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Characterization and Source Apportionment of Heavy Metals in Ambient Particulate Matter in Manesar, Gurugram

Vandana Yadav[1] | Vikram Mor[1]✉ | Wazir Singh[2]

1. Department of Environmental Science, Faculty of Applied and Basic Sciences, SGT University, Gurugram, Haryana 122505, India
2. Department of Environmental Science, GL Bajaj college, Varindavan, India

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ABSTRACT

This study provides insights into the ambient particulate matter (PM) concentration, chemical characterization, source apportionment, and associated heavy metals in Manesar, Gurugram. It is a rapidly growing industrial hub, experiencing severe air pollution. This highlights the urgent need for a comprehensive study to analyze ambient PM at the study site. Therefore, particulate matter (PM_{10} and $PM_{2.5}$) samples were collected on glass fiber filters over two years, excluding the monsoon season. The sampling was conducted from October 2022 to April 2023 and October 2023 to April 2024. Heavy metals were quantified using ICP-MS (Agilent 7800). The average concentration of PM_{10} and $PM_{2.5}$ during the study period were 180.98 µg/m³ and 107.25 µg/m³, respectively, exceeding the National Ambient Air Quality Standards (NAAQS) set by the Central Pollution Control Board (CPCB). A substantial seasonal variation was observed, with peak concentrations occurring in the post-monsoon season followed by winter. Among the analyzed heavy metals, Fe (10.89 µg/m³) exhibited the highest average concentration, followed by Mn (0.283 µg/m³). Seasonal variation was also evident in heavy metal concentrations, with maxima in post-monsoon, and followed by winter. Enrichment factor (EF) analysis classified nickel (Ni), copper (Cu), and cadmium (Cd) as less enriched, while lead (Pb) was highly enriched. Further, Principal Component Analysis (PCA) of Particulate matter, revealed that vehicles and industrial emissions were the primary sources of the heavy metals in the ambient air of study area. These findings highlight the necessity to implement the strategies for controlling vehicular and industrial emission to reduce the PM concentration.

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INTRODUCTION

Urban air pollution has become a global concern that endangers human health as well as ecosystems. In last few decades, India's sharp economic growth, accelerated industrialization, urbanization, increasing population, and an increase in vehicle emissions have had a detrimental effect on the urban air quality, especially due to the particulate matter contamination. Particulate matter is the most alarming pollutant and a significant contributor to this problem (Giri et al., 2023; Lalchandani et al., 2021; Kalaiarasan et al., 2018;. Recently, many studies reported that cities such as Delhi, Gurgaon, Noida, and Faridabad have poor air quality due to the alarmingly high levels of particulate matter ($PM_{2.5}$ and PM_{10}). These study indicates that pollution frequently surpasses safe thresholds, leading to serious health risks (Sharma et al., 2024; Singh et al., 2023). Manesar, a rapidly growing industrial hub in the National Capital Region (NCR) of India, has witnessed a significant increase in population over the past decade. This surge

*Corresponding Author Email: *vikramseemla@gmail.com*
vikram_fps@sgtuniversity.org

is primarily driven by industrial expansion, job opportunities, and improved infrastructure. However, the rapid urbanization has led to a sharp rise in vehicular traffic (Devi and Saha, 2024). Despite extensive research on air pollution in major urban centers, relatively few studies have investigated the heavy metal composition of particulate matter in Gurugram, particularly in industrial regions such as Manesar.

The PM varies widely in size, chemical makeup, origin, and concentration exhibiting dynamic spatial and temporal patterns. These PM encompasses a diverse array of chemical components, spanning from metals to various organic and inorganic compounds (Tian et al., 2024; Liu & Chan, 2022). Among the inorganic substances, heavy metals hold particular significance, originating from diverse natural and human-related sources like road dust, coal and oil combustion, vehicular emissions, crustal materials, as well as incineration, construction operations and various industrial processes (Patil et al., 2024; Yuan et al., 2022; Aziz et al., 2024; Shah et al., 2006; Arditsoglou and Samara, 2005). Geopolymers can be used in cement production which might help in reducing particulate matter (Abdelzaher et al., 2024). Many studies have revealed that resuspended particulate matter contains a significant amounts of heavy metals originating from anthropogenic sources, with traffic-related turbulence and tire stress being major contributors (Wu et al., 2019; Wang et al., 2022; Cattaneo et al., 2023; Zhao et al., 2023).

Exposure to these airborne particulate and heavy metals have been linked to potential health risks in both short and long term, including lung cancer, respiratory diseases, damage to other organs, and cardiovascular issue (Shang et al., 2024; Jia et al., 2022; Sakunkoo et al., 2022; Wild et al., 2009; Magas et al., 2007). Several epidemiological studies have confirmed a link between higher concentrations of airborne particulates especially and elevated rates of illness (Kalluri et al., 2022; Li et al., 2023; Kloepfer et al., 2023; Puthussery et al., 2020; Shah, 2009). Various studies have shown higher concentration of ambient particulate over industrial sites (Shi et al., 2021; Reddington et al., 2021; Suman et al., 2007). The chemical composition and quantity of PM in the air is primarily controlled by source emission and subsequent atmospheric processes, therefore, source analysis of PM become essential. Recently various studies have used PCA for PM source apportionment (Zhang et al., 2023; Kumar et al., 2023). PCA effectively reduces dimensionality while preserving variance, making it indispensable for uncovering patterns and structures in high-dimensional data (Smith et al., 2022; Johnson and Lee, 2023). It also helps in identifying and quantifying pollution sources, such as traffic and industrial emissions (Doe et al., 2021; Jones & Brown, 2018).

Pollution assessment in Manesar is crucial due to its dense industrial presence and potential health risks to workers and residents. The main objective of the study is to identify major sources of PM and associated heavy metals. This study will contribute to a deeper understanding of air quality in the region. The findings will provide essential data for policymakers, researchers, and environmental agencies to formulate effective strategies to control PM pollution.

MATERIALS AND METHODS

Description of Study Site

Manesar is a swiftly growing industrial town located in the neighbourhood of Gurugram, Haryana, India (Figure 1). It is the part of the National Capital Region (NCR) and lies between °22’20.36” N and 76°55’10.42” E at an average elevation of 140 meters above mean sea level. In terms of road link, it is on Delhi-Jaipur National Highway (NH48) which is eight-lane highway. The Western Peripheral Expressway passes by near Manesar. Manesar, 32 km from IGI Airport, boasts excellent urban infrastructure in northern India. Total area is 124.32 km^2 (48.00 sq. mi). A few decades ago, it was a small village that began attracting investments and has since transformed into a thriving community, often referred to as ‘A New Gurugram.’

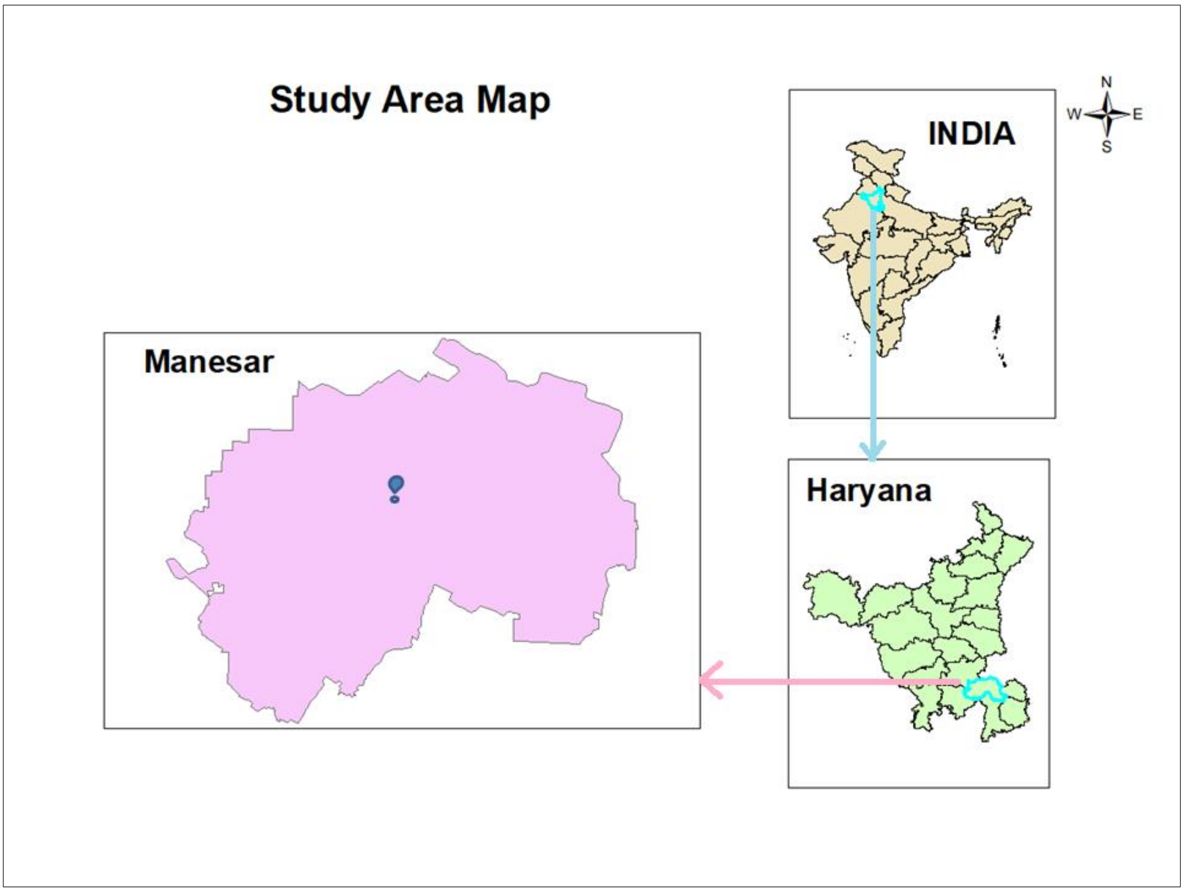


Fig. 1. Map of the study area along with sampling site at Manesar, Gurugram.

It is an industrial hub with more than 3000 industries, as per the Department of Industries and Commerce, Govt. of Haryana (Haryana Govt Gazette, 2019). The Industrial Model Township (IMT) Manesar contains many manufacturing industries. Maruti Suzuki, Jaquar, Toshiba, Honda, and Denso are among the leading companies in Manesar. Over 100,000 people commute to work in Manesar from nearby areas (Haryana Enterprises and Employment Policy, 2022). The Gurgaon-Manesar Master Plan anticipates a population of 37,00,000 people by 2021 (DTCP Govt. of Haryana, 2010).

PM_{10} and $PM_{2.5}$ Sampling

The sampling site was selected based on the criteria outline in IS 5182 Part-XIV and sampling was carried out from October 2022-April 2023 and October 2023-April 2024. The frequency of the sampling was once a week and study time was divided into three seasons (post-monsoon, winter and summer).Samples of PM_{10} were collected on Whatman EPM 2000 filter papers using Respirable Dust Sampler (RDS) 460 NL (Envirotech, India) and $PM_{2.5}$ were collected on Whatman Grade 42 ashless filter paper using Fine Particulate Sampler (FPS) 550 APM (Envirotech, India The samplers were run 24-hour and a total 56 samples of PM_{10} and 56 samples of $PM_{2.5}$ were collected in during two years. . Then, samples were placed into polyethylene bags, transported to the laboratory, and kept in a refrigerator at 4 °C. The PM samples were quantified using an A&D GR-202 microbalance with a precision value of ± 10 µg (Watson et al., 2019). The filter papers were weighed under controlled conditions (humidity and temperature) before and after PM collection. Blank filters weights were also recorded (Pervez et al., 2019). Before weighing, all glass fibre filter papers (EPM 2000) were allowed to equilibrate to the temperature conditions (20±1 °C) and humidity (around 50%) for 24 hours. The collected particle mass was determined by subtracting the weight measured before sampling from the weight measured after sampling the filter (Bano et al., 2018).

Sample Analysis

The experiment for metal determination using Inductively Coupled Plasma Mass Spectrometry (Agilent ICP-MS 7800) began with acid digestion according to standard guidelines (EPA Method 3050B). Then, dry filter samples in a nitric and perchloric acid mixture at a 20:2 ratio. After evaporating the digestates to 2-3 mL, the solution was filtered using Whatman Filter 42, and the final volume was adjusted to 50 mL with double-distilled water. Blanks were also prepared using the same procedure. To analyze heavy metals in the filtrates, calculated their concentrations by subtracting the blank values and comparing the absorbance to standard solutions. Atmospheric metal concentrations were determined using a calibration plot. The atmospheric concentration of a metal was then determined using the following relation (Sinha and Banerjee, 1997):

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

Source apportionment

To determine the origin of heavy metals in the Manesar, Principal component analysis (PCA) with varimax rotation and Kaiser normalization and Enrichment Factor (EF) were performed for source apportionment. Principal component analysis provided the best quantitative information on these metals and their sources (Watson et al., 2022; Shah, 2009; Park and Kim, 2005).

Principal component analysis

PCA is a statistical method used for dimensionality reduction while preserving as much variability in the data as possible. PCA simplifies the data structure without losing essential information by transforming a large set of variables into a smaller one (the principal components). It is an important tool in air pollution studies, offering insights into pollution sources, seasonal trends, and health risks while reducing the complexity of large environmental datasets. It enables better policy-making and targeted interventions to improve air quality and public health. PCA was used to identify vehicular emissions as the primary source of pollution during the winter months (Sharma & Ranjan, 2023). PCA linked seasonal variations in PM levels to traffic emissions during the monsoon and industrial pollutants during the dry season, with implications for public health (Gupta & Jain, 2022).

Enrichment factor analysis

Enrichment Factor (EF) is a widely used statistical method for identifying certain elements or pollutants' source and degree of pollution in air quality studies. It was first introduced to determine whether a specific metal is present in higher air concentrations than expected from crustal sources by Rahn (1971). EFs compare the concentration of metals in an air sample to that of a reference element, which is entirely crustal in origin, to assess the extent of anthropogenic influence (Huang et al., 2014; Tripathee et al., 2019; Al-Momani et al., 2005). EF is commonly used to determine whether pollutants such as heavy metals are due to natural processes or are significantly influenced by human activities (Sharma et al., 2023). The EF is calculated using the following equation:

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

where X is the mean concentration of the target element and F is the mean concentration of Fe in atmospheric PM and in the continental crust, respectively. EFs are based on the mean abundance of metals in the Earth's crust as listed in the CRC Handbook (Lide, 2008). An EF value >1 indicates that the pollutant has been enriched compared to its natural abundance, suggesting an anthropogenic source. Values close to 1 indicate natural sources, while values much higher than 1 indicate vital pollution contributions (Gupta & Jain, 2022). Common reference metals include Al, Mg, Ca, Na, K, Mn, and Fe.

RESULTS AND DISCUSSION

PM concentration and temporal variation

The annual average concentration of PM_{10} was 198.92 μg/m³ in 2022-2023 and 163.03 μg/m³ in 2023-2024. The annual mass concentration of PM_{10} is shown in Figure 2 (c). These average values were approximately three times higher than the National Ambient Air Quality Standard (60 μg/m³) prescribed by the Central Pollution Control Board (CPCB) of India (NAAQS, 2009) and about thirteen times higher than the World Health Organization (WHO, 2021) annual PM_{10}

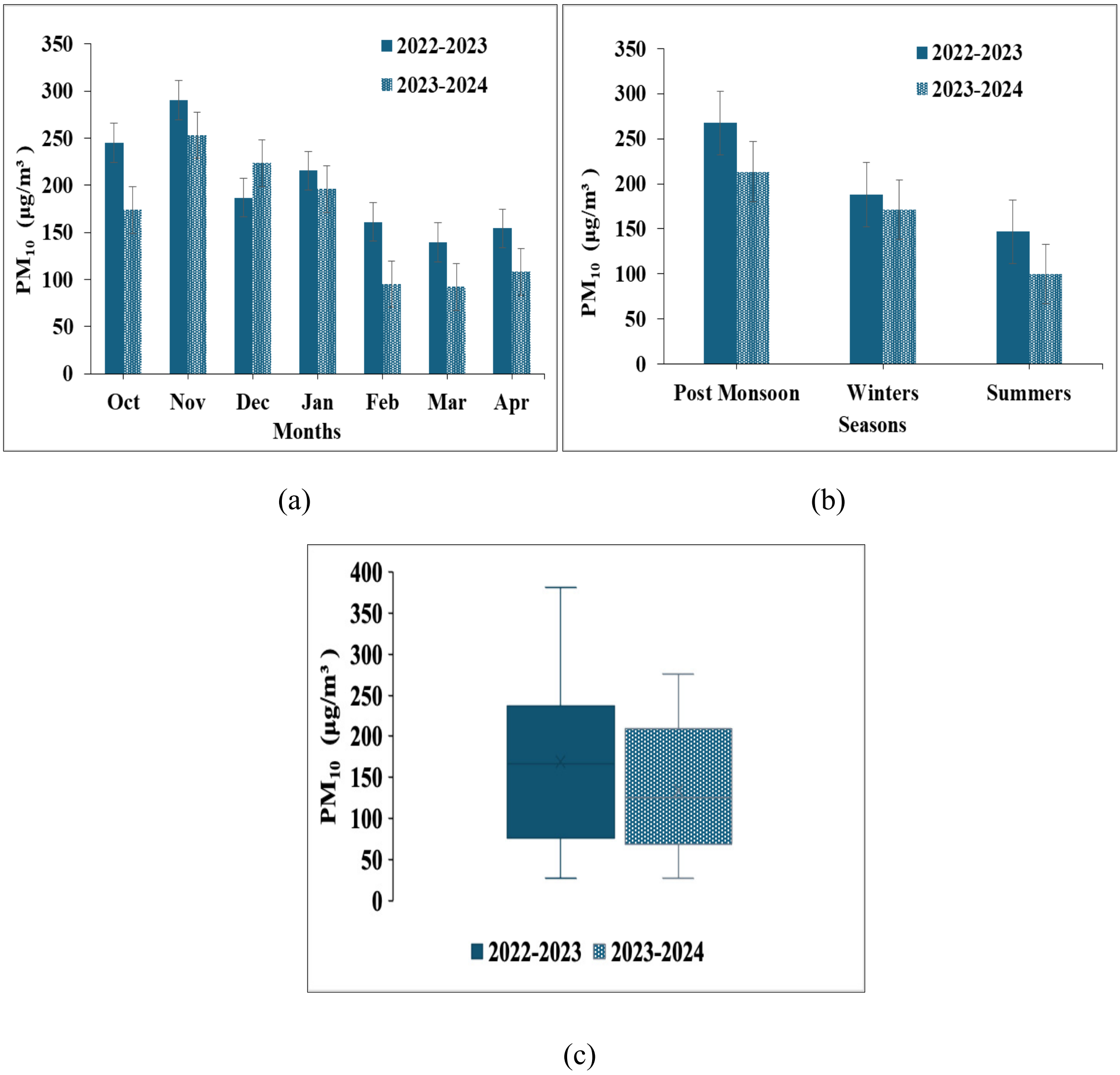


Fig. 2. Average PM_{10} mass concentration in the study area (a) Monthly (b) Seasonal (c) Annual.

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

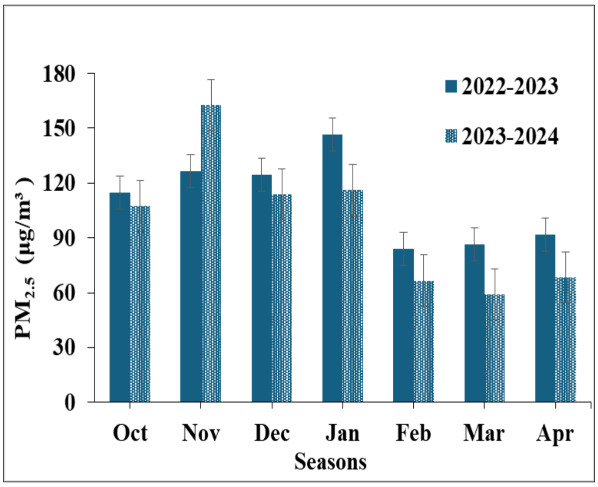
LOCATIONS	PM_{10} (µg/m³)	REFERENCES
Delhi	250	Chaudhary et al. (2022)
Kolkata	220	Sharma et al. (2023)
Cairo	200	Taha et al. (2022)
Lagos	180	Owoade et al. (2023)
Mumbai	180	Sharma et al. (2023)
Kanpur	250	Patel et al. (2022)
Beijing	150	Chen et al. (2023)
Lucknow	220	Patel et al. (2022)

air quality guideline of 15 µg/m³. Several studies have reported PM_{10} concentrations in India that significantly exceed both national and international air quality standards. For instance, Kumar et al. (2020) found that annual average PM_{10} levels in industrial areas of Himachal Pradesh were approximately three times higher than the National Ambient Air Quality Standard (NAAQS) of 60 µg/m³. Similarly, Sharma et al. (2020) observed that PM_{10} concentrations in various Indian cities often surpassed the NAAQS, with some regions exceeding the standard by more than double. Additionally, Gupta et al. (2021) reported that PM_{10} levels in Ghaziabad were about three times higher than the NAAQS, indicating severe air quality issues. The monthly average PM_{10} concentration typically rise in October and November due to factors such as crop residue burning, cooler temperatures causing atmospheric stagnation Figure 2 (a). Furthermore, festivals like Diwali and Dussehra exacerbate this increase, as the extensive use of firecrackers and festive activities release substantial amounts of particulate matter into the air (Bisth et al., 2023). The study was divided into three climatic seasons for evaluating seasonal variation: Post Monsoon (October and November), Winter (December, January, February) and Summer (March and April). The highest concentrations were observed during Post- Monsoon, followed by winters as shown in (Figure 2b). Several studies have reported that the highest concentrations of pollutants were observed during the Post-Monsoon season, followed by Winter, with significant seasonal variation (Patel et al., 2019; Sharma & Gupta, 2020; Verma et al., 2021). Factors such as low wind speed, moderate relative humidity, and low temperatures may contribute to the limited dilution of particulate pollution (Kulshrestha et al., 2009). As shown in Table 1, the average mass concentration of PM_{10} in the present study was higher than those in Beijing, Lagos and Mumbai (Chen et al., 2023; Owoade et al., 2023; Sharma et al., 2023). However, it was lower than earlier studies over Delhi (Chaudhary et al., 2022), Kolkata (Sharma et al., 2023) and Cairo (Taha et al., 2022).

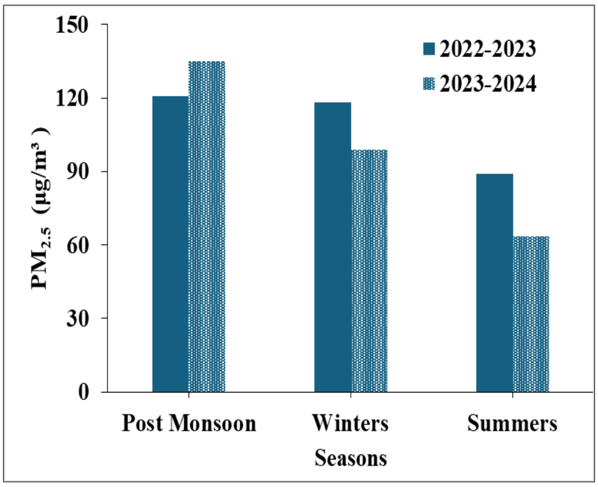
The annual average $PM_{2.5}$ concentration were 115.4 µg/m³ and 99.1 µg/m³ during 2022-2023 and 2023-2024, respectively. The annual mass concentration of $PM_{2.5}$ is shown in (Figure 3c). During both years, the highest average monthly concentration of $PM_{2.5}$ was recorded in November (Figure 3a). The average seasonal trend of $PM_{2.5}$ concentrations were Post-Monsoon> Winter> Summer (Figure 3b). Several studies have reported similar trends in $PM_{2.5}$ levels (Singh et al., 2020; Patel et al., 2022; Sharma and Gupta (2020). Table 2 presents the average concentrations of $PM_{2.5}$ across various urban cities in tropical countries. The results revealed that the average concentration of $PM_{2.5}$ in this study was higher compared to Mumbai (Sharma et al., 2023), Lagos (Owoade et al., 2023) and Kolkata (Sharma et al., 2023). However, it was considerably lower than in Delhi, Beijing, Cairo and Kanpur (Kumar et al., 2023; Chen et al., 2023; Taha et al., 2022; Patel et al., 2022).

Elemental Concentrations

The descriptive statistics of heavy metals concentration in PM_{10} (Cd, Ni, Cu, Cr, Mn, Pb and Fe) during study period presented in Table 3. The highest mean concentration for both year was of Fe (10.89 µg/m³) and followed by Mn (0.283) µg/m³). The general trend of heavy



(a)



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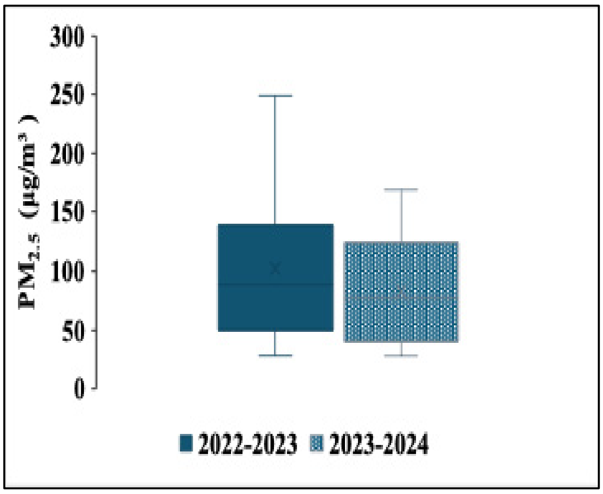


(c)

Fig. 3. Average $PM_{2.5}$ mass concentration in the study area (a) Monthly (b) Seasonal and (c) Annual.

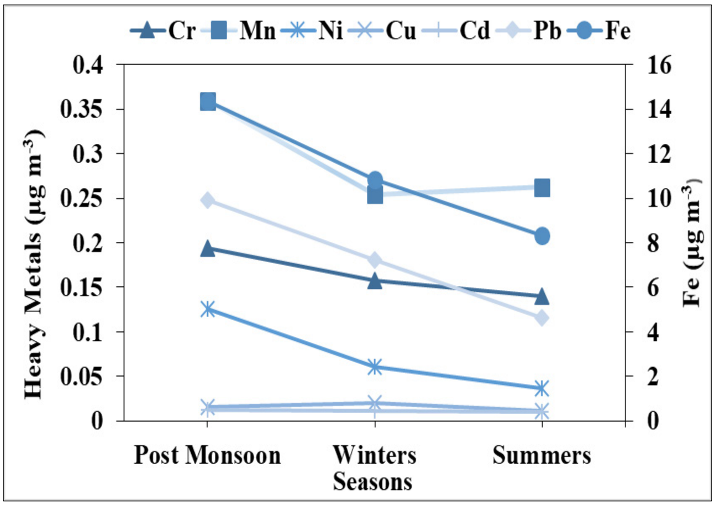
Table 2. Annual average $PM_{2.5}$ concentrations at different urban sites.

LOCATIONS	$PM_{2.5}$ ($\mu g/m^3$)	REFRENCES
Delhi	150	Kumar et al. (2023)
Beijing	120	Chen et al. (2023)
Lagos	100	Owoade et al. (2023)
Cairo	130	Taha et al. (2022)
Kolkata	100	Sharma et al. (2023)
Kanpur	150	Patel et al. (2022)
Lucknow	120	Patel et al. (2022)
Mumbai	60	Sharma et al. (2023)

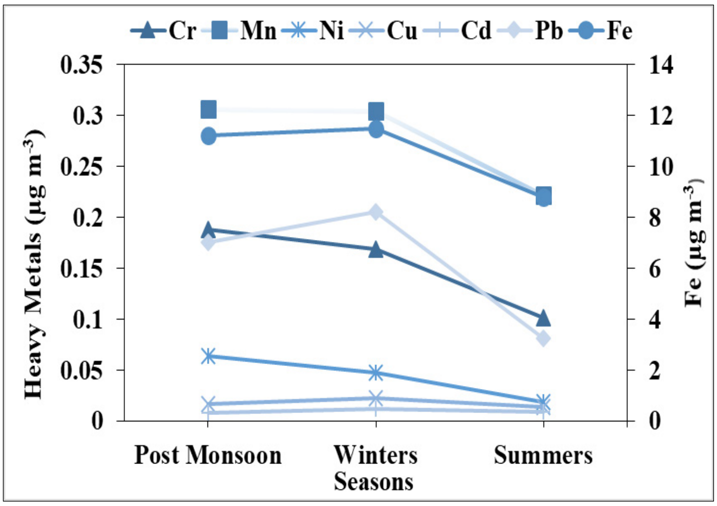
metal concentration was: Fe >Mn >Pb >Cr >Ni >Cu >Cd. Several studies have reported similar trends and demonstrate that iron (Fe) often has the highest concentration among heavy metals in PM_{10} (Kumari et al., 2021; Truong et al., 2022; De Gennaro et al., 2018). Seasonal Average concentrations of various heavy metals in 2022-2023 and 2023-2024 are shown in Figure 4a and Figure 4b, respectively. The prevalence of Fe (a crustal element) may be associated with PM from natural sources like windblown dust and resuspended road dust. In contrast, the high

Table 3. Descriptive statistics of annual concentration (µg/m3) of heavy metals in PM_{10}.

Pollutants	Maximum	Minimum	Mean	Median	SD
		2022-2023			
Fe	18.47	4.01	11.13	9.85	4.38
Pb	0.381	0.031	0.18	0.15	0.02
Cd	0.02	0.004	0.011	0.009	0.004
Ni	0.632	0.001	0.072	0.06	0.114
Cu	0.054	0.006	0.019	0.015	0.114
Cr	0.256	0.067	0.162	0.15	0.06
Mn	0.483	0.162	0.286	0.279	0.09
		2023-2024			
Fe	18.76	5.49	10.65	10.33	3.23
Pb	0.32	0.03	0.16	0.17	0.088
Cd	0.02	0.005	0.009	0.008	0.0008
Ni	0.103	0.005	0.043	0.048	0.005
Cu	0.046	0.005	0.018	0.016	0.011
Cr	0.291	0.073	0.154	0.163	0.059
Mn	0.486	0.133	0.281	0.288	0.091



(a)



(b)

Fig. 4. Seasonal average heavy metals concentration (a) 2022-23and (b) 2023-24

Table 4. Principal component loadings of the heavy metals for the study area

Heavy metals	Component		
	PC1	PC2	PC3
Fe	0.828	0.329	0.240
Pb	0.904	0.295	0.211
Cd	0.311	0.931	0.132
Ni	0.261	0.130	0.955
Cu	0.820	0.316	0.145
Cr	0.865	0.115	0.282
Mn	0.904	0.193	0.156
Eigenvalues	3.905	1.230	1.157
% of Variance	55.789	17.568	16.523
Cumulative %	55.789	73.356	89.879

levels of Ni and Pb are linked to PM from human activities such as tire wear, oil burning, and road dust resuspension. The average seasonal heavy metals concentrations in PM_{10} were higher in Post-Monsoon compared to winter and summer periods (Prodi et al., 2009), except Cu, Cd and Pb, as their highest concentrations were observed during winter. The notable rise in element concentrations during winter can be attributed to increased domestic heating, combustion sources, thermal inversion, and ground-level fog, which lead to air stagnation and higher pollutant levels (Padoan et al., 2016; Khare and Baruah, 2010). The positive correlation between Fe-Pb (0.892), Fe-Cr (0.734), Fe-Mn (0.794), Pb- Cd (0.580), and Pb-Cu (0.851), Pb-Cr (0.863) and Pb-Mn (0.885) was seen during the Pearson's correlation analysis of heavy metals in study area, which states that they are likely originated from common sources.

Principal Component Analysis

PCA is primarily used to reduce the number of variables, making it an effective data reduction method. In this study, using the Varimax Rotated Factor Matrix method and Kaiser normalization method, PCA was performed as based on the orthogonal rotation criterion that maximizes the variance of the squared metals in the columns of factor matrix. This method aims to produce factors with high correlation with smaller set of variables with little or no correlation with another set (Stevens, 1996). Table 4 presents the Principal Component (PC) loadings for the heavy metal data combined for both the years, including corresponding eigenvalues and variances.

Eigenvalues greater than 1.0 were extracted in three PCs, accounting for 55.78%, 73.35%, and 89.87% of the cumulative variance, respectively. PC1 states a total data variance of 55.78% with high Pb, Mn, Fe, and Cd loadings. These heavy metals could be from non- exhaust emissions and re-suspensions of road dust due to vehicular traffic. The presence of Fe suggests it may emitted from vehicle engine parts and wear and tear of brake pads (Roy et al., 2020; Karar et al., 2006; Shah et al., 2006; Chakraborty and Gupta, 2009).

The second factor (PC2) accounted for 17.56% and 24.89% of the variance% and cumulative%, respectively, with high loadings of Cd, Pb, and Cr. These heavy metals are commonly associated with automobile emissions and industrial emissions (Cetin et., 2007; Ahumada et al., 2007). Cr and Cd also derive significant contributions from vehicular emissions and metallurgical units in industrial areas, alongside crude oil combustion (Querol et al., 2007). Road traffic is a major source of cadmium, chromium and lead in urban environments. Geogenic dust and construction debris are the other possible contributors of the source (Cheng et al., 2018; Chen et al., 2012;). Ni and Pb high loadings are attributed to vehicular exhaust emissions (Hafner et al., 2004; Shah et al., 2006)

PC3 accounted for 16.52% and 89.87% of the variance% and cumulative%, respectively, with high loadings of Ni, Cr, Pb. Chromium and Nickel were contributed from automobile exhaust (Yadav et al., 2016; Guo et al., 2019). Chromium is mainly due to engine wear, as Cr is one of the metallic components of engine (Jeong et al., 2022; Tasdemir et al., 2006; Pandey et al., 2014).

The principal component analysis of Particulate matter revealed that vehicles (Diesel vehicles: 60-70% and Gasoline (Petrol) vehicles: 30-40%) and industrial emissions were the primary sources of the selected heavy metals in the ambient air of study area. These heavy metals can originate from both vehicle exhaust and non-exhaust sources. Non- exhaust sources encompass tire and brake wear, as well as the erosion caused by vehicle components. Vehicle exhaust emissions arise from fuel combustion and engine wear. Additionally, heavy metals can derive from other sources such as coal combustion and the resuspension of crustal materials and dust. The resuspension of road dust due to tire abrasion varies depending on meteorological conditions, road surface state and traffic volume. (Lough et al., 2005). Moreover, coal burning in stoves, a common practice in shops near roads, contributes to particulate matter emissions into the atmosphere (Suryawanshi et al., 2016).

Enrichment Factor Analysis

In this study, iron (Fe) was identified as the element most strongly associated with all others, making it the chosen reference element. The annual average percentage composition of metals in PM_{10} samples was determined (Nazir et al., 2011). Figure 5 presents the computed enrichment factors (EFs) for the study area, categorizing elements into two groups: highly enriched and mildly enriched. Lead (Pb) exhibited a significantly high EF value (63), indicating its primary origin from anthropogenic sources. In contrast, the EFs for Cd (1.3), Ni (1.6), Cr (2.2), Mn (1.4), and Cu (1.4) were below 5, suggesting contributions from both anthropogenic and crustal sources.

To reinforce the conclusion that anthropogenic activities are the dominant contributors to these heavy metals, various sources such as traffic emissions, brake and tire wear, fossil fuel combustion, industrial processes, and recycling industries (including rubber, plastics, powder, and oil) were identified as key contributors. Several studies support these findings, highlighting the role of human activities in heavy metal enrichment in urban air. For instance, Kumar et al. (2022) demonstrated that urban traffic emissions, particularly from diesel engine exhaust, significantly contribute to elevated levels of lead (Pb) and cadmium (Cd) in PM_{10}.

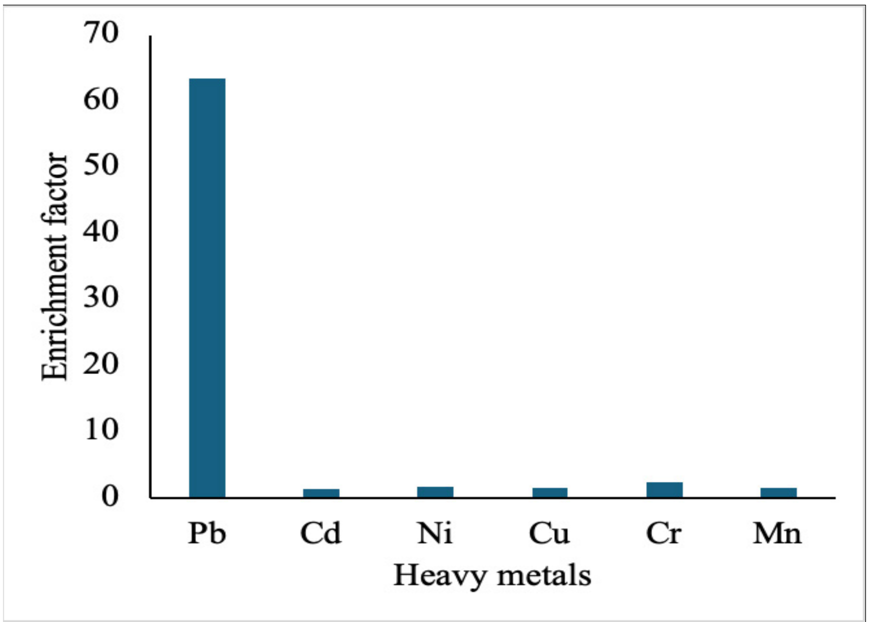


Fig. 5. Enrichment Factors values for heavy metals in PM_{10} in study area.

Table 5. Correlation analysis for heavy metals in the PM_{10}.

	Fe	Pb	Cd	Ni	Cu	Cr	Mn
Fe	1.000						
Pb	0.892	1.000					
Cd	0.560	0.580	1.000				
Ni	0.488	0.475	0.325	1.000			
Cu	0.838	0.851	0.523	0.410	1.000		
Cr	0.734	0.863	0.461	0.493	0.686	1.000	
Mn	0.794	0.885	0.509	0.412	0.740	0.868	1.000

Similarly, Smith et al. (2023) reported that industrial activities, such as metal smelting and waste incineration, are major sources of nickel (Ni) and copper (Cu) in urban air, aligning with the current study's findings.

The enrichment factors of other elements, including manganese (Mn) and chromium (Cr), indicated moderate enrichment, reflecting a combination of natural and anthropogenic origins. These elements are often linked to geological processes, such as rock weathering and soil erosion, alongside human activities (Zhang & Wang, 2022). Additionally, recent research has underscored the complex interplay between natural and anthropogenic sources, particularly in highly urbanized and industrialized areas (Lee et al., 2021). Understanding these contributions is essential for developing effective pollution control strategies and safeguarding public health.

Correlation Analysis

Pearson's correlation analysis was conducted to examine the relationships between all the heavy metals in terms of their concentrations and to develop an overall profile of the sources, since elements that show a strong correlation likely originate from common sources (Javed et al., 2015; Basha et al., 2014; Zhou et al., 2014). Table 5 shows the correlation coefficient (r) values for heavy metals that are significant at $P < 0.01$. Fe, Mn, and Cr were found to be well-correlated with each other, Fe-Mn ($r = 0.794$) and Fe-Cr ($r = 0.734$). These elements are lithophile, meaning they are more concentrated in the Earth's crust (White, 2013). It is likely that these elements are derived from windblown dust. Fe was also found to have a strong correlation with Pb (0.892) and Cr (0.560). The correlations between each pair of elements, Cd-Mn ($r = 0.509$), Pb- Cd ($r = 0.580$), Fe-Cd ($r = 0.560$) and Cd-Cr ($r = 0.461$) are also statistically significant. Many studies reported positive correlations between various heavy metals in PM_{10} samples (Kumari et al., 2021; Sharma et al., 2020; Park et al., 2014). These metals are typically introduced through anthropogenic activities, such as vehicular emissions and metal corrosion (Cu, Cd)), as well as coal burning (Cr, Pb) (Basha et al., 2014; Tian et al., 2017).

In this study, iron (Fe) and manganese (Mn) were identified as predominant factors, along with chromium (Cr), nickel (Ni), and lead (Pb). Traditionally, both lead (Pb) and nickel (Ni) have been used to trace automobile pollution sources. However, lead is no longer a reliable indicator of gasoline contamination due to the widespread use of unleaded gasoline since the late 1980s. Instead, lead contamination is increasingly linked to significant sources such as oil burning and vehicle emissions. Lead is also used to identify incineration sources. The primary contributors to lead pollution are believed to be manufacturing activities related to lead storage batteries, automobiles, and furniture painting. (Roy et al., 2020; Lim et al., 2012; Lee et al., 2006; Mishra et al., 2005). Paint abrasion from building materials and vehicle parts can also release lead (Pb) and cadmium (Cd) into the environment (Gupta et al., 2017). Cd compounds are used as antioxidants in lubricants and as an alloy in a car's battery or carburetor (Khan et al., 2019). Thus, the primary sources of trace elements in the study area are road dust resuspension from traffic turbulence, vehicular emissions (both exhaust and non-exhaust), and industrial emissions.

CONCLUSION

This study provides a critical understanding of the sources and seasonal variability of particulate matter (PM_{10}, $PM_{2.5}$) and associated heavy metals in the industrialized region of Manesar, Haryana. The findings reveal the complex nature of air pollution in this rapidly urbanizing and industrially expanding area, emphasizing the need for targeted mitigation strategies. The key finding of this study are as follows:

1. The average concentrations of PM_{10} and $PM_{2.5}$ exceeded the standard set by the CPCB, indicating significant PM contamination in the study area.
2. High levels of particulate-bound heavy metals including Fe, Cd, Pb, and Mn were observed, raising serious concerns about potential health risks for the residents.
3. PCA revealed that vehicular emissions were the dominant contributor (35.64%) to heavy metal pollution followed by industrial emissions (28.46%).
4. Crustal sources accounted for 20.34%, highlighting the effects of natural resuspension mechanisms on PM contamination.

The study reinforces existing theories on urban and industrial pollution, particularly highlighting the impact of vehicular and industrial activities on air quality. This clearly support the idea that industrial hubs significantly contribute to ambient PM pollution. Practically, these findings underscore the need of advanced dust suppression techniques, such as large-scale water flushing, which have been successfully implemented in developed nations to mitigate resuspended road dust.

Key lessons learned from this study include the need for season-specific strategies for controls PM_{10} and $PM_{2.5}$. Furthermore, source-apportionment results highlight the need for multi-sectoral interventions for reducing PM and associated heavy metals concentrations. Despite the valuable insights provided by this study, certain limitations exist. The spatial scope of this study was limited to Manesar, and further research should expand to neighbouring regions to assess cross-boundary pollution influences.

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CONFLICT OF INTEREST

The authors declare that there is not any conflict of interest 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 have been completely observed by the authors.

LIFE SCIENCE REPORTING

No life science threat was practiced in research.

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