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Urban Air Quality Nexus: $PM_{2.5}$ Bound-Heavy Metals and their Alarming Implication for Incremental Lifetime Cancer Risk

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ABSTRACT

Fine particulate matter ($PM_{2.5}$) have not only detrimental impacts on air quality but also acts as a source for a range of heavy metals that worsen the potential risks to public health. Notably, previous studies on $PM_{2.5}$-bound heavy metals in Pakistan have primarily focused on individual cities. This study offers a comprehensive analysis of pollution characteristics related to $PM_{2.5}$-bound heavy metals, including lead (Pb), cadmium (Cd), zinc (Zn), and nickel (Ni), in ten cities of Pakistan. Data was collected from a wide range of reliable sources spanning from 2013 to 2023. Additionally, the human health risk assessment methodology endorsed by the United States Environmental Protection Agency (US EPA) was employed to evaluate both carcinogenic and non-carcinogenic risks for adults (males and females) and children. Findings of the present study revealed that children faced a greater risk associated with $PM_{2.5}$-bound heavy metals as compared to adults. Cadmium, zinc, and nickel were found as the top three contributors to the average non-carcinogenic risk, while lead, cadmium, and nickel showed the highest carcinogenic risks. Based on these findings, this study strongly recommend that the government should strengthen the management of industrial and vehicular emissions. Furthermore, there is an imperative need to establish a real-time monitoring system capable of tracking toxic heavy metal pollutants transported through the atmosphere. Additionally, policymakers should seriously contemplate regional collaborations with the goal of creating metropolitan initiatives for pollution control, thereby effectively addressing these paramount environmental and public health concerns.

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INTRODUCTION

Air pollution is a matter of utmost concern due to its potential to cause significant harm to both human and environmental health. This problem goes beyond geographical boundaries and has endured for decades, primarily driven by unregulated industrial expansion and the relentless growth of urban areas (Li et al., 2022; Lima et al., 2021). A recent revelation underscores the gravity of the situation, revealing that one in every eight individuals succumbs to the effects of

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air pollution (Vural, 2020). The deleterious consequences of air pollution manifest in various forms, with lung diseases accounting for 23% of related fatalities, followed by cardiovascular diseases (19%), ischemic diseases (24%), and stroke (21%) (Sahu et al., 2021). The WHO has disquietingly reported that approximately 91% of the global population resides in areas where pollutant levels exceed recommended guidelines (WHO, 2019). Among the array of air pollutants studied extensively, nitrogen oxides, sulfur oxides, volatile organic compounds, stratospheric ozone, and atmospheric particulates stand out, as they not only pose direct threats to human health but also cause environmental degradation and contribute to climate change (Alves et al., 2023; Zhao et al., 2023).

Airborne particulates, including $PM_{2.5}$ and PM_{10}, represent a complex merger of tiny solid particles and liquid droplets that remain suspended in the atmosphere, shaped by atmospheric processes (Brodny & Tutak, 2021). Among these, the finer fraction known as respirable particulate matter ($PM_{2.5}$) has garnered significant attention due to its heightened atmospheric hazards (Ahmad et al., 2021; Liu et al., 2020). $PM_{2.5}$-bound heavy metals can originate from a variety of sources, primarily stemming from human activities and natural processes. Industrial emissions, including the combustion of fossil fuels and metal production, release significant amounts of heavy metals into the atmosphere. Additionally, vehicular exhaust and construction activities contribute to these pollutants in urban areas. Natural sources, such as dust storms and wildfires, can also disperse heavy metals into the air. Over time, these pollutants can accumulate and pose health and environmental risks, making it crucial to address their sources and implement effective mitigation strategies (Liu et al., 2020; Silva et al., 2022). Inhaling $PM_{2.5}$ presents a significant hazard to human health because these fine particles easily infiltrate the respiratory system, accumulating in the innermost lung regions and potentially causing respiratory issues (Schwela & Haq, 2020). Extensive research has illuminated the adverse effects of elevated $PM_{2.5}$ levels, including premature mortality and disturbances to sensory organs, cellular structure, and function (Nair et al., 2020; Tong, 2019). In recent years, Asian nations, particularly those within South Asia, have grappled with a disturbing upsurge in airborne particulate pollution, marked by elevated levels of suspended particles. Recent surveys emphasized the gravity of this issue, with countries like Bangladesh, India, and Pakistan in South Asia facing the problem of air quality (Anjum et al., 2021). Notably, the city of Lahore in Pakistan has gained notoriety as one of the world's most polluted urban centers, plagued by a consistently dismal air quality index (Nawaz et al., 2023, Nawaz et al., 2022; Malhi et al., 2023). The underlying causes of this escalating air quality crisis in Pakistan are multifaceted. Rapid and unplanned urbanization, coupled with a growing industrial sector, has given rise to an unhealthy environment characterized by a surge in anthropogenic emissions (Lv et al., 2019).

Urbanization, despite fostering economic growth and societal development, has given rise to a pressing concern that extends beyond geographical borders and impacts the health and well-being of millions across the globe by degrading urban air quality. The rapid industrialization, increasing vehicular traffic, and high population density in metropolitan areas have converged to intensify the levels of fine particulate matter. Beyond the well-established health risks associated with $PM_{2.5}$ exposure, a growing concern has emerged regarding its role as a carrier for transporting toxic heavy metals into the lungs and bodies of urban residents. In light of the well-documented adverse effects associated with heavy metals, notorious for their harmful properties, including their link to various health issues, notably cancer, it has become increasingly crucial to develop a comprehensive understanding of the intricate connection between urban air quality and the presence of heavy metals bound to $PM_{2.5}$ particles. This research initiative is dedicated to thoroughly examining the air quality in urban areas within metropolitan regions, with a specific emphasis on heavy metals like Pb, Cd, Zn, and Ni that are intricately associated with $PM_{2.5}$ particles. Additionally, it seeks to unveil the potential consequences of this relationship through a meticulous evaluation of risks to human health. The significance of this study lies

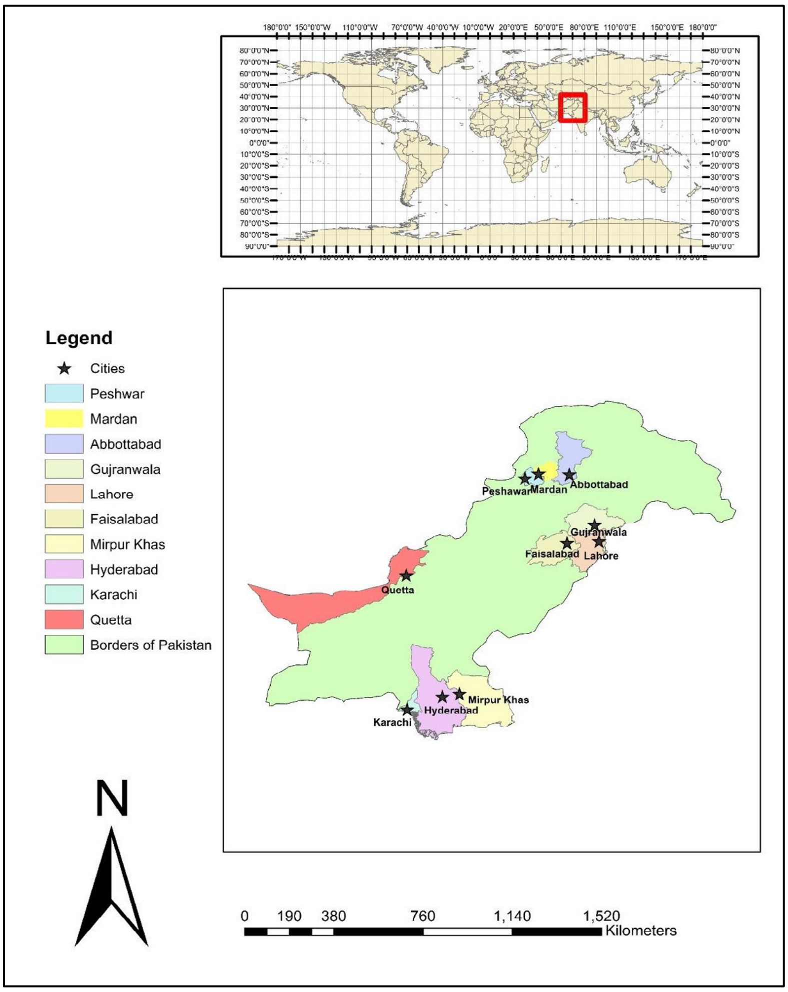

Fig. 1. GIS map showing selected study areas

in its substantial contribution to bridging the current gap in our understanding of the complex interplay between urban air pollution and exposure to heavy metals. It also sheds light on the alarming long-term health risks, notably cancer, faced by urban populations. This study provides a new outlook as it systematically assesses the complex relationship between urban air quality, emphasizing the need for specific mitigation measures and highlighting the urgency of protecting public health in densely populated metropolitan regions.

MATERIAL AND METHODS

Pakistan, in southern Asia along the Arabian Sea, with a population of 243 million have four seasons i.e. summer, winter, spring, and autumn. Its four provinces have diverse climates, ranging from sweltering summers in Punjab to hot and arid conditions in Sindh. Khyber Pakhtunkhwa has varied rainfall, while Baluchistan is consistently hot and arid. These climatic differences make Pakistan an intriguing subject for exploration (Nawaz et al., 2022).

The study encompassed a diverse selection of cities spanning all provinces of Pakistan. Lahore, Faisalabad, and Gujranwala were chosen to from the Punjab province, while Karachi, Mirpur Khas, and Hyderabad were selected from the Sindh province. Peshawar, Mardan, Abbottabad, and Quetta were selected from the Khyber Pakhtunkhwa (KPK) and Baluchistan regions (Figure 1). For this extensive investigation, the data was gathered from various reliable

Table 1. $PM_{2.5}$ bound heavy metals concentrations and WHO guidelines

Provinces	Cities	Lead (ng/m^3)	Cadmium (ng/m^3)	Zinc (ng/m^3)	Nickel (ng/m^3)	References
Punjab	Lahore	3810	64	7290	28.7	Ahmad et al., 2021
	Gujranwala	98.9	339.8	94.3	8.35	Awan et al., 2013
	Faisalabad	88.6	11.4	25.5	110	Awan et al., 2013 Javed et al., 2015
Sindh	Karachi	1250	185	350	30	Khan et al., 2019; Moryani et al.,2020
	Hyderabad	102	7.2	95	21.7	Shahid et al., 2016
	Mirpur Khas	680	0.11	37.7	7.05	Asian Development Bank Report, 2015
KPK	Peshawar	563	22.7	4720	720	Ahmad et al., 2021
	Mardan	900	27	112	110	Subhanullah et al., 2022
	Abbottabad	20	3	30	20	Yousuf et al., 2022
Baluchistan	Quetta	405	25	101	10.8	Khalid, 2019
WHO		500	5	500	25	

and authentic sources for a study period from 2013 to 2023. These sources included secondary resources like research papers, Google Scholar, and Library Genesis, in addition to reference materials such as websites, books, and official publications, including reports from the Environmental Protection Agency (EPA) and Asian Development Bank (ADB). The primary focus of the study revolved around the assessment of $PM_{2.5}$-bound heavy metals, specifically Cd, Zn, Pb, and Ni. These measurements were compared with the standards established by the World Health Organization, as outlined in Table 1. This extensive data collection and rigorous comparison framework formed the foundation for a comprehensive and insightful evaluation of air quality and associated health risks in these regions over the specified time period.

Heavy metals present in the atmosphere can enter the human body via three primary routes: skin contact, ingestion, and predominantly through inhalation. Since fine particulate matter primarily affects health through inhalation. The evaluation process has three parts:

i. Measuring how much heavy metals are absorbed through breathing each day (average daily dose or ADD),

ii. Assessing non-carcinogenic risks using a hazard Index (HI), and

iii. Evaluating carcinogenic risks using the incremental lifetime cancer risk (ILCR)

The formula given below (USEPA, 1989) can be used to compute the ADD [mg/(kg·day)] of $PM_{2.5}$-bound heavy metals that enters the body through inhalation. The input parameter values are shown in Table 2.

$$ADD = \frac{C \times IR \times EF \times ED}{BW \times AT} \quad \text{Equation I}$$

The Hazard Quotient (HQ) was employed to evaluate the non-carcinogenic risk associated with individual $PM_{2.5}$-bound heavy metal pollutants. This assessment was conducted by analyzing the average daily exposure levels for each group of individuals, following the methodology in equation II as recommended by USEPA in 1989. Furthermore, the comprehensive non-carcinogenic impact of multiple heavy metal components was assessed through the Hazard Index, using equation III.

$$HQi = \frac{ADDi}{RfDi} \quad \text{Equation II}$$

Table 2. Values of input parameters for the calculation of average daily dose of pollutants in age groups

Sr. No.	Parameters	Abbreviation	Unit	Adult Male	Adult Female	Children	Reference
1	Concentration of $PM_{2.5}$ bound Heavy metals	C	mg/m^3	-	-	-	-
2	Inhalation rate	IR	mg/m^3	16.6	13.5	8.6	USEPA, 1989
3	Exposure frequency	EF	day/year	356	365	365	USEPA, 1989
4	Exposure duration	ED	Year	30	30	6	USEPA, 1989
5	Body weight	BW	kg	67.3	57.3	15	USEPA, 1989
6	Average non-carcinogenic risk exposure time	AT-non-carcinogenic	days	365×72.4	365×77.4	365×18	USEPA, 1989
7	Average carcinogenic risk exposure time	AT-carcinogenic	days	365× ED	366× ED	367× ED	USEPA, 1989

$$HI = \sum HQI = \sum \frac{ADDi}{RfDi}$$ Equation III

In equation III, the term "reference dose (RfD)" signifies the amount of a particular pollutant that can be ingested through the process of respiration. It helps determine if there are harmful health effects from long-term exposure to that pollutant in the environment (USEPA, 1989). By using the HI, we assess the overall non-carcinogenic risk posed by various elements. If HI is less than or equal to 1, it means that the combined non-carcinogenic health risk from multiple elements is considered low or negligible. However, if HI is greater than 1, it indicates a non-carcinogenic health risk (USEPA, 2004). Additionally, when HQi (the hazard quotient for a specific pollutant) is less than 1, it means the non-carcinogenic health risk associated with that particular pollutant is minimal. On the other hand, if HQi is greater than 1, it suggests there is a non-carcinogenic risk associated with that pollutant.

The ILCR risk method was employed to assess the carcinogenicity of individual cancerous heavy metal contaminants after determining the average daily dosage of each category of exposed people.

$$ILCR = ADD \times SF$$ Equation IV

The slope factor, abbreviated as SF (USEPA, 1989), is the highest likelihood that the human body would be subjected to a particular dosage of a particular pollutant to have carcinogenic consequences. The specific information is displayed in table 3 concerning the RfD and SF of the heavy metals. Long-term contact with a certain carcinogen may result in cancer in humans. Therefore, ILCR is used to determine whether cancer has a potential in the human body. According to the USEPA (2009), the pollutant can be deemed to provide a risk of cancer to those who are exposed when the ILCR is (10^{-6}, 10^{-4}). This is due to the increased likelihood of one cancer case occurring among every 10,000 to 1 million individuals. Consequently, the study classified the carcinogenic risk into three levels as follows:

- Low risk ($-\infty$ to 10^{-6}): Deemed acceptable
- Medium risk (10^{-6} to 10^{-4}): Signifying potential carcinogenic risk
- High risk (10^{-4} to $+\infty$): Demanding immediate and close attention (USEPA, 2009).

Table 3. Input parameters for reference dose and slope factor of selected heavy metals

Sr. No	Heavy Metal	RfD	SF	Carcinogenic/non carcinogenic
1	Lead	0.003	0.0042	Carcinogenic
2	Cadmium	0.001	6.3	Carcinogenic
3	Nickel	0.02	0.84	Carcinogenic
4	Zinc	0.003	NA	Non-carcinogenic

(Source: USEPA, 2009)

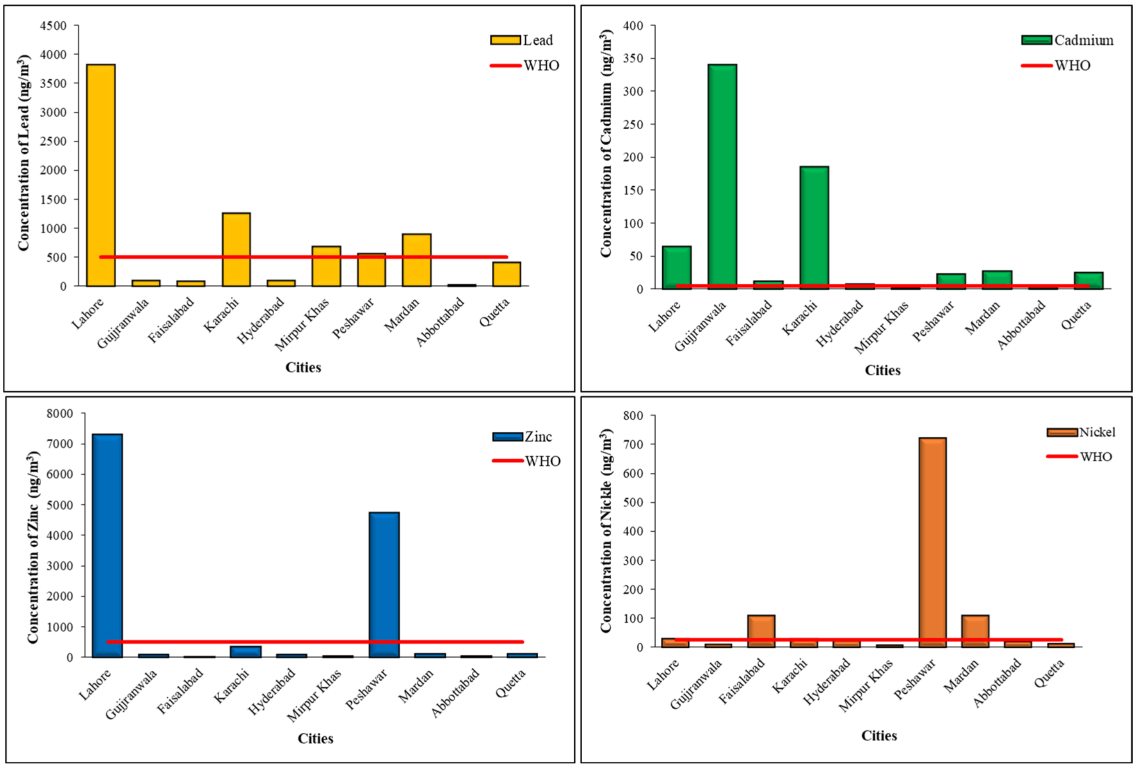

Fig. 2. Heavy metal concentrations in selected cities of Pakistan compared to WHO guidelines

RESULTS AND DISCUSSION

Levels of heavy metal, such as Cd, Ni, Zn, and Pb, exert detrimental effects on the ecology of many cities. These heavy metals are released into the environment from various sources, including vehicle emissions, industrial activities, mining, battery manufacturing, and refinery facilities. In selected cities, the concentration of $PM_{2.5}$-bound Cd ranged from 0.11 ng/m^3 to 339.8 ng/m^3. Notably, Lahore, Gujranwala, Faisalabad, Karachi, and Peshawar recorded concentrations of 77 ng/m^3, 326.5 ng/m^3, 320.8 ng/m^3, 185 ng/m^3, and 85 ng/m^3, respectively, exceeding the WHO guidelines. Similarly, $PM_{2.5}$-bound Pb concentrations in Lahore, Mirpur Khas, and Mardan exceeded WHO guidelines, with concentrations of 3810 ng/m^3, 680 ng/m^3, and 900 ng/m^3, respectively. Regarding zinc, the WHO limit was 500 ng/m^3, but Lahore exceeded this guideline by a significant margin, with an emission of 7,290 ng/m^3. For nickel, with a WHO guideline of 25 ng/m^3, this limit may be exceeded in all selected cities, with Peshawar and Mardan reaching 720 and 110 ng/m^3, while Gujranwala had the lowest concentration at 8.35 ng/m^3 (Figure 2). The excessive emissions can have adverse environmental impacts on air, water, and soil quality.

The results of the present study showed a worrisome and persistent trend of higher concentrations of $PM_{2.5}$-bound heavy metals, especially Pb, Cd, and Ni, exceeding the existing WHO guidelines in selected cities of Pakistan. This startling discovery sheds light on Pakistan's ongoing and pervasive heavy metal pollution, which poses serious risks to both the environment and public health. A well-known and extremely dangerous heavy metal contaminant, Pb has a substantial negative impact on human health, especially on young children's brain growth. Concerning findings from recent study showed that lead concentrations in $PM_{2.5}$ particles in a few Pakistani cities are higher than the WHO guidelines. This raises major concerns because excessive lead levels might have substantial health risks like cognitive decline, developmental delays, and other serious health problems.

In addition, this study revealed the presence of Cd that is another deadly heavy metal. The levels of Cd were higher than the WHO guidelines in all of the selected cities. A number of health problems, including kidney damage, decreased bone mineral density, and an increased risk of cancer, are linked to cadmium exposure. These findings highlight the critical need for quick action to address and reduce the health risks brought on by heavy metal pollution in metropolitan settings. There is an urgent need for attention and action since excessive $PM_{2.5}$-bound cadmium levels are very common in Pakistani cities. Ni is recognized to have harmful health consequences, such as respiratory issues and probable carcinogenic qualities, but it may not have garnered as much attention in prior research as lead and cadmium. Findings of this study indicated that $PM_{2.5}$-bound nickel levels exceeded WHO guidelines in selected Pakistani cities. Furthermore this study also highlighted the extensive nature of heavy metal pollution in the country. Interestingly, Zn levels in the atmosphere was not consistently higher than WHO guidelines, with Karachi being the exception. This variation in zinc levels may be attributed to localized factors such as industrial activities and emissions sources specific to Karachi.

In accordance with equation I, figure 3 illustrates the ADD of three distinct visible groups across ten cities of Pakistan. Each color within the scale corresponds to one of these ten cities,

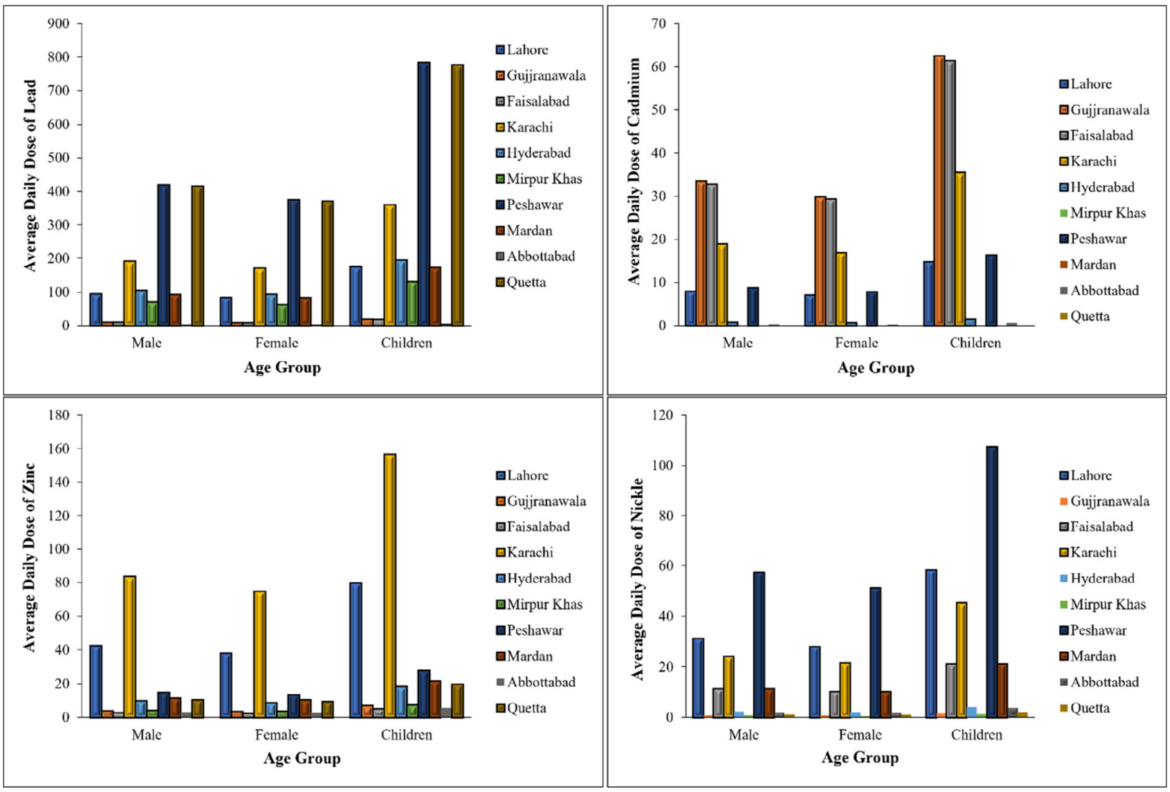

Fig. 3. Estimating the Average Daily Dose of Heavy Metal Exposure in selected cities of Pakistan to indicate the Environmental Health Assessment

with each column signifying the average daily exposure to pollutants for male adults, female adults, and children, respectively. Figure 3 highlights striking disparities in ADD distribution among different cities and exposed groups. Notably, the average ADD for $PM_{2.5}$-bound Pb, Cd, Zn and Ni exhibited the highest values in all age groups. An intriguing observation emerges when evaluating ADD; it becomes evident that children face notably higher ADD levels of $PM_{2.5}$-bound heavy metals compared to adults. However, it is important to emphasize that relying solely on ADD for assessing health risk is not sufficiently accurate. To comprehensively gauge the potential health hazards, it becomes imperative to conduct evaluations encompassing both non-carcinogenic and carcinogenic risks.

The results of the present study revealed significantly higher ADD of $PM_{2.5}$-bound Pb, Cd, Zn, and Ni across all age groups. Results provide valuable insights into the differential exposure patterns and risks faced by different segments of the population. It has been found that children consistently experience markedly higher ADD levels of $PM_{2.5}$-bound heavy metals as compared to the adults. These results underscores the urgent need for targeted interventions to protect the most vulnerable population in the developing countries. The higher ADD values of $PM_{2.5}$-bound heavy metals in all age groups highlight the pervasive nature of heavy metal pollution in the ambient air of the cities of the study. This extensive exposure holds profound implications for public health, given the well-established association of heavy metals with various detrimental health effects. These include neurological disorders, respiratory ailments, cardiovascular diseases, and an elevated risk of cancer. The fact that these pollutants are present at elevated levels in the air, and are inhaled by individuals of all age groups, is a matter of great concern. However, perhaps the most striking discovery lies in the disproportionately higher levels of ADD observed in children when compared to the adults. Children are a particularly vulnerable demographic due to their developing organ systems, greater inhalation rates, and behavioral factors that lead to increased exposure. The observed higher ADD values in children suggest that such group is not only at greater risk for immediate health problems but also face potential long-term health consequences as a result of chronic exposure to $PM_{2.5}$-bound heavy metals.

Hazard Quotient (HQ) for each individual heavy metal pollutant was estimated using equation II. Subsequently, equation III was employed to ascertain the comprehensive non-carcinogenic Hazard Index (HI) considering multiple heavy metals. Figure 4 illustrates the breakdown of HQ contributions to HI in terms of percentages. The results showed that the relative impact of individual heavy metal pollutants on the non-carcinogenic risk index, as follows: Cd had the highest contribution (31.3%), followed by Ni (27.8%), Zn (23.6%), and Pb (17.4%). Consequently, $PM_{2.5}$-bound Cd emerges as the primary contributor to non-carcinogenic risk, demanding heightened attention. It is important to note that the HQ values for $PM_{2.5}$-bound Cd, Zn, and Ni, experienced by adult males, females, and children in Gujranwala, Karachi, Mirpur Khas, Peshawar, Mardan, and Quetta, surpass the threshold of 1, highlighting the probability of non-carcinogenic risk. Moreover, the HQ for $PM_{2.5}$-bound Pb estimated for children in Karachi surpasses the same threshold, implicating that the children group had a notably elevated non-carcinogenic risk.

Figure 5 depicts the comprehensive non-carcinogenic Hazard Index (HI) for each exposed group in the selected cities. For male adults, the HI varies from 0.50 in Abbottabad to 1.74 in Faisalabad. Female adults exhibit HI ranging from 0.55 in Mirpur Khas to 1.95 in Hyderabad, while children's HI ranges from 0.75 in Lahore to 2.28 in Karachi. These findings underscore the substantial impact of PM2.5-bound heavy metals, with children facing the highest average comprehensive non-carcinogenic risk at 1.34, followed by females at 1.28, and male adults at 1.15. Furthermore, it is evident that in Gujranwala, Karachi, Peshawar, and Quetta, the comprehensive non-carcinogenic risk posed by $PM_{2.5}$-bound heavy metals to children is deemed unacceptable. Similarly, female adults in Faisalabad, Hyderabad, Peshawar, and Abbottabad, as well as male adults in Faisalabad and Peshawar, also face an elevated risk level. In contrast,

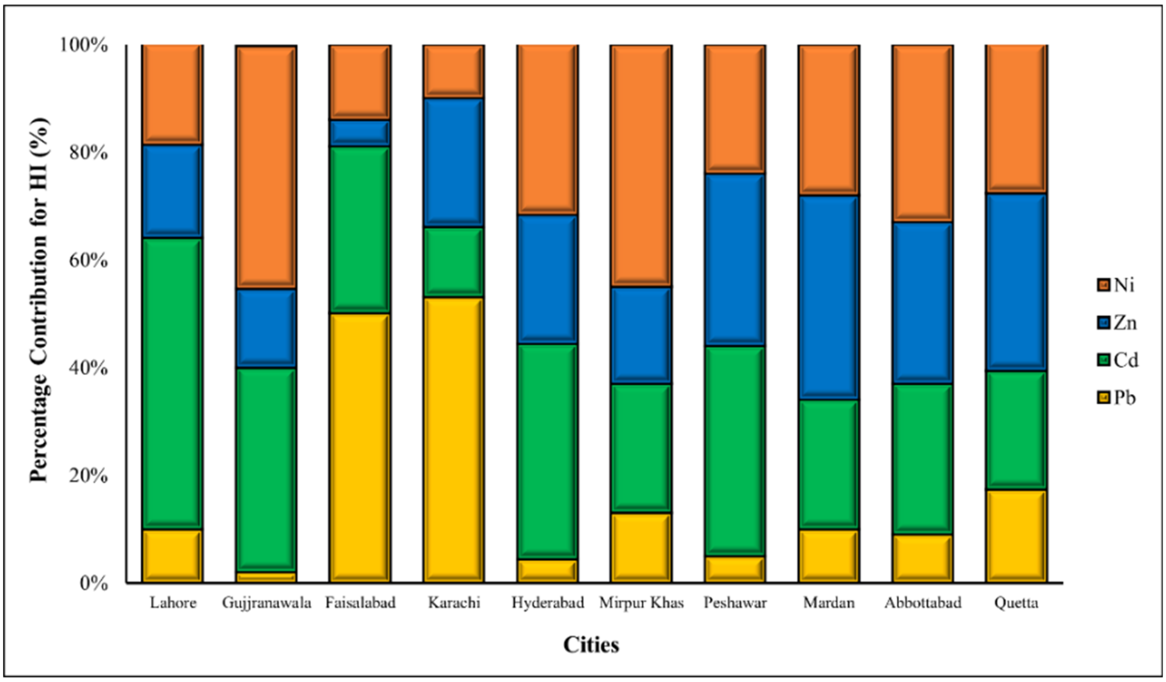

Fig. 4. Percentage Contribution of Health Index (HI) in selected cities of Pakistan to indicate the major contributor heavy metal in Urban Environmental Health Risk

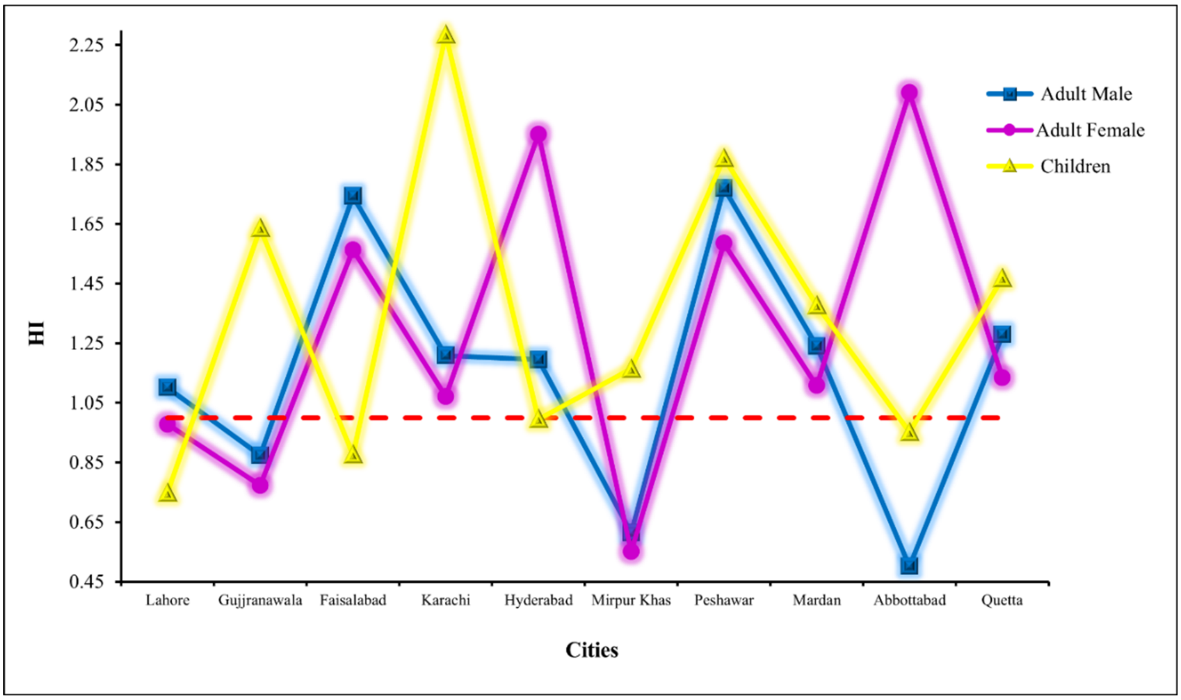

Fig. 5. Non-Carcinogenic Risk Assessment of $PM_{2.5}$-Bound Heavy Metals by Hazard Index (HI) Calculations for Exposed Groups in selected cities of Pakistan

exposed groups in other regions fall within the acceptable range of non-carcinogenic risk values.

The present study highlighted a concerning HI level, indicative of potential chronic health risks. Interestingly, these findings align with those of a study conducted by Pongpiachan et al. in 2017, which investigated metal concentrations in $PM_{2.5}$ in Bangkok. Pongpiachan's study concluded that the HI values for Cu, Zn, Cd, and Pb remained within safe ranges. Additionally, an investigation into $PM_{2.5}$-bound heavy metals within the urban area of Kitakyushu, Japan, reported an overall heavy metal concentration with a corresponding HI of 7.8. Remarkably, the primary contributor to this HI was inhalation, ingestion and dermal contact following closely, especially among adults. Present research study has determined that children are exposed to heavy metals through ingestion, inhalation, and dermal contact. This highlight the diverse pathways through which individuals may potentially come into contact with heavy metals present in $PM_{2.5}$. Furthermore, this study has introduced indices such as HI_{ing} (for inhalation), HI_{inh} (for ingestion), and HI_{der} (for dermal contact), shedding light on the predominant sources of exposure. Inhalation has emerged as the most prominent route, followed by ingestion and skin contact.

Additionally, a study conducted in Malaysia's Klang Valley by Hisamuddin et al. in 2020 unveiled that exposure to air pollution from urban traffic had genotoxic effects on children. These findings recommend the urgent need for long-term strategies aimed at reducing the levels of Cd and Pb in the urban dust. Promoting the use of electric vehicles, bicycles, and public transportation, as advocated by Pongpiachan et al. in 2017, represents a crucial step in this direction. Additionally, it is imperative to conduct further research into the sources of air pollution and implement measures to control them, including addressing issues such as open burning and the management of waste incineration facilities. Such multifaceted approaches are essential to safeguard public health and mitigate the adverse effects of air pollution.

In accordance with the 2021 classification of chemicals with established carcinogenicity by the International Agency for Research on Cancer (ILCR), it was determined that elements such as Pb, Cd, and Ni exhibit carcinogenic properties. The assessment of ILCR values was carried out using equation IV, with detailed results presented in the figure 6. Red line in the figure shows the high-risk threshold. The analysis revealed that children face higher ILCR

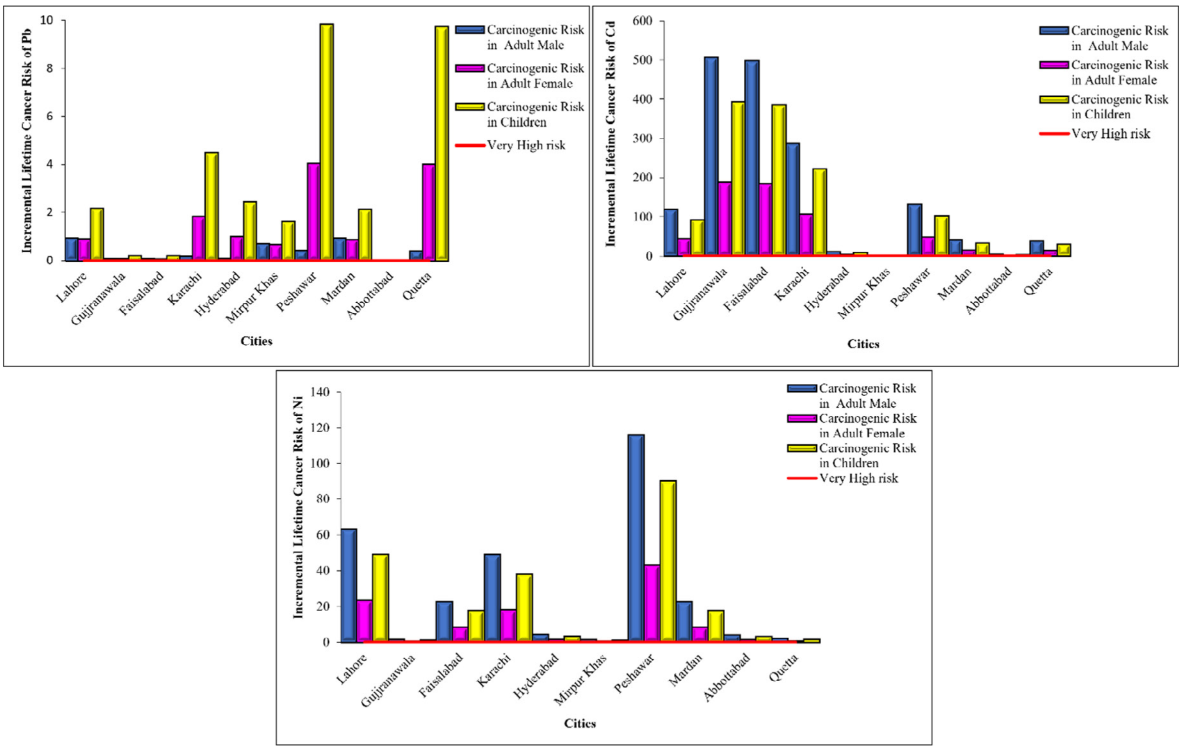

Fig. 6. Incremental lifetime cancer risk assessment of heavy metal in different age group of selected cities of Pakistan

Table 4. Comparison of $PM_{2.5}$ bound heavy metal concentrations in present and previous studies

Study	Country	City	Pb (ng/m^3)	Cd (ng/m^3)	Zn (ng/m^3)	Ni (ng/m^3)	References
Present	Pakistan	Lahore	3810	64	7290	28.7	Ahmad et al., 2021
		Gujranwala	98.9	339.8	94.3	8.35	Awan, 2013
		Faisalabad	88.6	11.4	25.5	110	Awan, 2013
		Karachi	1250	185	350	30	Javed, 2015 Khan et al., 2019; Moryani et al.,2020
		Hyderabad	102	7.2	95	21.7	Shahid et al., 2016
		Mirpur Khas	680	0.11	37.7	7.05	Asian Development Bank, 2025
		Peshawar	563	22.7	4720	720	Ahmad et al., 2021
		Mardan	900	27	112	110	Subhanullah et al., 2022
		Abbottabad	20	3	30	20	Yousaf et al., 2022
		Quetta	405	25	101	10.8	Khalid, 2019
Previous	China	Wuhan	615	12	863	12	Cheng et al 2017
		Bejing	340	9	780	7	
		Shanghai	224	/	398	11	
		Chongqing	37.9	/	94.2	1.39	Han et al 2021
		Chengdu	320	9.5	/	5.1	Li et al 2015
		Taiyuan	73.41	0.87	195.5	14.17	Liu et al., 2020
		Xian	159	3.3	1264.8	21.5	Liu et al., 2018
	Spain	Tarragona	671	8	35	4	Moreno et al., 2006
	Saudi Arabia	Jeddah	98	98	77	11	Khodeir et al 2012
	India	Dhanbad	150	60	680	10	Dubey et al., 2012
	Vietnam	Hanoi	/	/	16.3	/	Nguyen et al., 2022
	Thailand	Bangna	7	1.2	35.4	85.8	Ahmad et al., 2022
	Japan	Kitakyushu	10.5	/	29.5	3.3	Zhang et al., 2021
WHO			500	5	500	25	

values compared to adults, with female adults exhibiting higher ILCR levels than the male adults. Specifically, the average ILCR values for $PM_{2.5}$-bound heavy metals among children are as follows: 3.29×10^{-0} (Pb), 2.0×10^{-0} (Ni), and 1.27×10^{-2} (Cd). For female adults, ILCR values are as follows: 6.08×10^{-1} (Cd), 1.36×10^{-0} (Pb), and 1.07×10^{-0} (Ni). Among male adults, the ranking stands 3.94×10^{-1} for Pb, 2.88×10^{-0} for Ni, and 1.64×10^{-2} for Cd. Notably, the average ILCR value for $PM_{2.5}$-bound Pb among children reaches 2.16×10^{-0}, indicating a significantly high level of risk. Moreover, the ILCR values linked to other heavy metals for all three exposed groups consistently fall within the unacceptable range, signifying a heightened risk level with potential carcinogenic implications. Based on these findings, it becomes evident that $PM_{2.5}$-bound Cd poses a substantial carcinogenic risk to all three groups across all selected cities in Pakistan, except for Mirpur Khas and Abbottabad. Additionally, $PM_{2.5}$-bound Ni presents a significant carcinogenic threat to all three exposed groups in most of the cities, demanding immediate and critical attention, with exceptions being Gujranwala, Mirpur Khas, and Quetta. These exceptions highlight the gravity of the situation in such areas and the urgency of addressing the associated risks.

Li et al. (2022) conducted a study in China and found that children faced a significantly greater risk associated with $PM_{2.5}$-bound heavy metals compared to adults. Findings also shed light on the heightened vulnerability of children to the adverse effects of fine particulate matter. Li et al. (2022) revealed that the concentration of $PM_{2.5}$-bound heavy metals in the atmosphere poses a considerably greater health risk to children as compared with the adults. This observation underscores the critical importance of recognizing and addressing the heightened vulnerability of children to environmental pollutants. Children's susceptibility is often increased due to different factors including their ongoing development of respiratory and immune systems. Higher respiratory rates and increased outdoor activities can result in greater exposure to airborne pollutants. Additionally, their smaller body size and lower weight can lead to higher pollutant doses relative to their body weight, further magnifying their risk.

This revelation underscores the pressing necessity for customized policies and interventions designed specifically to protect children from the detrimental health effects arising from $PM_{2.5}$-bound heavy metals. It underscores the crucial importance of monitoring and reducing these pollutants in areas where children are exposed, such as schools and residential neighborhoods, with the aim of preserving the health and well-being of the younger population.

Table 4 presents a comparison of heavy metals in $PM_{2.5}$ of the findings of the present study regarding with data from various other countries, including China and other nations. Results were also compared with established guidelines for specific metals. Significantly exceeding the recommended limits, the levels of Pb, Cd, Zn, and Ni in industrialized nations are notably high. Furthermore, levels of heavy metals in China, Spain, India, and Pakistan exceed the WHO guidelines. This observation emphasizes the crucial need to address and mitigate the elevated levels of heavy metals in $PM_{2.5}$, both on a global scale and in these particular regions, in order to protect public health and environmental quality.

CONCLUSION

The objective of this study was to conduct a comprehensive assessment of $PM_{2.5}$-bound heavy metal pollution in ten major cities of Pakistan over a decade, spanning from 2013 to 2023. The investigation specifically focused on critical heavy metals (Pb, Cd, Zn, and Ni). In addition to pollution profiling, this study employed the USEPA human health risk assessment framework to quantify risks to the population, encompassing both carcinogenic and non-carcinogenic factors. Among the cities studied, Karachi, Lahore, Gujranwala, Faisalabad, Peshawar, and Mardan emerged as the most severely affected by $PM_{2.5}$-bound heavy metal pollution. The research revealed that children faced a higher risk of experiencing significant health issues due to $PM_{2.5}$-bound heavy metal pollution. Heavy metal pollutants had varying contributions to the non-carcinogenic risk index, with Cd being the highest (31.3%), followed by Ni (27.8%), Zn (23.6%), and Pb (17.4%). Notably, $PM_{2.5}$-bound Cd, Zn, and Ni exposures for adults and children in multiple cities exceeded the threshold of 1, indicating a higher non-carcinogenic risk, particularly in children from Karachi due to PM2.5-bound Pb exposure. Heavy metal-induced non-carcinogenic risks vary for all study sites, with the highest Hazard Index (HI) observed in Faisalabad for male adults (1.74), Hyderabad for female adults (1.95), and Karachi for children (2.28). Notably, children experience the most significant comprehensive non-carcinogenic risk at 1.34, followed by females at 1.28, and male adults at 1.15. Average ILCR values for $PM_{2.5}$-bound heavy metals among children are as follows: 3.29×10^{-0} (Pb), 2.0×10^{-0} (Ni), and 1.27×10^{-2} (Cd). For female adults, ILCR values are as follows: 6.08×10^{-1} (Cd), 1.36×10^{-0} (Pb), and 1.07×10^{-0} (Ni). Among male adults, the ranking stands 3.94×10^{-1} for Pb, 2.88×10^{-0} for Ni, and 1.64×10^{-2} for Cd. Notably, the average ILCR value for $PM_{2.5}$-bound Pb among children reaches 2.16×10^{-0}, indicating a significantly high level of risk. Based on these findings, it is evident that urgent and coordinated efforts are essential to mitigate the future consequences of air pollution effectively. To achieve this, it is imperative to enhance public awareness and control the sources of generation of particulate matter, including construction activities, transportation sector and burning of crop residues and wastes. These comprehensive strategies represent crucial steps in safeguarding public health and the environment against the detrimental impacts of $PM_{2.5}$-bound heavy metal pollution.

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CONFLICT OF INTEREST

The authors declare that there is not any conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/ or falsification, double publication and/or submission, and redundancy has been completely observed by the authors.

LIFE SCIENCE REPORTING

No life science threat was practiced in this research.

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