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Health Risk Assessment of PM$_{10}$-Bound Heavy Metals in the Ambient Air of Gurugram Urban Area

Vandana Yadav and Vikram Mor†
Department of Environmental Science, School of Basic and Applied Sciences, SGT University, Gurugram, Haryana 122505, India
†Corresponding author: Vikram Mor; vikramseemla@gmail.com, vikram_fps@sgtuniversity.org

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ABSTRACT

Gurugram is a rapidly developing corporate and industrial hub facing severe air pollution. In this study, ambient particulate matter (PM$_{10}$)-bound heavy metals, their source apportionment, and potential human health risks were investigated in the urban area of Gurugram, Haryana. A total of 56 samples were collected using a respirable dust sampler (APM 460) with Whatman filter paper (EPM 2000) from October 2022 to April 2024, excluding the monsoon months. The annual average PM$_{10}$ concentration was 169.5 µg.m^{-3}, which is about 11 times higher than the WHO (2021) guidelines and 3 times higher than the NAAQS by CPCB. Seasonal variations were observed, with the highest PM$_{10}$ levels recorded during the post-monsoon season, followed by winter. Heavy metals (Cr, Mn, Ni, Pb, Cd, Cu, Fe) were analyzed using ICP-MS, with Fe (10.9 µg.m^{3-}) being the most abundant. Enrichment factor analysis revealed high Pb levels, indicating anthropogenic sources. Human health risk assessment revealed that the hazard index (HI) values exceeded the threshold limit (=1) for all three exposure pathways. This finding indicates that the population residing in the study area is prone to non-carcinogenic risks due to PM$_{10}$-bound heavy metals. Excess cancer risk (ECR) values for the HI were found to be above the safe limit (10^{-4} – 10^{-6}). Consequently, this suggests that exposure to PM$_{10}$ in the study area may lead to an elevated risk of developing cancer over a lifetime, thereby underscoring the potential public health threat posed by these heavy metals. The conclusions demonstrate that tougher measures and stronger efforts must be taken to tackle heavy metal pollutants and the risks they pose to health.

INTRODUCTION

Concern about urban air pollution is mainly due to excessive particulate matter (PM). Increased urbanization, industrial activities, and economic growth have led to rising global levels of air pollution (Shi et al. 2021, Jeong et al. 2022, Idah et al. 2019). Nearly half of the population in Asia (55%) lives in cities, and in most cities, air quality does not meet the standards set by the World Health Organization (WHO) (UN 2018). High PM$_{10}$ levels in India have led to a serious decline in air quality in that country (Gandhi et al. 2021, Kumar et al. 2019). Several studies have emphasized that Indian cities, such as Delhi, Kanpur, and Varanasi, consistently rank among the most polluted globally (Das et al. 2025, Guttikunda & Gurjar 2012, Pant et al. 2015); however, region-specific chemical and health risk assessments are limited. In addition, air pollution by particulate-bound heavy metals results from both urban growth and industrial activity. These heavy metals have the potential to biomagnify and accumulate in the food chain (Jia et al. 2022, Zhang et al. 2017). Therefore, owing to its negative impacts on human health, air pollution has become a major concern for environmentalists and policymakers (Moura et al. 2024, Sa'adeh et al. 2024). Previous investigations have reported elevated cancer and non-cancer risks associated with inhalation of PM-bound metals in several Indian urban centers, underscoring the need for localized studies (Singh et al. 2019, Kumar et al. 2023a, Liu & Chan 2022)

The long-term consequences of exposure to heavy metals bound to PM_{10} have attracted much attention recently. Although identifying the precise sources of PM is challenging, vehicles, industry, and the Earth's crust are thought to contribute to PM. Heavy metals in the air can greatly affect people's well-being and the rules set for health. Based on several studies, people might experience a mild increase in cardiovascular mortality after exposure to PM_{10} (Liu & Chan 2022, Araujo et al. 2009). Moreover, reports that describe health hazards linked to heavy metal exposure rarely detail the exact processes by which these health effects occur. There is also a scarcity of studies that combine source identification and risk characterization in rapidly developing cities, such as Gurugram.

The concentration of PM can vary significantly locally depending on temperature, relative humidity, wind speed, rainfall, and atmospheric stability (Smith et al. 2023, Johnson et al. 2020). Air movement can be controlled by considering wind direction and speed, which has a direct effect on the spread of PM (Gomez & Lee 2020, Harris et al. 2021). In addition, RH can affect changes in the environment over time and during the day and night periods, as well as pollution levels (Gomez & Lee 2020, Patel et al. 2022). Low-layer winds and stable conditions, accompanied by low wind speeds and less variation, are regularly linked to increased PM levels.

India must significantly improve its air quality because it is a developing nation. Because Gurugram produces a lot of pollution owing to its many vehicles, factories, and fast city growth, checking its air pollution is needed. It is difficult to cover the entire study area because of many different sources of air pollution. While earlier studies have focused on the Delhi-NCR (Banerjee et al. 2025, Rajesh et al. 2025, Tiwari et al. 2015), a targeted investigation of Gurugram's PM composition and health implications remains underexplored. Air quality analysis was conducted at one location to demonstrate how atmospheric PM_{10} levels affect the Gurugram District. The presence of heavy metals was detected using ICP-MS, and the quantity of PM_{10} was determined using gravimetric analysis. The U.S. Environmental Protection Agency (US-EPA) health risk assessment method was used to evaluate the possible risks to human health, and statistical techniques such as principal component analysis (PCA) and Pearson's correlation were used in SPSS 26 to identify the sources.

This study contributes to the limited literature on Gurugram by combining chemical speciation, multivariate statistical analysis, and health risk assessment in one framework. Efforts to curb particulate matter will play a key role in meeting sustainable development goals in cities and boosting public health. The results of this study will greatly advance our knowledge of the sources and distribution of heavy metals in the atmosphere. The findings will also provide important information for controlling air pollution and guaranteeing adherence to air quality standards. Overall, this study fills important gaps in current air pollution research in Indian urban areas by delivering localized and actionable insights. Research from this study could help officials understand the link between heavy metals and people's health and cancer.

MATERIALS AND METHODS

Description of Study Site

Gurugram, a rapidly developing city in the Indian state of Haryana, is situated southwest of New Delhi (Fig. 1). The sampling site coordinates are latitude: 28.4750°N and longitude: 77.0104°E. Before the early 2000s, this place was just a tiny village; it has undergone a significant transformation since then because of economic growth and urbanization (Saxena 2019). The sampling site coordinates are Latitude: 28.4750°N and Longitude: 77.0104°E. Before the early 2000s, this place was just a tiny village; it has undergone a significant transformation since the early 2000s due to economic growth and urbanization (Saxena 2019). With a population exceeding 1.5 million, it is a significant financial and technology hub, hosting numerous multinational corporations, start-ups, and IT firms that contribute significantly to India's economy (Nasscom 2020, Census of India 2011). Due to its rapid growth, the city faces challenges of air pollution and associated human health risks.

PM_{10} Sampling

The site for collecting samples was selected as per IS 5182 Part-XIV and samples were collected every week, except during the monsoon season. Respectively, 56 PM10 samples were taken on Whatman filter paper (EPM 2000) with the help of a respirable dust sampler (APM 460 NL), as required by IS 5182 part-XXIII for 24 hours of complete run. Before sampling, filter papers were pre-conditioned by placing them in a desiccator at constant temperature (20–23°C) and relative humidity (40–50%) for 24 hours. After sampling, the filters were again conditioned under the same controlled conditions for another 24 h before weighing and weighed using an A&D GR-202 microbalance, which has a maximum difference of ±10 µg. PM_{10} was measured using Equation 1.

$$C\ PM_{10} = \frac{(Wf - Wi) \times 10^6}{V} \qquad \text{...(1)}$$

Sample Analysis

The samples were analyzed for heavy metals using

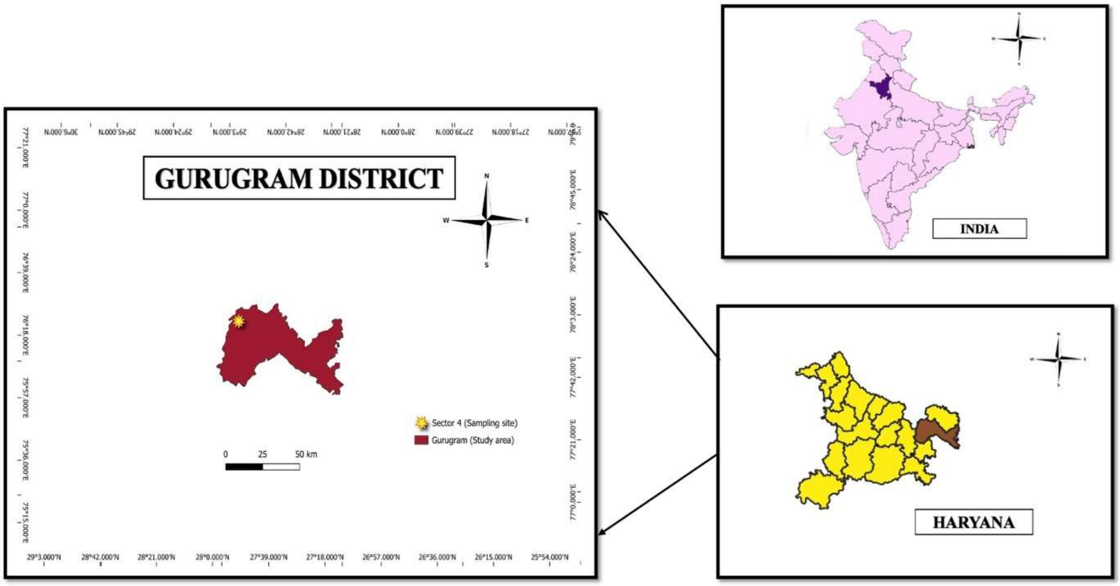

Fig. 1: Map of the study area and sampling site.

inductively coupled plasma mass spectrometry (Agilent ICP-MS 7800) following the guidelines of EPA Method 3050B. Filter papers were dried and subsequently placed in a container with 20 parts nitric acid and 2 parts perchloric acid. The digestates were then evaporated to 2–3 mL, and the solution was passed through a Whatman 42 filter. To obtain the final solution, 50 mL of double-distilled water was added. Blanks were also prepared using the same method to monitor background contamination. The ICP-MS instrument was calibrated using multi-element standard solutions at five concentration levels. The concentration of heavy metals in the filtrate was measured using Equation 2 (Sinha & Banerjee 1997):

$$C\left(\frac{\mu g}{m^3}\right) = \frac{Conc\ of\ the\ element\ in\ digested\ sample\ \left(\frac{\mu g}{mL}\right)}{Vol.\ of\ air\ sample\ (m3)} \times \frac{Total\ vol.\ of\ the\ sample\ (mL)}{\%\ of\ filter\ area\ used\ for\ analysis} \quad ...(2)$$

Source Apportionment

The sources of heavy metals were determined by computing the EF and performing PCA with varimax rotation combined with Kaiser normalization. The most accurate quantitative explanation of metals and their origins is obtained using PCA (Watson et al. 2022, Shah et al. 2006, Park & Kim 2005).

Principal Component Analysis

PCA was applied to identify potential sources of heavy metals in PM_{10} samples (Bui et al. 2022). This method combines correlated variables into new main components to simplify all the variables (Debnath et al. 2023). It provides the opportunity to understand how the measured variables are associated with the samples. The matrix for atmospheric analysis was constructed using Varimax rotation. When the matrix is rotated, each element in PM_{10} is separated into different parts, indicating that these substances may have different origins. The analysis was performed in IBM SPSS Statistics for Windows, version 26.0.0.1 (IBM, Armonk, NY, USA).

Enrichment Factor Analysis

The EF provides insights into whether an element is from geogenic or anthropogenic sources. Rahn (1971) first proposed this theory to calculate the contribution of human activity to the total concentration of elements in the atmosphere (Tripathee et al. 2019, Rovira et al. 2011, Feng et al. 2009). The value is obtained by dividing the concentration of the element of interest by the chosen reference element of known crustal origin and comparing it to the average ratio observed in the Earth's crust. Iron (Fe), aluminum (Al), and silicon (Si) are typically used as reference elements. Because iron has a significantly higher natural concentration than any of the other elements, it was chosen as the reference element for this study (Wedepohl 1995). Using Equation (3), the enrichment was determined as follows:

$$EF(x) = \frac{\left(\frac{X}{F}\right) Sample}{\left(\frac{X}{F}\right) Crust} \quad ...(3)$$

X and F represent the concentrations of the target and reference elements, respectively. Lide (2008) used the CRC Handbook of Chemistry and Physics to determine the standard percentage of the elements studied in the Earth's crust. Elements with EFs between 1 and 5 are thought to have contributions from two crustal and anthropogenic sources, whereas those with EFs near unity indicate a crustal origin. Anthropogenic emissions are the main source of heavy metals with an EF higher than 5.0 (Hsu et al. 2010).

Health Risk Assessment Model

Exposure Dose

In this study, the U.S. Environmental Protection Agency (EPA) model was used to determine people's exposure to airborne heavy metals. The main methods used to determine exposure to each element are (a) ingestion of airborne particulates through deposition, (b) inhalation through the nose and mouth, and (c) dermal absorption of heavy metals from particulates adhering to the exposed skin (Li et al. 2016, Hu et al. 2012). For CDI, EC, and DAD, we calculated using the Supplemental Guidance for Inhalation (Part F), Supplemental Guidance for Dermal (Part E), and Human Health Evaluation Manual (Part A), and applied their respective equations (Equations 4–6) (US EPA 1989, 2004, 2009):

$$CDI = \frac{C \times R_{ing} \times CF \times EF \times ED}{BW \times AT} \quad ...(4)$$

$$EC = \frac{C \times ET \times EF \times ED}{AT} \quad ...(5)$$

$$DAD = \frac{C \times SA \times AF \times EV \times ABS \times CF \times EF \times ED}{BW \times AT} \quad ...(6)$$

C denotes the number of elements found in $PM_{10,}$ which is given as the average yearly concentration (in mg.kg^{-1} for CDI and DAD or µg.m^{3-} for EC) in this study.

Non-Carcinogenic Health Risk

Once the values for CDI, EC, and DAD are obtained, the next step is to use a hazard quotient (HQ) and hazard index to assess the non-carcinogenic health risk. The HQ for ingestion, inhalation, and dermal contact was calculated using Equation (7).

$$HQ = \frac{CDI}{RFD_O} = \frac{EC}{(RFC_i \times 1000 \frac{\mu g}{m^3})} = \frac{DAD}{(RFD_O \times GIABS)} \quad ...(7)$$

RfCi is the inhalation reference concentration in mg per cubic meter per day, RfDo is the oral reference dose in mg per kilogram per day, and GIABS is the gastrointestinal absorption factor. The U.S. EPA (2016) provided regional screening-level tables from which the RfDo, RfCi, and GIABS values were derived.

If CDI, EC, and DAD are < the cut-off value, there are no negative health effects. HQ>1 (when CDI, EC, and DAD exceed the threshold dose/concentration) suggests that exposure might be harmful (US EPA 1989).

Additionally, assessing the hazard potential of single elements at a time may significantly underestimate the risks of simultaneous exposure to multiple elements. To evaluate the risk of mixed exposures, the HQs of the individual components should be summed to create a hazard index (HI) (Equation (8)). For different chemical exposures, the HI is the sum of several HQs.

$$HI = \sum_{i=1}^{n} HQ1 + HQ2 + ... + HQi \quad ...(8)$$

where HQi is the hazard quotient for the ith element. If HI equals or falls below 1, the chances of non-carcinogenic effects are considered low; conversely, if HI is above 1, such risks are likely and increase with increasing HI (Zheng et al. 2010, US EPA 1989).

Excess Cancer Risk

The evaluation of ECRs is based on the increased risk of cancer development in an individual's lifetime because of exposure to carcinogens. ECR was computed using Equation (9) (Hu et al. 2012, US EPA 2011, 2016).

$$ECR = \frac{C \times ET \times EF \times ED \times IUR}{AT} \quad ...(9)$$

The variable C represents the annual average of heavy metals (µg.m^{3-}), AT is the average lifetime of carcinogens (70 years × 365 days/year × 24 h/day), IUR is the amount needed for inhalation risk (mg.m-^{3})$^{-1}$, ET is the number of hours of exposure per day, and the other parameters are defined as above. When the ECR is between 10^{-6} and 10^{-4}, it indicates that any resulting cancer risk from contamination is minimal (Hu et al. 2012, US EPA 1989).

RESULTS AND DISCUSSION

PM_{10} Concentration and Meteorological Parameters

The average annual concentration of PM_{10} was 176 µg.m^{3-} in 2022–2023 and 163.4 µg.m^{3-} in 2023–2024. These levels were approximately three times higher than the national ambient air quality standard (60 µg.m^{3-}) set by the Central Pollution Control Board (CPCB) of India (NAAQS 2009) and approximately 11 times higher than the World Health Organization's (WHO 2021) annual PM_{10} air quality guideline of 15 µg.m^{3-}. During October and November, the level of PM_{10} in the air often increases because of crop residue fires and cooler temperatures that reduce air movement (as shown in Fig. 2a). In addition, celebrations such as Diwali and Dussehra cause the atmosphere to become more polluted, as many firecrackers and activities discharge a large amount of particulate matter into the air (Bisth et al. 2023).

The study was categorized into three meteorological seasons to assess seasonal variations: post-monsoon (October and November), winter (December, January, and February), and summer (March and April). The highest pollution levels could be seen when the country was experiencing the post-monsoon period and the winter season, as Fig. 2a depicts in (Fig. 2b). From Table 1, it can be seen that the average PM_{10} mass concentration in this study was higher than that found in Beijing, Kanpur, and Mumbai (Chen et al. 2023, Patel et al. 2022, Ahmad et al. 2024). However, the values found here were lower than the results from similar studies in Delhi, Kolkata, Cairo, Lagos, and Lucknow (Chaudhary et al. 2022, Sharma et al. 2023, Taha et al. 2022, Owoade et al. 2021, Patel et al. 2022).

Throughout the study period, a statistically significant correlation (r=0.27) was observed between PM_{10} concentration and temperature (Fig. 3a). Rising temperatures cause the earth's surface to dry, which results in dust and debris rising with the right wind and disruption, ultimately increasing the PM10 level. Hotter temperatures facilitate air movement and dispersion, which is beneficial for gas dispersion. Similar trends have been observed in several parts of the world. El-Sharkawy & Zaki (2015) established that there is a positive correlation between temperature and PM_{10} in the eastern province of Saudi Arabia. Tai et al. (2012) noticed that there is a positive connection between PM_{10} and temperature in the United States. Similarly, Munir et al. (2014) discovered that an increase in temperature was linked to higher levels of PM_{10} in Makah, Saudi Arabia. Sirithian et al. (2011) discovered that the relationship between PM_{10} and temperature was also positive (r = 0.528) in Thailand. These findings demonstrate that temperature is related to PM10 levels, especially in different climatic zones.

The level of mass concentration for PM is significantly affected by wind speed. During the study period, PM_{10} and WS recorded a correlation coefficient of -0.83 and had a negative relationship. As WS increases, pollutants spread across the sky, which thins out the PM layer and reduces its concentration (Ravindra et al. 2008). The current study found that the negative relationship between WS and PM mass concentration resembled what other studies have shown. In Patras, Karagiannidis et al. (2017) stated that higher PM10 levels were associated with a drop in WS; however, Li et al. (2016) mentioned in their study of the Sichuan Basin metropolis that the correlation was only moderately negative. In the study by Kliengchuay et al. (2019) conducted in Lamphun, Thailand, the researchers noted that PM_{10} and wind speed were weakly negatively correlated (r = -0.14).

PM_{10} concentrations were positively correlated (r = 0.41) with relative humidity (Fig. 3c). Lou et al. (2017) explained that there was a positive association between PM_{10} and relative humidity (r = – 0.41) in China and Gupta et al. (2019) reported a similar result in Bangladesh. However, various studies have noted a negative association between PM_{10} and relative humidity (Pateraki et al. 2012, Munir et al. 2014, Kliengchuay et al. 2019).

Heavy Metals Concentration

The pollution load of heavy metals showed strong seasonal variations, as shown in Fig. 4. Table 2 presents the descriptive statistics of heavy metals for both years. The average amount of heavy metal in PM_{10} was the highest during the post-monsoon season, supporting the results reported by Prodi et al. (2009). However, metals, such as copper (Cu), cadmium

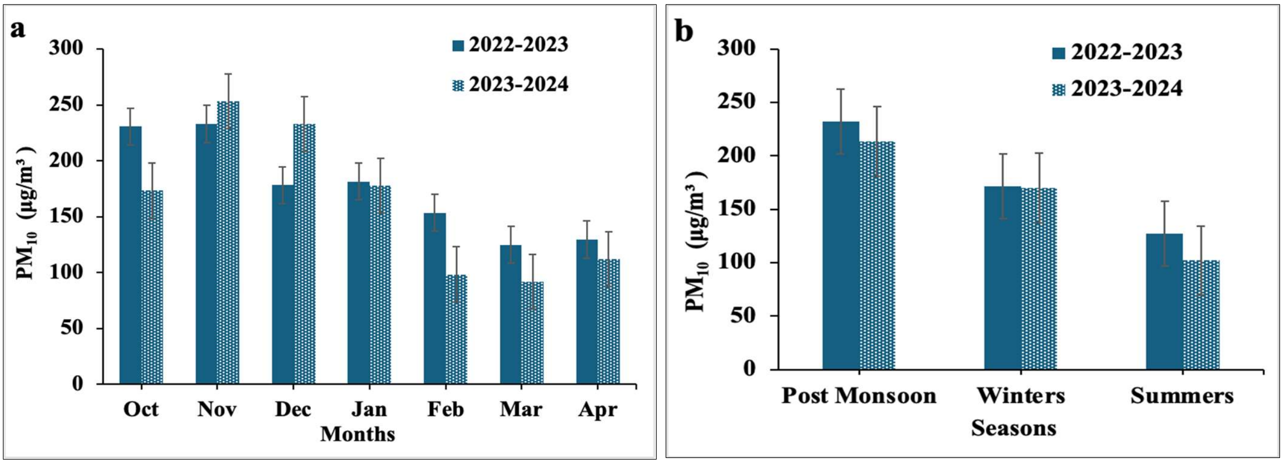

Fig. 2: Temporal variations in the average PM_{10} concentration ($\mu g.m^{-3}$) (a) on a monthly and (b) seasonal basis.

Table 1: Annual average PM_{10} concentrations at different urban sites.

LOCATIONS	PM_{10} [µg.m^{-3}]	REFERENCES
Delhi	250	Chaudhary et al. (2022)
Kolkata	220	Sharma et al. (2023)
Cairo	200	Taha et al. (2022)
Lagos	180	Owoade et al. (2021)
Mumbai	128	Ahmad et al. (2024)
Kanpur	166	Patel et al. (2022)
Beijing	150	Chen et al. (2023)
Lucknow	220	Patel et al. (2022)

(Cd), and lead (Pb), exhibited the highest concentrations during winter in 2023–2024. Seasons have an important effect on heavy metal levels, and this is mostly due to the reduced dispersion of atmospheric gases, reduced rainfall, emissions from cars and factories, and wood burning (Khare & Baruah 2010).

In both years, the highest average concentration of heavy metals was Fe (10.91 µg.m^{3-}), followed by Mn (0.28 µg.m^{3-}). The overall trend in heavy metal content followed the order Fe > Mn > Pb > Cr > Ni > Cu > Cd, consistent with previous studies reporting Fe as the dominant heavy metal in PM_{10} (Kumari et al. 2023b, Truong et al. 2022, De Gennaro et al. 2018). The main sources of Ni and Pb in the atmosphere are tire wear and oil burning, but Fe mainly comes from natural sources, such as windblown dust and dust generated by cars and trucks (Kurosaki et al. 2019, Sahu et al. 2021). All heavy metal concentrations were corrected for blank filter values prior to analysis to ensure the accuracy and reliability of the reported data. These findings, with ramifications for public health and air quality management, highlight the intricate interactions between natural and human activities that determine seasonal variations in the concentration of heavy metals in PM_{10}. Furthermore, the studies by Hossain et al. (2022) and Malek et al. (2021) lend credence to the idea that human activity has a major impact on the elevated concentrations of some metals, especially in urban areas. Because heavy metals are present in many ways, pollution control strategies should be implemented to reduce the risk of exposure.

Source Apportionment

Possible sources of PM10-associated heavy metals were

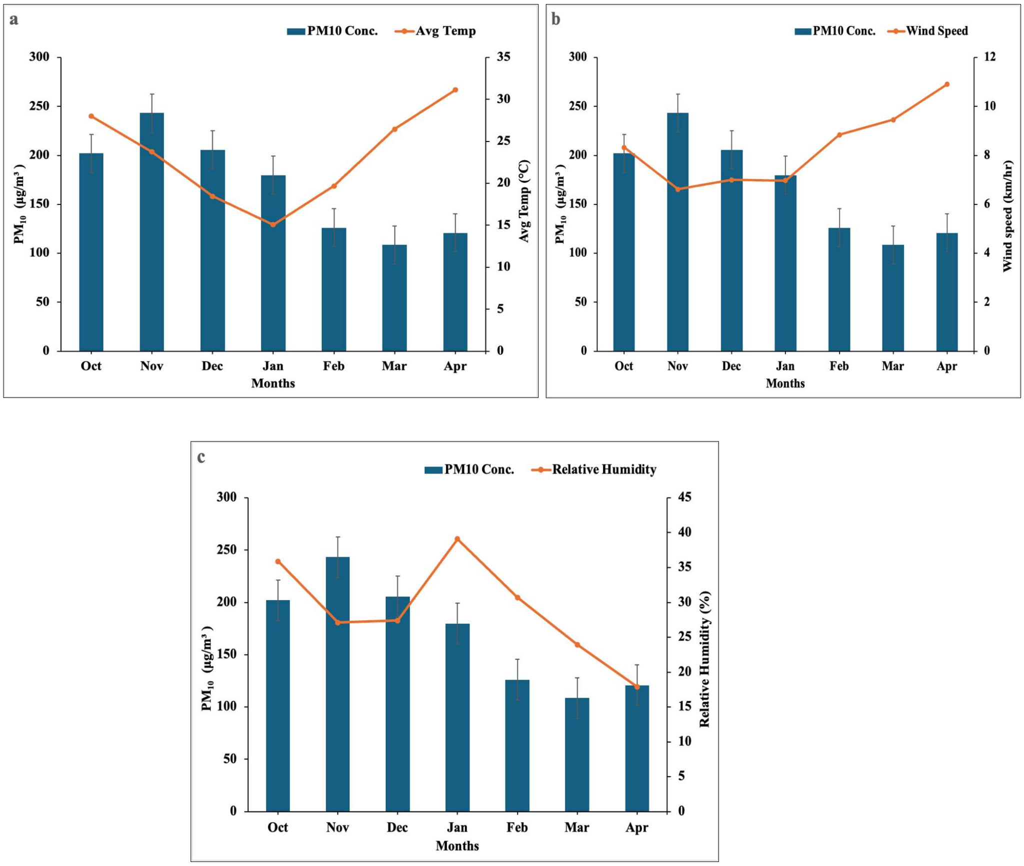

Fig. 3: Relationship between PM_{10} and meteorological parameters (a) average temperature, (b) wind speed, and (c) relative humidity.

Table 2: Descriptive statistics of heavy metals for both years.

Heavy metals	Range		Mean		Median	
	2022-23	2023-24	2022-23	2023-24	2022-23	2023-24
Pb	0.027 - 0.416	0.031 - 0.314	0.151	0.135	0.157	0.133
Cr	0.071 - 0.271	0.012 - 0.312	0.150	0.128	0.149	0.134
Ni	0.003 - 0.591	0.004 - 0.113	0.074	0.036	0.059	0.032
Cu	0.005 - 0.047	0.004 - 0.042	0.015	0.016	0.014	0.015
Cd	0.003 - 0.201	0.005 - 0.106	0.031	0.022	0.012	0.011
Mn	0.151 - 0.567	0.019 - 0.465	0.258	0.240	0.265	0.262
Fe	5.024 -18.328	5.273 -16.93	9.5125	9.473	9.445	10.450

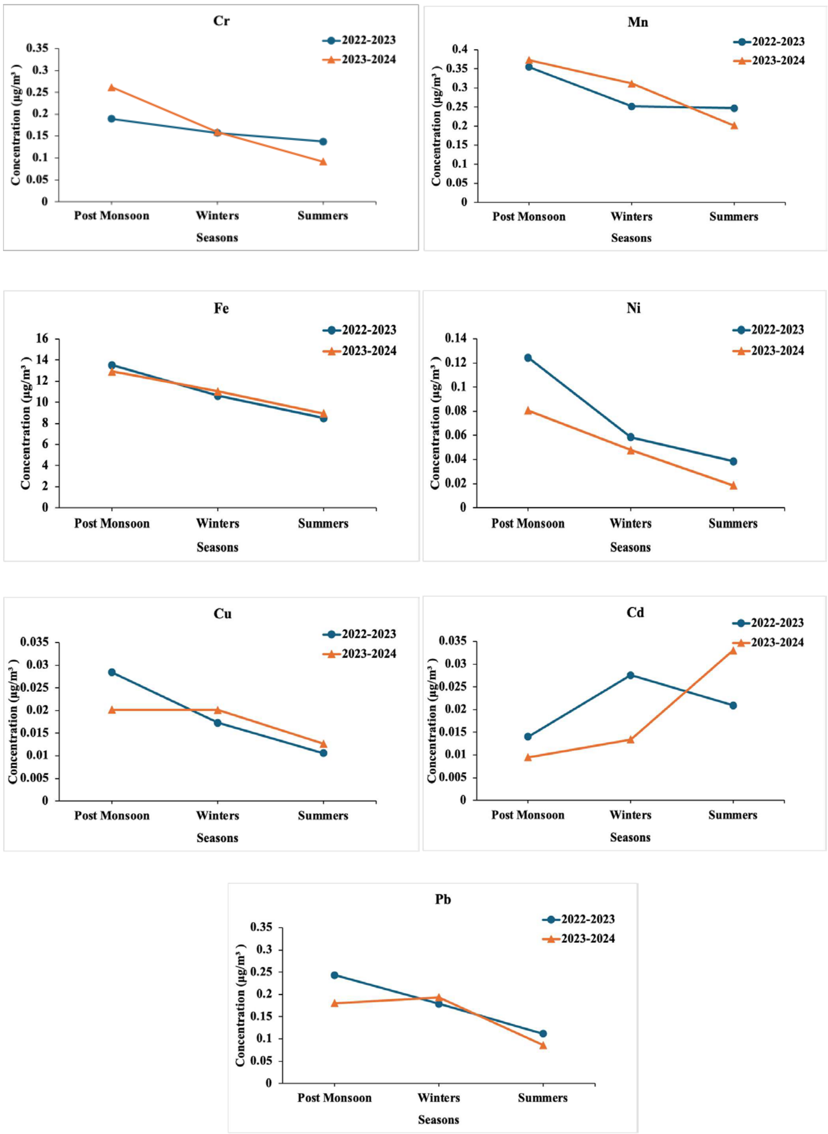

Fig. 4: Seasonal trends of average heavy metal concentration (µg.m^{-3}).

identified based on the results of Pearson correlation analysis, PCA with varimax rotation, and the EN factor.

Principal Component Analysis

The principal component (PC) loadings for the combined heavy metal data for both years, along with their related eigenvalues and variances, are presented in Table 3. Three PCs with extracted eigenvalues greater than 1.0 explained 54.73%, 72.66%, and 89.7% of the variance overall, respectively. With a total data variance of 54.73%, PC1 shows significant loadings of lead (Pb), manganese (Mn), iron (Fe), and cadmium (Cd). The resuspension of road dust brought on by vehicle traffic and non-exhaust emissions may be the source of these heavy metals, including iron (Fe), found in both brake pads and other mechanical parts of the engine (Roy et al. 2020, Chakraborty & Gupta 2009). Hence, this component is labeled as the Vehicular and Road Dust Source**.**

The second factor (PC2) accounted for 17.92% of the total variation and 72.66% of the cumulative variation, with substantial cadmium (Cd), lead (Pb), and chromium (Cr) loadings. Generally, Cr and Cd are pollutants at the end because of burning crude oil and operating metal factories across the region (Querol et al. 2007). Geogenic dust and construction waste are two other possible sources (Cheng et al. 2018). Vehicle exhaust emissions are linked to high loadings of Ni and Pb (Shah et al. 2006). Thus, this factor was labeled as Industrial and Combustion Source**.**

PC3 accounted for 17.04% of the variance and 89.7% of the cumulative variance, with substantial loadings for chromium (Cr), nickel (Ni), and lead (Pb). Chromium and nickel are found in automotive exhaust (Guo et al. 2019). Chromium is mainly caused by engine wear, as chromium (Cr) is a component of the engine (Jeong et al. 2022, Pandey et al. 2014).

Principal component analysis of PM revealed that motor vehicles, commercial activities, resuspension of road dust, and industrial emissions were the primary sources of the selected heavy metals in the study area. Therefore, PC3 was interpreted as a mixed vehicular and industrial emission source**.**

Correlation Matrix

Another statistical method**,** Pearson's correlation analysis, was used to investigate the relationships among all heavy metal concentrations and to create an overall profile of the sources, as elements with high correlations are likely to come from the same source (Javed et al. 2015). Pearson correlation matrix, showing correlation coefficient (r) values for each pair of heavy metals, is presented in Table 4. Iron (Fe), manganese (Mn), and chromium (Cr) were found to be moderately correlated, particularly Fe–Mn (r = 0.770) and Fe–Cr (r = 0.699). These elements belong to the lithophilic group; therefore, they are significantly present in the Earth's crust (White 2013). Wind-blown dust is most likely the source of these components. Another correlation observed between Fe and Pb was 0.841, and between Fe and Cu was 0.808. Additionally, the correlations between Ni–Mn (r = 0.438) and Cr–Pb (r = 0.744) were statistically significant. Generally, human activities, such as coal combustion (Cr, Pb), metal corrosion (Cu, Cd), and vehicle emissions, introduce these elements (Tchounwou et al. 2012). Meanwhile, weak or inconsistent correlations involving Cd and Ni suggest that these may arise from more diverse and isolated anthropogenic sources, such as industrial processes, localized combustion, or use in alloys and lubricants, resulting in less consistent spatial co-distribution. These patterns reflect how different emission sources (natural dust, traffic-related abrasion, fuel combustion, and industrial processes) influence metal concentrations differently across space and time.

Table 3: Principal component loadings of the heavy metals for the study area.

Heavy metals	Component		
	PC1	PC2	PC3
Fe	0.845	0.273	0.168
Pb	0.889	0.260	0.211
Cd	0.089	0.012	0.977
Ni	0.310	0.945	0.009
Cu	0.774	0.395	0.375
Cr	0.872	0.216	0.145
Mn	0.930	0.129	0.061
EigenValues	3.832	1.254	1.193
% of Variance	54.743	17.920	17.043
Cumulative %	54.743	72.663	89.706

The results showed that the most important elements in this assessment were iron (Fe), manganese (Mn), chromium (Cr), nickel (Ni), and lead (Pb). The main causes of lead pollution are lead batteries, lead used in cars, and lead-based paints for various items (Lim et al. 2012, Mishra et al. 2005, Roy et al. 2020). During abrasions caused by construction work and various auto parts, paint can release lead and cadmium, toxic metals (Gupta et al. 2021). Cadmium (Cd) compounds are used as antioxidants in lubricants and in the alloys of batteries and carburetors for cars (Khan et al. 2019). Thus, the principal sources of heavy metals in the study area were road dust resuspension, automotive emissions (both exhaust and non-exhaust), and industrial emissions.

Enrichment Factor Analysis

The calculated EFs for the seven heavy metals are shown in Fig. 5. The other elements in this report were found to be strongly linked with iron (Fe); therefore, it was chosen as the reference. The elements were classified into two groups based on their EFs: highly and mildly enriched. The computed EF value for lead (Pb) was significantly high (62.3), indicating that it is derived from anthropogenic sources. The observed EFs of Cd (2.4), Ni (1.7), Cr (2.3), Mn (1.5), and Cu (1.3) were less than five, indicating anthropogenic and crustal origins. To support the results that anthropogenic sources were the primary contributors of these heavy metals, this clearly indicates that anthropogenic sources, such as traffic emissions, brake and tire wear, fossil fuel combustion, industrial emissions, and recycling factories (such as rubber, plastics, powder, and oil), were likely the most significant sources.

Furthermore, several studies have reported similar findings regarding the contribution of anthropogenic activities to the enrichment of heavy metals in urban air. Kumar et al. (2023a, 2023b) linked urban traffic emissions, especially diesel engine exhaust, to the elevated levels of lead (Pb) and cadmium (Cd) in PM_{10}. Similarly, Smith et al. (2023) reported that metal smelting and waste incineration are major industrial sources of nickel (Ni) and copper (Cu) in urban air. These findings corroborate the contribution of anthropogenic sources to PM10-associated heavy metal pollution. Based on the enrichment analysis, targeted interventions are needed in Gurugram to mitigate anthropogenic emissions. These include strengthening vehicle emission regulations**,** monitoring and regulating small-scale industries, and establishing real-time air quality monitoring stations near traffic and industrial hotspots to track heavy metal concentrations.

Health Risk Assessment

Non-Carcinogenic Health Risk of Heavy Metals Via Inhalation Exposure

Inhalation exposure is generally the primary direct contact route with particulate-bound heavy metals (US EPA 1989). This study could not determine the hazard quotients (HQ) and hazard indices (HI) for iron (Fe) and manganese (Mn) because the necessary reference values are not available for these metals. This is because these elements are fundamental to humans, and the reference doses could be above the amounts found (Izhar et al. 2016). However, it is important to note that the exclusion of Fe and Mn from the

Table 4: Correlation matrix for heavy metals in $PM_{10.}$

	Fe	Pb	Cd	Ni	Cu	Cr	Mn
Fe	1.000						
Pb	0.841	1.000					
Cd	0.214	0.259	1.000				
Ni	0.505	0.513	0.064	1.000			
Cu	0.808	0.882	0.397	0.589	1.000		
Cr	0.699	0.744	0.006	0.490	0.665	1.000	
Mn	0.770	0.842	0.163	0.438	0.764	0.812	1.000

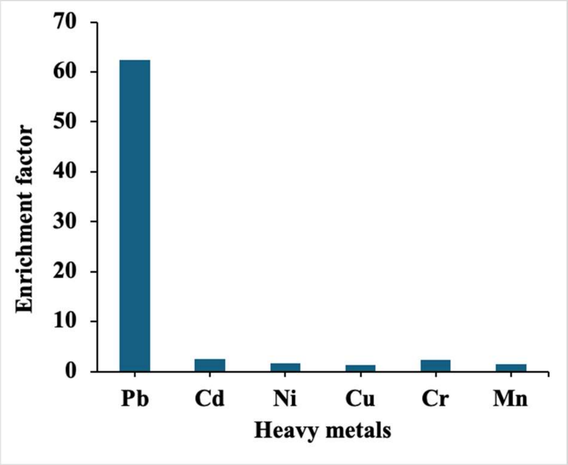

Fig. 5: Enrichment Factor values for heavy metals in PM_{10} in the study area.

risk assessment could lead to an underestimation of the total non-carcinogenic risk**,** especially for Mn**,** which has been documented to cause neurological effects at high inhalation exposures (e.g., cognitive and motor impairments). In urban environments with elevated Mn levels from vehicular or industrial sources, chronic exposure may pose a concern for vulnerable populations**.**

Hazard Quotient (HQ) and Hazard Index (HI) for inhalation are shown in Table 5. Owing to heavy metal ingestion, the values of HQs were higher than the threshold values (=1) for all except copper (Cu) in adults. HI values for children and adults were 5.05E+02 and 5.41E+01, respectively; thus, the results indicated a potential health risk owing to exposure to different elements. The data clearly indicate that people in the study area face non-carcinogenic risks because of PM_{10} containing heavy metals.

Non-Carcinogenic Health Risk of Heavy Metals Via Ingestion Exposure

Ingestion of airborne particles may occur when they are deposited on food, beverages, or surfaces in both indoor and outdoor areas. Particles can be transferred directly to the mouth by hands or indirectly via objects touched by hands (Hu et al. 2012). The findings for HQ and HI are shared in Table 6. The HQ values were higher than the safe level (=1) for Pb and Cr and lower than the safe limit for Ni, Cu, and Cd; however, the HI (1.41 E +02) was higher than the safe limit (=1), indicating adverse health effects from exposure to a mixture of elements for children and adults. Recent research has revealed that places near busy roads tend to experience higher amounts of heavy metals attached to particles, which can result in more non-cancerous health problems from eating or drinking them (Singh et al. 2019). In addition, research suggests that children are at greater risk of health problems caused by PM_{10} exposure because of their tendency to consume a large amount of dust and soil particles (Liu et al. 2022).

Non-Carcinogenic Health Risk of Heavy Metals Via Dermal Exposure

Hazard Quotients (HQ) via dermal contact are presented in Table 7. Except for copper (Cu), all HQ values were higher than the safe dose (=1). Additionally, the risk from various elements was summarized through the hazard index (HI), the values of which were also higher than the safe threshold (=1). This indicates that the residents in the area might face significant health issues due to these heavy metals.

Table 5: Hazard Quotient and Hazard Index for inhalation exposure.

Heavy metals	HQinh	
	Children	Adult
Pb	1.93E+02	2.07E+01
Cr	2.20E+02	2.36E+01
Ni	1.20E+01	1.29E+00
Cu	1.83E+00	1.96E-01
Cd	7.76E+01	8.31E+00
Hazard Index	5.05E+02	5.41E+01

Table 6: Hazard Quotient and Hazard Index for ingestion exposure.

Heavy metals	HQing	
	Children	Adult
Pb	1.15E+00	1.15E+00
Cr	1.38E+02	1.38E+02
Ni	4.11E-01	4.11E-01
Cu	1.09E-02	1.09E-02
Cd	4.65E-01	4.65E-01
Hazard Index	1.41E+02	1.41E+02

Table 7: Hazard Quotient and Hazard Index for dermal exposure.

Heavy metals	HQderm	
	Children	Adult
Pb	1.81E+00	2.76E+00
Cr	1.58E+02	2.41E+02
Ni	2.81E+00	4.29E+00
Cu	1.71E-02	2.61E-02
Cd	2.90E+01	4.42E+01
Hazard Index	1.92E+02	2.92E+02

The results of numerous studies that evaluated the risk of heavy metals in industrial and urban settings are in line with the current investigation. For instance, studies by Zhang et al. (2017) and Kumar et al. (2023a, 2023b) demonstrated that children may be especially at risk if they are exposed to Pb, As, and Cd from PM. Exposure to air pollution was found to occur mostly through the skin in places with high levels of PM_{10}, despite the fact that ingestion can lead to a much higher risk.

Carcinogenic Health Risk Assessment

Four metals–chromium (Cr), cadmium (Cd), nickel (Ni), and lead (Pb)–were selected for risk assessment studies on cancer because they are known to be either carcinogenic or likely to cause cancer by the International Agency for Research on Cancer (IARC). In particular, lead substances belong to Group 2A and are described as likely carcinogenic to humans, whereas nickel, cadmium, and chromium are considered Group 1 carcinogens because they are known to cause cancer in people. According to the Carcinogenic Risk Assessment, the U.S. Environmental Protection Agency's RSL provides IUR values used to estimate ECR from the inhalation of PM10-bound heavy metals. A significant gap in environmental risk assessments is highlighted by the fact

Table 8: Hazard Quotient and Hazard Index for dermal exposure.

Heavy metals	ECR	
	Children	Adult
Pb	4.88E-05	4.88E-05
Cr	4.75E-02	4.75E-02
Ni	3.47E-04	3.47E-04
Cd	8.38E-04	8.38E-04
Hazard Index	4.88E-02	4.88E-02

that this study was unable to assess carcinogenic risk via dermal exposure and ingestion pathways because reference values for these pathways were not available (USEPA 2016).

Equation (9) was used to calculate the estimated excess cancer risk (ECR) for both adults and children. The results are presented in Table 8. The results showed that the carcinogenic risk from these heavy metals was higher than the U.S. Environmental Protection Agency (EPA)-acceptable threshold of 1×10^{-6} for both adults and children. This highlights the possible threat that PM10 contaminants pose to public health, as exposure to PM10 in the study area may result in an increased lifetime risk of cancer. Research conducted by Boudou et al. (2020) also supports the finding that PM-bound carcinogenic metals can pose significant long-term health risks, especially in urban and industrial environments. The studies indicate that living close to factories and highly trafficked roads contaminated with Cd and Cr can increase cancer risk in people. Contact with heavy metals in early life is very dangerous for health because children inhale more air and developing bodies put them at greater risk of cancer (Zhang et al. 2017). Elevated risks could be minimized by implementing roadside green buffers, strengthening industrial and vehicular emission regulations, and raising community awareness.

CONCLUSIONS

This study found that particulate pollution and its associated heavy metals in Gurugram, Haryana, primarily originated from vehicular emissions, resuspension of dust particles, and ongoing construction activities. Higher contamination levels and greater health risks were caused by these factors. Notably, the post-monsoon season had the highest average PM_{10} concentration, with a mean of 169.7 $\mu g.m^{3-}$ over the two years. Additionally, ICP-MS heavy metals analysis showed that PM_{10} samples contained iron (Fe), lead (Pb), chromium (Cr), nickel (Ni), copper (Cu), and cadmium (Cd). Additionally, the resuspension of road dust and motor vehicles was found to be the main source of heavy metals through source apportionment using principal component analysis (PCA). Furthermore, Pb had a notably high enrichment factor (EF) value (62.3), suggesting that it came from human sources. According to the human health risk assessment, all three exposure pathways had hazard index (HI) values above the threshold limit (=1), suggesting possible non-carcinogenic risks for the populations living in the study area. Furthermore, the hazard quotient (HQ), hazard index (HI), and excess cancer risk (ECR) values also exceeded the safe limit (10^{-4}–10-6), suggesting that lifetime exposure to air contaminated with heavy metals may increase the risk of developing cancer. Although this study provides valuable insights, it also acknowledges limitations, such as limited spatial representativeness due to single-point sampling, and potential uncertainties in exposure assessment exist, as the use of default Environmental Protection Agency (EPA) exposure parameters may not accurately reflect local behavior patterns. In addition, this study could not include ingestion and dermal exposure routes for ECR, owing to the lack of available reference values, which may lead to an underestimation of total carcinogenic risk**.**

Sustainable Solutions

High PM_{10} concentrations beyond permissible limits necessitate stringent regulations, enhanced air quality monitoring, and real-time data access. Vehicular emissions and industrial activities are primary pollution sources, highlighting the need for sustainable transport, electric vehicles, and cleaner energy. Elevated hazard index (HI) and excess cancer risk (ECR) values underscore the urgency of public health interventions, including respiratory care centers and air purification measures. Expanding green infrastructure and investing in renewable energy can mitigate pollution while promoting biodiversity. Strengthening research and policy enforcement is crucial to minimizing the impact of air pollution on public health and the environment.

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