an additional 22%. Together, these two components collectively account for a noteworthy 81% of the total data variation. The interpretation assembled from the analysis aligns well with the observed trends. The first group, prominently featuring TVOCs and HCHO, emerges as a result of environmental conditions affected by drainage-related factors. This implies that elements linked to drainage systems, such as potential pollutants or chemicals, exert a significant influence on this particular group. Conversely, the second group's patterns can be attributed to road and construction activities. This suggests that variations within this group predominantly arise from factors associated with roads and construction work, including the generation of dust and particulate matter from these operational contexts. This analytical approach is particularly beneficial in environmental investigations as it aids in identifying key sources of fluctuations in measured parameters and offers a deeper understanding of potential environmental impacts. The hotspots identified in the urban areas required further detailed investigation to manage air quality in the study area.

Cytotoxicity Against Red Blood Cells (RBCs)

Cytotoxicity of airborne particulate matter, $PM_{2.5}$ and PM_{10}, was measured against in-vitro red blood cells (RBCs) with slight modification [1]. The results revealed

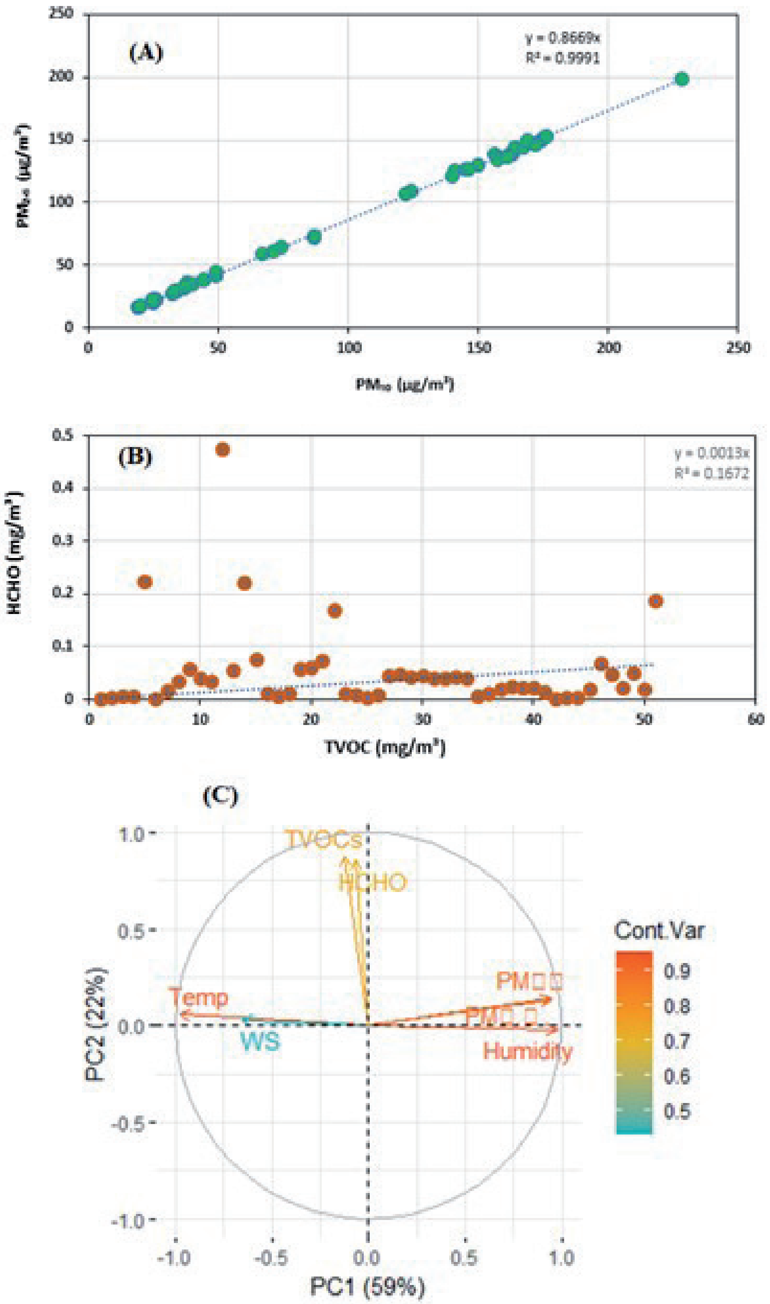

Fig. 2. (a-b) Scatter plots illustrating measured air pollutants in the residential areas and c) Principal Component Analysis (PCA) biplot of field data measured in the study area.

that different particulates having particle sizes around 2.5-micron showed 37.5±2.8 cell lysis. Only short-term exposure for 24 hours with these particulates having a size of 2.5 microns, the following medical consequences are possible: premature mortality, increased hospital admissions for heart or lung causes, acute and chronic bronchitis, asthma attacks, and respiratory symptoms [35]. PM_{10}, or particulate matter with a diameter of 10 micrometers or less, predominantly originates from various sources such as dust generated at construction sites, landfills, and agricultural activities. Other contributors include wildfires, burning of brush and waste, industrial emissions, wind-blown dust from open areas, as well as pollen and bacterial fragments. Notably, cellular toxicity against PM_{10} has been observed, resulting in a significant cell lysis percentage of 27.32±3.54. Short-term exposure to PM_{10} has been conclusively linked to the exacerbation of respiratory conditions, notably asthma and chronic obstructive pulmonary disease (COPD). On the other hand, the implications of long-term exposure to PM_{10} are not fully elucidated, although multiple studies suggest an association between prolonged exposure and increased respiratory mortality. Further research is required to comprehensively understand the long-term effects of exposure to PM_{10} on respiratory health [35].

Conclusions

In summary, the concentrations of major atmospheric pollutants were assessed in various locations: residential areas, drain areas, and roadside sites. The findings revealed that a significant number of samples exceeded the air quality standards set by both the WHO and the PEQS. Specifically, for PM_{10}, 17 samples out of 30 exceeded the recommended limits, indicating higher risk exposure in these areas. Similarly, for $PM_{2.5}$, 34 samples out of 50 exceeded the standards, indicating an even greater risk of adverse health effects. Regarding other pollutants, the standards for TVOC set by the Hong Kong Special Administrative Region government were not met, as 20 samples exceeded the specified limit of less than 0.6 mg/m³. This poses a serious health risk. However, the standard for HCHO (formaldehyde) was exceeded in only 5 samples out of the specified limit of less than 0.1 mg/m³. The cytotoxicity analysis of $PM_{2.5}$ and PM_{10} was performed and the findings revealed a significant toxicity to the RBCs, which caused health risks in the residents of the area. Hence, it is crucial to raise awareness about air pollution and its consequences. This can be achieved through various campaigns, advertisements, multimedia, and news dissemination. People need to be familiar with and adhere to the WHO and PEQS air quality standards to prevent exceeding the limits. Implementing mitigation measures is essential to reduce air pollution. This involves adopting modern technologies in industries and transportation systems and controlling excessive urban transportation. Other specific recommendations include increasing the number of trees and vegetation cover to mitigate atmospheric pollution and promote environmental purity.

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Conflict of Interest

The authors declare no conflict of interest.

References

1. MANNUCCI P.M., FRANCHINI M. Health effects of ambient air pollution in developing countries. International Journal of Environmental Research and Public Health. **14** (9), 1048, **2017**.
2. HUSSAIN S., AZIZ I., WAQAS M., AHMAD T., AHMAD I., TAHIR M.B., AL HUWAYZ M., ALWADAI N., IQBAL M., NAZIR A. Potential Antifungal and Antimicrobial Effects of Nano Zinc Oxide Particles Obtained from <i>Cymbogobon citratus</i> Leaf Extract Using Green Technology. Polish Journal of Environmental Studies. **32** (5), 4065, **2023**.
3. ABBAS Q., BUKHARI T.H., USMAN M., MUNIR M., IQBAL M., NAZIR A., TALIB N.B., ELQAHTANI Z.M., ALWADAI N., AHMAD N. Efficient Removal and Conditions Optimization of Textile Dyes Using UV/TiO₂ Based Advanced Oxidation Process. Polish Journal of Environmental Studies. **32** (3), 2465, **2023**.
4. BOKHARI T.H., MUSTAFA G., AHMED N., USMAN M., AKRAM N., HAQ A.U., SALMAN M., NAZ S., AL-FAWZAN F.F., ALISSA S.A., IQBAL M., NAZIR A. Degradation of a Pigment Red 238 using UV, UV/H₂O₂, UV/H₂O₂/SnO₂ and Fenton Processes. Polish Journal of Environmental Studies. **31** (1), 619, **2022**.
5. JABEEN F., ALI Z., MAHARJAN A. Assessing health impacts of winter smog in Lahore for exposed occupational groups. Atmosphere. **12** (11), 1532, **2021**.
6. ANJUM M.S., ALI S.M., SUBHANI M.A., ANWAR M.N., NIZAMI A.-S., ASHRAF U., KHOKHAR M.F. An emerged challenge of air pollution and ever-increasing particulate matter in Pakistan; a critical review. Journal of Hazardous Materials. **402**, 123943, **2021**.
7. KHWAJA M.A., SHAMS T. Pakistan National Ambient Air Quality Standards: A comparative Assessment with Selected Asian Countries and World Health Organization (WHO). **2020**.
8. ABBAS M., HUSSAIN T., IQBAL J., REHMAN A.U., ZAMAN M.A., JILANI K., MASOOD N., AL-MIJALLI S.H., IQBAL M., NAZIR A. Synthesis of Silver Nanoparticle from <i>Allium sativum</i> as an Eco-Benign Agent for Biological Applications. Polish Journal of Environmental Studies. **31** (1), 533, **2022**.
9. MA C.-J. Experimental Verification of the Particle Blocking Feature of Nasal Hair. Asian Journal of Atmospheric Environment. **13** (2), 99, **2019**.
10. ROY D., SINGH G., GOSAI N. Identification of possible sources of atmospheric PM_{10} using particle size, SEM-EDS and XRD analysis, Jharia Coalfield Dhanbad, India. Environmental Monitoring and Assessment. **187**, 1, **2015**.
11. LI J., HAO Y., SIMAYI M., SHI Y., XI Z., XIE S. Verification of anthropogenic VOC emission inventory through ambient measurements and satellite retrievals. Atmospheric Chemistry and Physics. **19** (9), 5905, **2019**.
12. RÖSCH C., KOHAJDA T., RÖDER S., VON BERGEN M., SCHLINK U. Relationship between sources and patterns of VOCs in indoor air. Atmospheric Pollution Research. **5** (1), 129, **2014**.
13. SALTHAMMER T. Formaldehyde in the ambient atmosphere: from an indoor pollutant to an outdoor pollutant? Angewandte Chemie International Edition. **52** (12), 3320, **2013**.
14. AL-THANI H., KOÇ M., ISAIFAN R.J. A review on the direct effect of particulate atmospheric pollution on materials and its mitigation for sustainable cities and societies. Environmental Science and Pollution Research. **25**, 27839, **2018**.
15. HAO J., LI G. Air pollution caused by industries. Point Sources Pollut Local Eff Control I (I). 171, **2009**.
16. MANISALIDIS I., STAVROPOULOU E., STAVROPOULOS A., BEZIRTZOGLOU E. Environmental and health impacts of air pollution: a review. Frontiers in Public Health. **8**, 14, **2020**.

17. GHEORGHE I.F., ION B. The effects of air pollutants on vegetation and the role of vegetation in reducing atmospheric pollution. The impact of air pollution on health, economy, environment and agricultural sources. Publisher InTech, Chapter 12, pp. 243-280, **2011**.
18. ASHRAF N., MUSHTAQ M., SULTANA B., IQBAL M., ULLAH I., SHAHID S.A. Preliminary monitoring of tropospheric air quality of Lahore City in Pakistan. Sustainable Development. **3** (1), 19, **2013**.
19. SIDRA S., ALI Z., NASIR Z.A., COLBECK I. Seasonal variation of fine particulate matter in residential micro–environments of Lahore, Pakistan. Atmospheric Pollution Research. **6** (5), 797, **2015**.
20. ALMAS A.S., RAHIM C., BUTT M., SHAH T.I. Metropolitan growth monitoring and land use classification using geospatial techniques. Citeseer. **2005**.
21. JABLONSKY J. MS Excel based software support tools for decision problems with multiple criteria. Procedia Economics and Finance. **12**, 251, **2014**.
22. QUEROL X., ALASTUEY A., RUIZ C., ARTIÑANO B., HANSSON H., HARRISON R., BURINGH E.T., TEN BRINK H., LUTZ M., BRUCKMANN P. Speciation and origin of PM_{10} and $PM_{2.5}$ in selected European cities. Atmospheric Environment. **38** (38), 6547, **2004**.
23. ZHANG Y.-L., CAO F. Fine particulate matter ($PM_{2.5}$) in China at a city level. Scientific Reports. **5** (1), 14884, **2015**.
24. VARSHNEY C., PADHY P.K. Total volatile organic compounds in the urban environment of Delhi. Journal of the Air & Waste Management Association. **48** (5), 448, **1998**.
25. NEAMTIU I.A., CIMPAN T., ZHOU J., SCHIOPU I., SURCEL M., LIN S. Monitoring and assessment of formaldehyde levels in residential areas from two cities in Romania. Reviews on Environmental Health. **34** (3), 267, **2019**.
26. MALEKI H., SOROOSHIAN A., GOUDARZI G., NIKFAL A., BANESHI M.M. Temporal profile of PM_{10} and associated health effects in one of the most polluted cities of the world (Ahvaz, Iran) between 2009 and 2014. Aeolian Research. **22**, 135, **2016**.
27. LEILI M., ASL F.B., JAMSHIDI R., DEHDAR A. Mortality and morbidity due to exposure to ambient air PM10 in Zahedan city, Iran: The AirQ model approach. Urban Climate. **49**, 101493, **2023**.
28. DUAN J., CHEN Y., FANG W., SU Z. Characteristics and relationship of PM, PM_{10}, PM2.5 concentration in a polluted city in Northern China. Procedia Engineering. **102**, 1150, **2015**.
29. MOZAFFAR A., ZHANG Y.-L. Atmospheric volatile organic compounds (VOCs) in China: a review. Current Pollution Reports. **6**, 250, **2020**.
30. YAN L. Legislation of air pollution control in China. IOP Conference Series Earth and Environmental Science. **512** (1), 012029, **2020**.
31. SINGH B. P., SINGH M., ULMAN Y., SHARMA U., PRADHAN R., SAHOO J., PADHI S., CHANDRA P., KOUL M., TRIPATHI P.N. Distribution and temporal variation of total volatile organic compounds concentrations associated with health risk in Punjab, India. Case Studies in Chemical and Environmental Engineering. **8**, 100417, **2023**.
32. MEYER C. Overview of TVOC and indoor air quality. Renesas Electronics Corporation: Tokyo, Japan. **2018**.
33. LEI W., ZAVALA M., DE FOY B., VOLKAMER R., MOLINA M., MOLINA L. Impact of primary formaldehyde on air pollution in the Mexico City Metropolitan Area. Atmospheric Chemistry and Physics. **9** (7), 2607, **2009**.
34. CRUZ L.P., DA ROCHA F.O., MOREIRA M.S., CAMPOS V.P., SOUZA K.S. Probabilistic human health risk assessment and contributions to ozone and SOA formation potentials associated with BTEX and formaldehyde emissions in a tropical city (Salvador, Bahia, Brazil). Air Quality Atmosphere & Health. **16** (4), 1, **2023**.
35. DAS K., DAS CHATTERJEE N., JANA D., BHATTACHARYA R.K. Application of land-use regression model with regularization algorithm to assess $PM_{2.5}$ and PM_{10} concentration and health risk in Kolkata Metropolitan. Urban Climate. **49**, 101473, **2023**.