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Nature Environment & Pollution Technology

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(Original Research)

Health Risk Assessment of PM_{10} Bound Heavy Metals in the Ambient Air of Gurugram Urban Area

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Key Words	PM_{10}, Heavy metals, Enrichment factor, Principal component analysis, Health risk assessment
DOI	https://doi.org/10.46488/NEPT.2026.v25i02.B4361 (DOI will be active only after the final publication of the paper)
Citation for the Paper	Yadav, V. and Mor, V. 2026. Health risk assessment of PM_{10} bound heavy metals in the ambient air of Gurugram urban area. *Nature Environment and Pollution Technology*, 25(2), B4361. https://doi.org/10.46488/NEPT.2026.v25i02.B4361

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 monsoon months. The annual average PM_{10} concentration was 169.5 µg/m³, which is about 11 times higher than the WHO (2021) guidelines and 3 times higher than the NAAQS by CPCB. Seasonal variation was observed, with the highest PM_{10} levels recorded in 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/m³) being the most abundant. Enrichment factor analysis showed 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. The Excess Cancer Risk (ECR) values for Hazard Index (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

The concern about urban air pollution is mainly caused by excessive amount of particulate matter (PM). Because of more urbanization, industrial activities and economic growth, global levels of air pollution are still going up (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, the air quality does not reach the standards set by the WHO (UN, 2018). Due to high PM_{10} levels in the air, India has seen a serious fall in its air quality (Gandhi et al., 2021; Kumar et al., 2019). Several studies have emphasized that Indian cities like Delhi, Kanpur, and Varanasi consistently rank among the most polluted globally (Das et al., 2025; Guttikunda & Gurjar, 2012; Pant et al., 2015), yet region-specific chemical and health risk assessments are limited. Besides, air pollution by particulate-bound heavy metals results from both urban growth and industrial activity. These heavy metals have the potential to biomagnify and build up in the food chain (Shang et al., 2024; Jia et al., 2022; Zhang et al., 2007). Therefore, because of its negative impacts on human health, this has grown to be 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., 2023; Liu et al., 2022)

The study of the long-term consequences of exposure to heavy metals bound to PM_{10} has attracted a lot of attention lately.Vehicles, industry and Earth's crust are thought to contribute to PM, although finding out the precise sources is hard. Our well-being and the rules set for health are greatly affected by heavy metals in the air. Based on several studies, people might experience a mild increase in cardiovascular deaths after exposure to PM_{10} (Liu et al., 2009; 202et al., 2009). Moreover, the reports that describe health hazards linked to heavy metal exposure rarely detail the exact processes by which these health effects happen. There is also a scarcity of studies that combine both source identification and risk characterization in rapidly developing cities like Gurugram.

The concentration of particle matter can vary a lot locally depending on temperature, relative humidity, wind speed, rainfall, and atmospheric stability, according to Smith et al. (2019) and Johnson et al. (2020). Movement of air can be controlled by considering wind direction and speed which has a direct effect on spreading PM (Gomez & Lee, 2020; Harris et al., 2021). Also, RH can impact the changes in the environment over days and during the day and night periods, as well as pollution levels (Gomez & Lee, 2020; Patel, 2021). Low-layer winds and stable conditions, accompanied by low wind speeds and less variation, are regularly linked to increased levels of PM (Taylor et al., 2017).

India needs to significantly improve the quality of its air because it is a developing nation. Since Gurugram produces much pollution due 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 there are so many different sources of air pollution. While earlier studies have focused on Delhi-NCR at large (Banerjee et al., 2025; Rajesh et al., 2025; Tiwari et al., 2015), a targeted investigation of Gurugram's PM_{10} composition and health implications remains underexplored.The air quality analysis was completed in one location to show how atmospheric PM_{10} levels affected the Gurugram district. With ICP-MS, the presence of heavy metals was found and the quantity of PM_{10} was determined by gravimetric analysis. The US-EPA health risk assessment method was used to evaluate the possible risks to human health, and statistical techniques like Principal Component Analysis (PCA) and Karl Pearson correlation were used by 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. Making efforts to curb particulate matter will play a key role in meeting the Sustainable Development Goals in cities and boosting health for the public. 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, the 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 grasp the link between heavy metals and people's health and cancer.

2. MATERIALS AND METHODS

2.1. Description of Study Site

Gurugram, a rapidly developing city in the Indian state of Haryana is situated just southwest of New Delhi (Fig. 1). Located at a mean sea level elevation of 217 meters, Gurugram is between 28.4595° N and 77.0299° E latitudes, are spreads over 300 square kilometers and is known for its progress in infrastructure (Kumar & Jain, 2018). 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 risk.

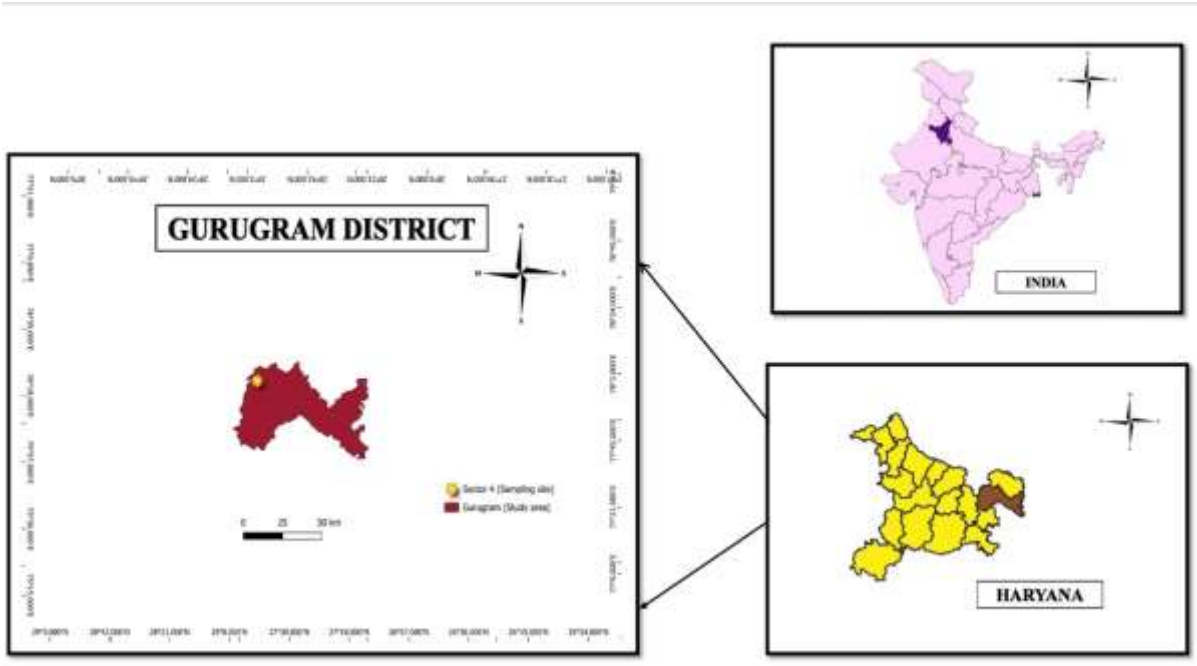


Figure 1. Map of the study area and sampling site.

2.2. 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, PM_{10} samples were taken on Whatman filter paper (EPM 2000) with the help of 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, filters were again conditioned under the same controlled conditions for another 24 hours before weighing and weighed with the A&D GR-202 microbalance which has a maximum difference of ±10 µg. PM_{10} was measured by using equation 1.

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

2.3. Sample Analysis

The samples were analysed for heavy metals using Inductively Coupled Plasma Mass Spectrometry (Agilent ICP-MS 7800) under the rules set by EPA Method 3050B. Filter papers were dried and afterward put in a container with 20 parts of nitric acid and 2 parts of perchloric acid. The digestates were then evaporated to 2-3 mL and the solution was then passed through Whatman Filter 42. To make the final solution, 50 mL of double-distilled water was added. Blanks were also created using the same method to monitor background contamination. The ICP-MS instrument was calibrated using multi-element standard solutions across five concentration levels. The filtrates' concentration of heavy metals was measured with equation 2 (Sinha and Banerjee, 1997):

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

2.4. Source apportionment

The source of heavy metals were detected by computing Enrichment Factor and PCA with varimax rotation combined with Kaiser normalization was performed. The most accurate quantitative explanation of metals and their origins was given by using PCA (Watson et al., 2022; Shah, 2009; Park and Kim, 2005).

2.4.1. Principal component analysis

PCA was applied to identify potential sources of heavy metals in PM_{10} samples (Bui et al., 2022). The method does this by combining correlated variables into new main components which helps to simplify all the variables (Debnath et al., 2023). It gives the opportunity to understand how the measured variables are associated with the samples. With the use of Varimax rotation, the matrix for atmospheric analysis was built. When the matrix is rotated, each element in the PM_{10} is separated into different parts which could mean that these substances came from different possible origins. The analysis were done in SPSS 26 by performing both principal component analysis and correlation matrix analysis.

2.4.2. Enrichment factor analysis

The Enrichment Factor (EF) provides insights into whether an element is from geogenic or anthropogenic sources. Rahn (1971) first proposed this theory to calculate how much human activity contributes to the total concentration of elements in the atmosphere (Tripathee et al., 2019; Rovira et al., 2011; Feng et al., 2009). The value is set by dividing the concentration of the concerned element by the chosen reference element, of known crustal origin and then comparing it to the average ratio seen in the Earth's crust. The

elements iron (Fe), alimunium (Al) and silicon (Si) are usually used as reference elements. Since iron has a far higher natural concentration than any of the other elements, it was chosen as the reference element for this study (Wedepohl, 1995). Using Equation (3), it was determined what the enrichment was:

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

X stands for the concentration of the target element and F represents the concentration of the reference element. Lide (2008) used the CRC Handbook of Chemistry and Physics to find out 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 each 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).

2.5. Health risk assessment model

2.5.1. Exposure dose

The US Environmental Protection Agency (EPA) model was used in this study to determine people's exposure to airborne heavy metals in the air. The main ways to find out the exposure to each element (a) ingestion of airborne particulates through deposition, (b) inhalation by the nose and mouth, and (c) dermal absorption of heavy metals from particulates adhering to exposed skin (Li et al., 2015; Hu et al., 2012). For the CDI, EC and DAD, we calculated using the Supplemental Guidance for Inhalation (Part F), the Supplemental Guidance for Dermal (Part E) and the Human Health Evaluation Manual (Part A) and applied their respective equations shown in (4) to (6) (US EPA, 1989, 2004a, 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 stands for the amount of elements found in PM_{10} which is given as the average yearly concentration (in mg/kg for CDI and DAD or μg/m³ for EC) in this study.

2.5.2. Non carcinogenic health risk

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

If CDI, EC and DAD are less than 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 for health (US EPA, 1989).

Additionally, assessing the hazard potential of single element 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 one component should be summed together to create a Hazard Index (HI) (Equation (8). For different chemical exposures, the HI is the total of several HQs.

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

HQi mean 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 they rise with the increase in HI (Zheng et al., 2010; US EPA, 1989).

2.5.3. Excess cancer risk

Evaluation of ECRs is based on the greater chances of an individual developing cancer throughout their life because of contact with carcinogens. ECR was computed by using Equation (9) (Hu et al., 2012; US EPA, 2011).

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

The variable C represents the annual average of heavy metals (μg/m³), AT is the average lifetime of carcinogens (70 years × 365 days/year × 24 hours/day), IUR is the amount needed for inhalation risk $(mg/m^3)^{-1}$, ET is the number of hours we are exposed daily and the rest of the parameters are as defined before. When the ECR is between 10^{-6} and 10^{-4}, it shows that any resulting cancer risk from contamination is considered minimal (Hu et al., 2012; US EPA, 1989).

3. RESULTS AND DISCUSSIONS

3.1. PM_{10} concentration and Meteorological parameters

The average annual concentration of PM_{10} was 176 μg/m³ in the year 2022-2023 and 163.4 μg/m³ in 2023-2024. These levels were approximately three times higher than the National Ambient Air Quality Standard (60 μg/m³) stated by the Central Pollution Control Board (CPCB) of India (NAAQS, 2009) and about 11 times higher than the World Health Organization's (WHO, 2021) annual PM_{10} air quality guideline of 15 μg/m³. During October and November, the level of PM_{10} in the air often increases because of crop residue

fires and cooler temperatures that make the air stop moving (as seen 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 lot of particulate matter into the air (Bisth et al., 2023).

The study was categorised into three meteorological seasons to assess seasonal variation: post-monsoon (October and November), winter (December, January, 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 the figure depicts in (Fig. 2b). From Table 1, it can be seen that the average PM_{10} mass concentration in this study was more than what was found in Beijing, Kanpur and Mumbai (Chen et al., 2023; Patel et al., 2022; Ahmad et al., 2024). But, the values found here were less 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).

During the entire study period, there was a statistically notable link (r=0.27) between PM_{10} concentration and temperature (Fig. 3a). Rising temperatures mean the earth's surface dries up which results in dust and debris rising with the right wind and disruption, ultimately making the amount of PM_{10} higher. Hotter temperatures help air to move more freely and spread which is better for the dispersion of gases. The same trends have appeared in several parts of the world. Giving their results, El-Sharkawy and Zaki (2015) established that there is a positive connection 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. In the same way, Munir et al. (2014) discovered that an increase in temperature was linked to higher levels of PM_{10} in Makah, Saudi Arabia. In their research, Sirithian et al. (2011) discovered that the relationship between PM_{10} and temperature was also positive (r = 0.528) in Thailand. These findings prove that temperature is related to the levels of PM_{10} gas, especially in different climatic zones.

The level of mass concentration for PM is greatly affected by wind speed. Between 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 causes it to be less concentrated (Ravindra et al., 2008). It is found in the current study that the negative relationship between WS and PM mass concentration resembles what other studies have similarly shown elsewhere. In Patras, Karagiannidis et al. (2017) stated that higher levels of PM_{10} were associated with a drop in WS, but 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 related in a negative manner (r = -0.14).

PM_{10} concentration had a positive correlation (r = 0.41) with relative humidity (Fig. 3c).Lou et al. (2017) explained that there was a positive link between PM_{10} and RH (r = -0.41) in China and Gupta et al. (2019) shared a similar result in Bangladesh. Still, various studies noted that there is a negative link between PM_{10} and relative humidity (Pateraki et al., 2012; Munir et al., 2014; Kliengchuay et al., 2019).

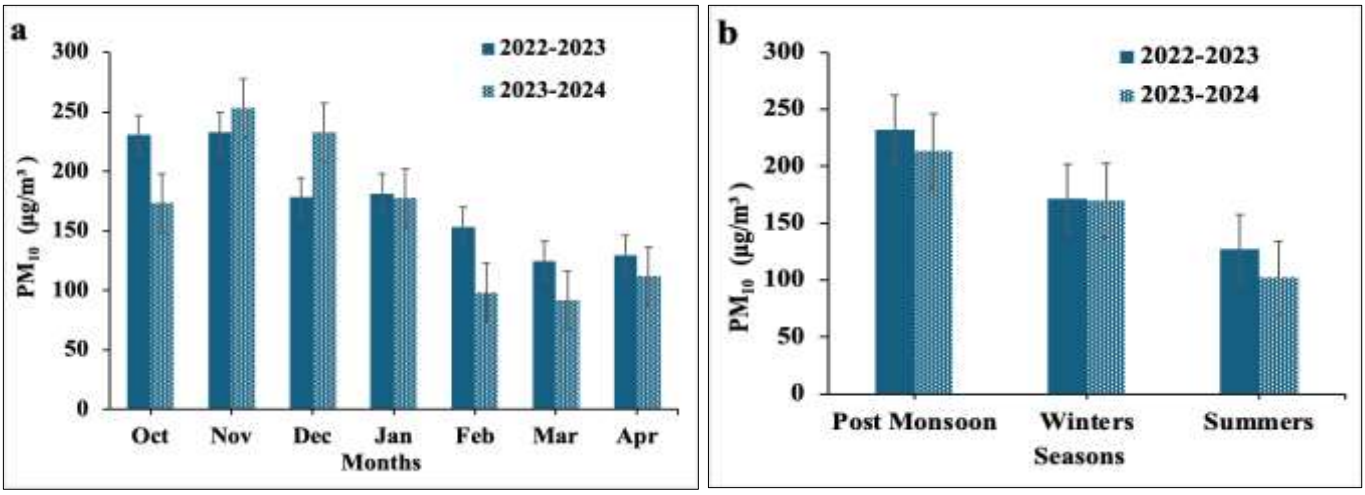
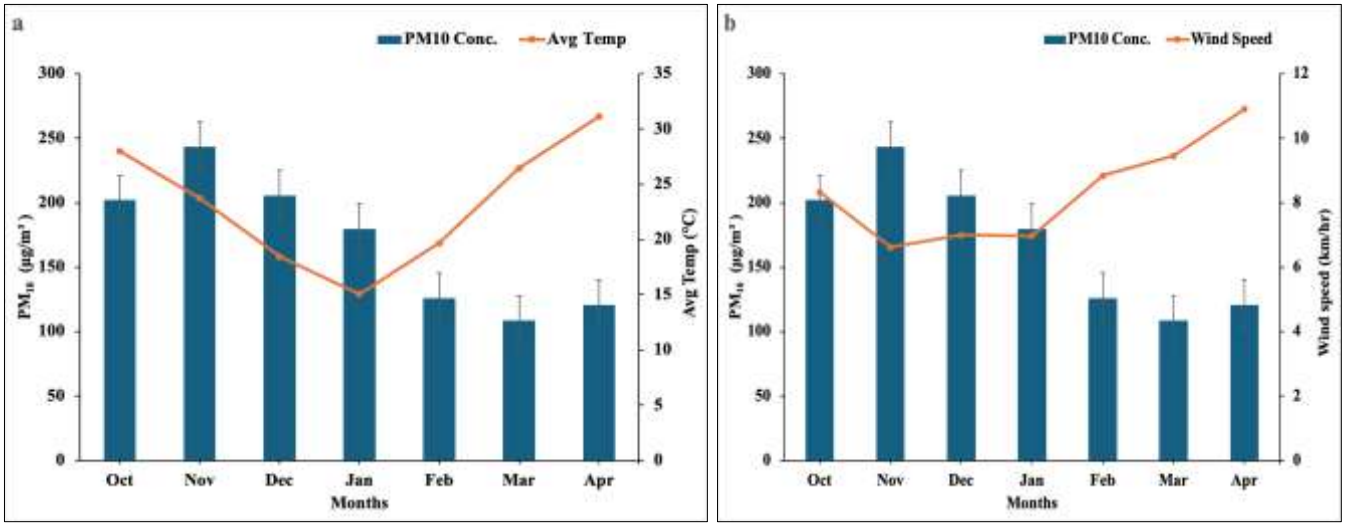


Figure 2. Temporal variation in average PM_{10} concentration($\mu g/m^3$) (a) Monthly and (b) Seasonal.

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

LOCATIONS	PM_{10} ($\mu g/m^3$)	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)



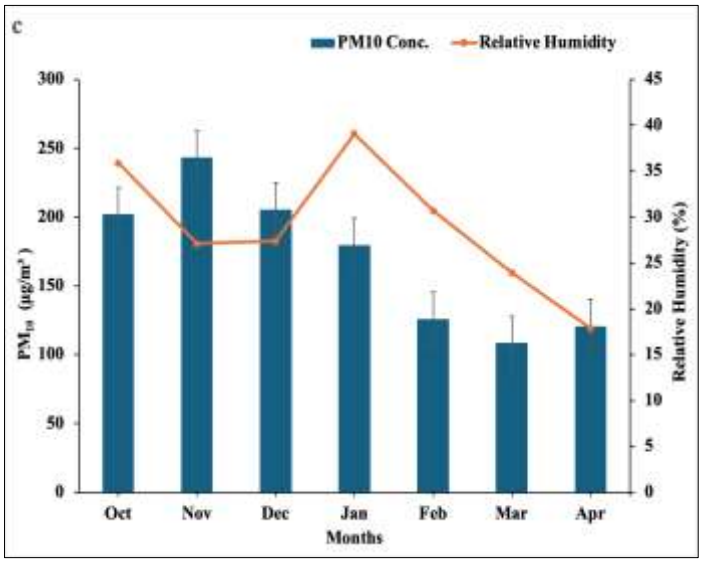


Figure 3. Relation between PM_{10} and meteorological parameters (a) Average Temperature, (b) Wind Speed (c) Relative Humidity.

3.2. Heavy Metals Concentration

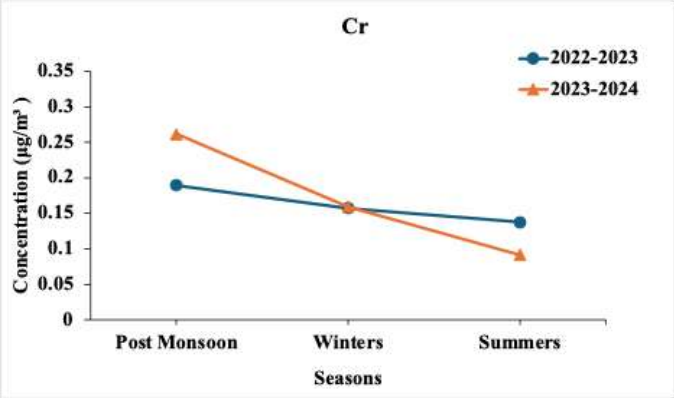
Pollution load of heavy metals showed strong seasonal variation as shown in Fig. 4. The descriptive statistics of heavy metals for both years shown in table 2. The average amount of heavy metal in PM_{10} was the highest in the post-monsoon, supporting the same result reported by Prodi et al. (2009). However, metals like copper (Cu), cadmium (Cd), and lead (Pb) exhibited the highest concentrations during the winter in year 2023-24. Seasons had an important effect on heavy metal levels and this was mostly due to less spreading of atmospheric gases, reduced rain, emissions from cars and factories and wood burning (Khare and Baruah, 2010).

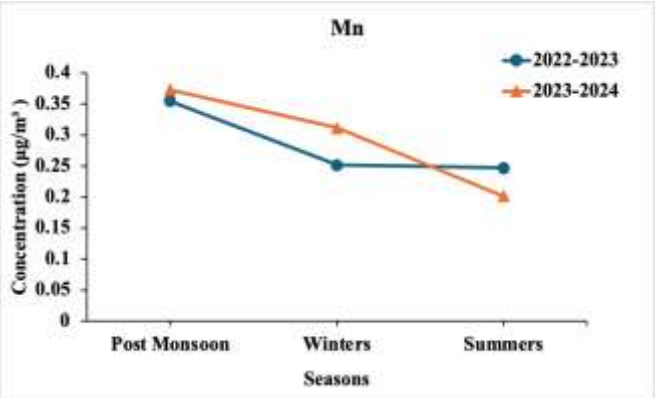
In both years, the highest average concentration of heavy metals was found for Fe (10.91 µg/m³), followed by Mn (0.28 µg/m³). The overall trend in heavy metal content followed the order Fe > Mn > Pb > Cr > Ni > Cu > Cd, consistent with previous studies that reported iron (Fe) as the dominant heavy metals in PM_{10} (Kumari et al., 2023; Truong et al., 2022; De Gennaro et al., 2018). The main source of nickel (Ni) and lead (Pb) in the atmosphere is tires wearing and oil burning, but iron (Fe) mainly comes from nature such as windblown dust and dust turned up by cars and trucks (Kurosaki et al., 2019 and Sahu et al., 2021). All heavy metal concentrations were corrected for blank filter values prior to analysis to ensure accuracy and reliability of the reported data. With ramifications for public health and air quality management, these findings highlight the intricate interactions between natural and human activities that determine seasonal variations in the concentration of heavy metals in PM_{10}. Furthermore, research by Hossain et al. (2022) and Malek et al. (2021) lends 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 found in many ways, pollution control strategies should be put in place to reduce the chances of exposure.

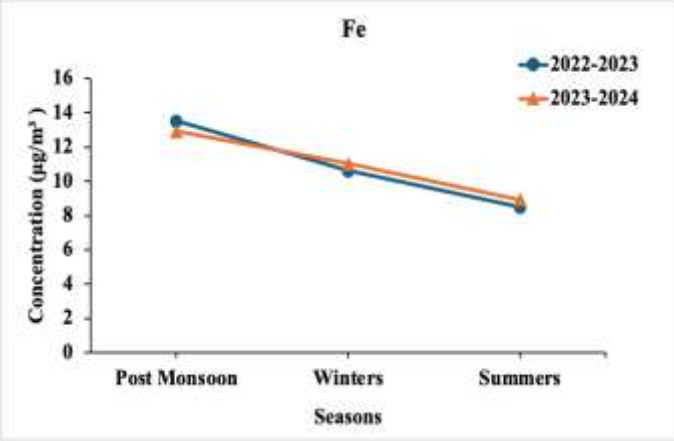
Table 2. Descriptive statistics of heavy metals for both years.

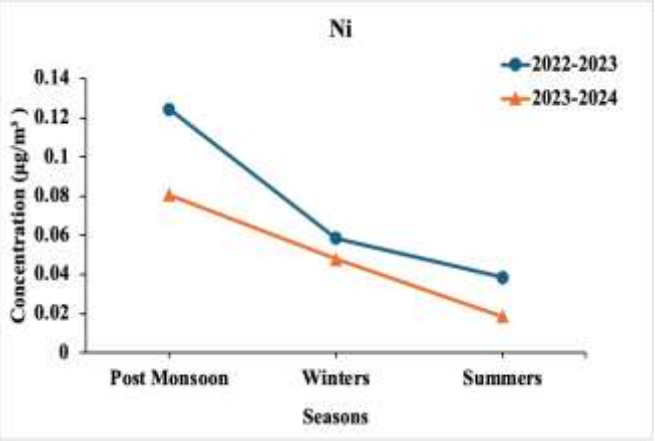
Heavy metals	Range		Mean		Median	
	2022-23	2023-24	2022-23	2023-24	2022-23	2023-24
Pb	0.027 - 0.416	0.031 - 0.314	0.151	0.135	0.157	0.133

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









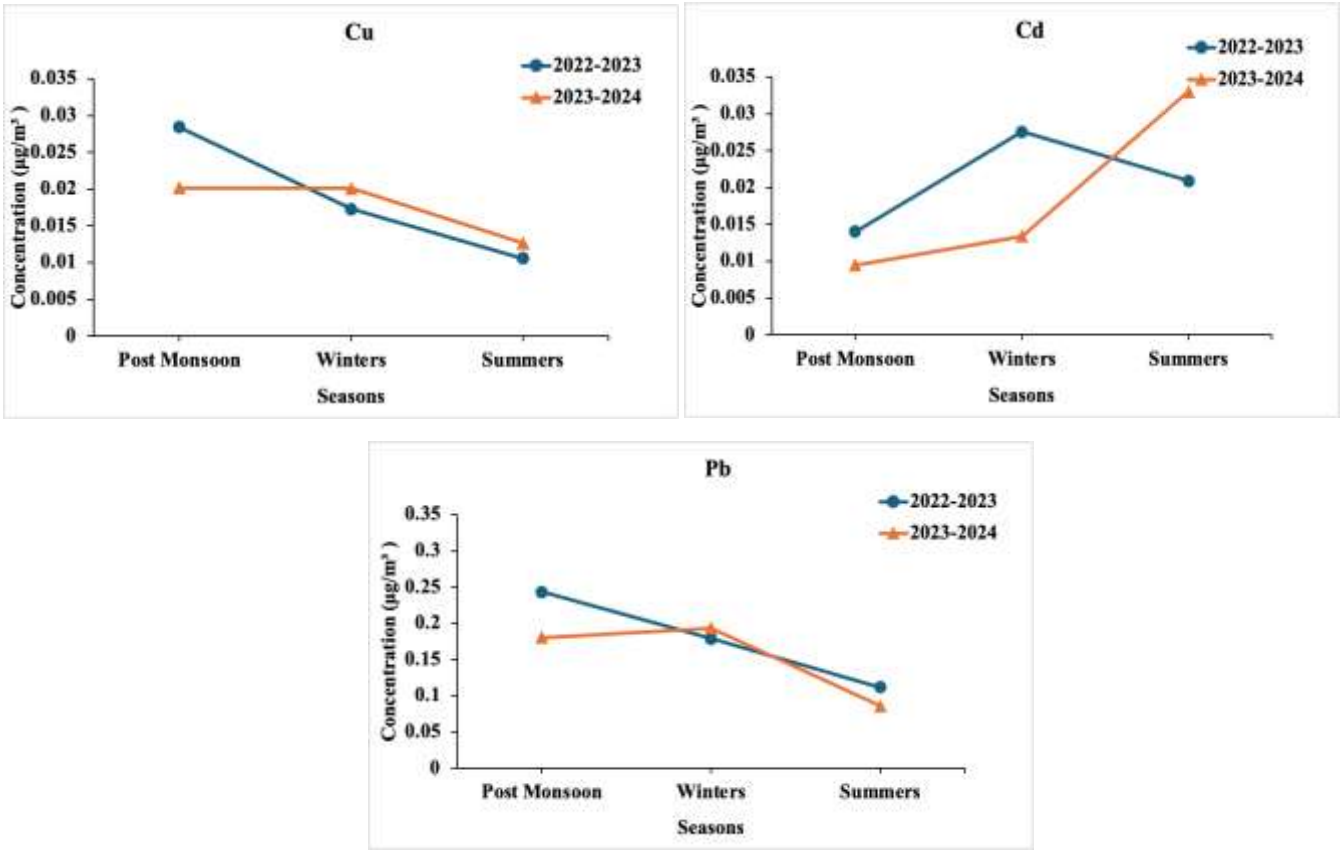


Figure 4. Seasonal trends of average heavy metals concentration (µg/m^3)

3.3. Source apportionment

Using the Karl Pearson correlation coefficient, PCA with Varimax rotation and the enrichment factor, possible sources of PM_{10} -associated heavy metals were identified.

3.3.1. Principal Component Analysis

The Principal Component (PC) loadings for the combined heavy metal data for both years, along with their related eigenvalues and variances is 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 sources of these heavy metals Iron (Fe) found in both brake pads and other mechanical parts of engine. (Roy et al., 2020; Chakraborty and Gupta, 2009). Hence, this component labeled as Vehicular and Road Dust Source**.**

The second factor (PC2) accounted for 17.92% of the variation percentage and 72.66% of the cumulative percentage, with substantial cadmium (Cd), lead (Pb), and chromium (Cr) loadings. Generally, chromium (Cr) and cadmium (Cd) end up as pollutants in 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 more possible sources (Cheng et al., 2018). Vehicle exhaust emissions are linked to high loadings of nickel (Ni) and lead (Pb) (Shah et al., 2006). Thus, this factor labeled as Industrial and Combustion Source**.**

PC3 accounted for 17.04% of the variance percentage and 89.7% of the cumulative percentage, with substantial chromium (Cr), nickel (Ni) and lead (Pb) loadings. Chromium and nickel were found in automotive exhaust (Guo et al., 2019). Chromium is mostly caused by engine wear, as chromium (Cr) is one of the engine's metallic components (Jeong et al., 2022; Pandey et al., 2014).
The principal component analysis of particulate matter revealed that motor vehicles, commercial activities, resuspension of road dust and industrial emissions were the primary sources of selected heavy metals in the research area. Therefore, PC3 interpreted as a Mixed Vehicular and Industrial Emission Source**.**

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

	Component		
Heavy metals	**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

3.3.2. Correlation matrix

Another statistical method**,** Pearson's correlation analysis was used to investigate the relationships between all heavy metal concentrations and to create an overall profile of the sources, as elements with a high correlation 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 metal is presented in table 4. Iron (Fe), manganese (Mn), and chromium (Cr) were found moderately correlated, particularly Fe-Mn (r = 0.770) and Fe-Cr (r = 0.699). They are of the lithophilic group, so these elements are significantly found in the Earth's crust (White, 2013). Wind blowing dust is most probably the source of these components. Another correlation seen between Fe and Pb was 0.841 and between Fe and Cu was 0.808. Additionally, it was determined that the correlations between Ni-Mn (r = 0.438) and Cr-Pb (r = 0.744) were statistically significant. Usually, human activities like 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 these may arise from more diverse and isolated anthropogenic sources such as industrial processes, localized combustion, or use in alloys and lubricants, lead to less consistent spatial co-distribution. These patterns reflect how different emission sources (natural dust, traffic-related abrasion, fuel combustion, industrial processes) influence metal concentrations differently across space and time. Results have shown that the most important elements in this assessment are iron (Fe), manganese (Mn) and also chromium (Cr), nickel (Ni) and lead (Pb). The main causes of lead pollution were related to 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). The use of cadmium (Cd) compounds as antioxidants can be found in lubricants and in the alloys of batteries and carburettors 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.

Table 4. Correlation matrix for heavy metals in the 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

3.3.3. Enrichment factor analysis

All the calculated EFs for the 7 heavy metals can be seen in Fig. 5. All the other elements in this report were found to have the strongest link with iron (Fe), so that element 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 5, 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 shown similar findings regarding the contribution of anthropogenic activities to the enrichment of heavy metals in urban air. Kumar et al. (2023) 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 were major industrial sources of nickel (Ni) and copper (Cu) in urban air. These findings corroborate the contribution of anthropogenic sources in PM_{10} associated heavy metals pollution. Based on the enrichment analysis, targeted interventions are needed in Gurugram to mitigate anthropogenic emissions. These includes 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.

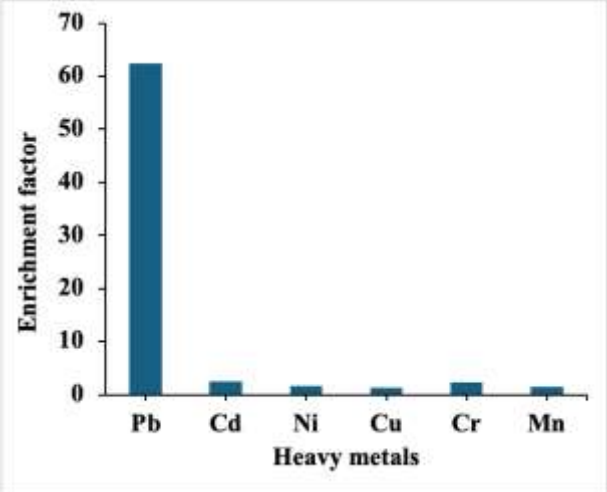


Figure 5. Enrichment Factors values for heavy metals in PM_{10} in study area

3.4. Health risk assessment

3.4.1. 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 figure out the Hazard Quotient (HQ) and Hazard Index (HI) for iron (Fe) and manganese (Mn), as the necessary reference values are not available for these metals. Such results are caused by the fact that these elements are fundamental for 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 risk assessment could lead to an underestimation of total non-carcinogenic risk**,** especially for manganese (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 is shown in Table 5. Due to ingestion of the heavy metals, values of HQing were higher than the threshold values (=1) for all except copper (Cu) in adults. HI values for children and adults were obtained as 5.05E+02 and 5.41E+01 respectively, so the results indicated a chance health risk due to exposure to different elements. It is obvious from the data that people in the study area face non-carcinogenic risk because of PM_{10} containing 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**

3.4.2. Non carcinogenic health risk of heavy metals via ingestion exposure

Ingesting airborne particles may happen when they are deposited on foods, beverages or the surfaces in both indoor and outdoor areas. One can transfer these particles directly to the mouth by their hands or indirectly via objects touched by their hands (Hu et al., 2012). In Table 6, the findings for HQ and HI are shared. The HQ values resulted higher than the safe level (=1) for lead (Pb) and chromium (Cr) and lower than the safe limit for nickel (Ni), copper (Cu) and cadmium (Cd), but the HI was higher (1.41E+02) than the safe limit (=1), indicating the adverse health impacts by the exposure of mixture of elements for children and adults. Recent research reveals 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 due to their tendency to consume a lot of dust and soil particles (Liu et al., 2022).

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**

3.4.3. Non carcinogenic health risk of heavy metals via dermal exposure

Hazard Quotient (HQ) via dermal contact are presented in Table 7. With the exception of copper (Cu), all HQ values were more than the safe dose (=1). Additionally, the amount of risk from various elements was summarized through Hazard Index (HI), the values of which were also greater than the safe threshold (=1). It means that the area's residents might face significant health issues from these heavy metals.

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 from Zhang et al. (2022) and Kumar et al. (2023) demonstrate 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 be mostly through the skin in places with high levels of PM_{10}, despite the fact that swallowing can lead to much higher risk.

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**

3.4.4. Carcinogenic health risk assessment

For the study of the risk of cancer, four metals, chromium (Cr), cadmium (Cd), nickel (Ni) and lead (Pb), were picked, as they are identified as being either carcinogenic or likely to cause cancer by the International Agency for Research on Cancer (IARC). Especially, lead substances belong to Group 2A and are described as likely carcinogenic to humans, whereas nickel, cadmium and chromium are considered Group 1 carcinogens since they are known to cause cancer in people. According to the Carcinogenic Risk Assessment, the US Environmental Protection Agency's RSL gives IUR values used to estimate ECR from inhalation of PM_{10} bound heavy metals. A significant gap in environmental risk assessments is highlighted by the fact that this study was unable to assess carcinogenic risk via the 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 shown in Table 8. The results showed that the carcinogenic risk from these heavy metals was higher than the US EPA-acceptable threshold of 1×10^{-6} for both adults and children. This highlights the possible threat that PM_{10} contaminants pose to public health since exposure to PM_{10} 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 boost cancer risk for people. Getting in contact with heavy metals in early life is very dangerous for health because children take in more air and developing bodies put them at greater risk of cancer (Zhang et al., 2017). The elevated risks could be minimized

by implementing roadside green buffers, strengthening industrial and vehicular emission regulations, and raising community awareness.

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**

4. CONCLUSIONS

This research found that particulate pollution and its associated heavy metals in Gurugram, Haryana were primarily originated from vehicular emissions, resuspension of dust particles, and ongoing construction activities. Higher contamination levels and greater health risks for the locals were caused by these factors. Notably, the post-monsoon season had the highest average PM_{10} concentration, with a mean of 169.7 µg/m³ 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 were found to be the main sources of heavy metals through source apportionment using Principal Component Analysis (PCA). Furthermore, Pb had a notably high enrichment factor (EF) value (62.3), suggests 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), suggest 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}), suggests that lifetime exposure to air contaminated with heavy metals may increase the risk of developing cancer. While the 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 EPA exposure parameters may not accurately reflect local behavior patterns. Also the study could not include ingestion and dermal exposure routes for ECR, due to the lack of available reference values, which may lead to underestimation of total carcinogenic risk**.**

Sustainable solutions

The high levels of PM_{10} concentrations beyond permissible limits necessitates 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 air pollution's impact on public health and the environment.

Author Contributions: V. Yadav contributed to writing – original draft, sample collection, formal analysis, and conceptualization. **V. Mor** contributed to writing – review & editing, data curation, supervision, and methodology.

Funding: This research received no external funding.

Acknowledgments: The authors would like to gratefully acknowledge the Department of Environment Science, Faculty of Applied and Basic Sciences, SGT University, Gurugram and Vardan Envirolab LLP, Sector 5, Manesar for all their technical support with the experiments.

Conflicts of Interest: The authors declare no conflicts of interest.

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