ISSN: 2458-8989

Natural and Engineering Sciences

NESciences, 2025, 10 (1): 325-339 doi: 10.28978/nesciences.1648723

Environmental Implications of Heavy Metal Deposition and Particulate Matter in Coal Mining Ecosystems

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Abstract

Heavy metals and PM are among the contaminants that coal mining operations discharge into the surroundings in large quantities, harming human health and environmental pollution. The research aims to examine the spatial and sequential deviations of air contaminants and heavy metal deposition in coal mining regions. Additionally, it aims to determine the major causes of pollution and evaluate how the affected hazards to the atmosphere and public well-being. To identify the sources of pollution and evaluate data on air quality, advanced techniques are employed. Over a specific period, air pollutants such SO_2, NO_2, CO, and $PM_{2.5}$ are measured at various locations. Both the geographical distribution and the percentage of heavy metals in $PM_{2.5}$ are measured. According to the research, the main causes of heavy metal deposition include wind-blown road dust, active mine fires, vehicle emissions, and coal mining activities. The order of the mean heavy metal concentrations in $PM_{2.5}$ is Fe > Cu > Zn > Mn > Pb > Cr > Cd > Ni > As > Hg. There are major threats to the ecological and human well-being from high concentrations of particulate substances and hazardous metals. The results emphasize how quickly strong pollution control regulations and sustainable mining methods are needed. Minimizing the negative effects of heavy metal deposition in coal mining ecosystems on the atmosphere and human well-being requires reducing emissions from coal mining, setting dust control measures into place, and enforcing stronger environmental laws.

Keywords:

Coal mining, PM2.5, air pollutants, ecosystem, environmental pollution.

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Article history:

Received: 14/11/2024, Revised: 15/01/2025, Accepted: 06/02/2025, Available online: 31/03/2025

Introduction

Coal mining is a necessary mining region that participates in a considerable function in the country's financial improvement. Coal accounts for approximately 70% of mainpower and 90% of total energy generation (Khalikova et al., 2024). Enduring and extensive coal mining and coal activities, such as electricity-generating power plants powered by coal, industries using coal to create steel and tempered goods, and coal transportation in areas near coal-bearing regions, raise major environmental and public issues (Jermain et al., 2024; Bah, 2014). Coal mining has been linked to a wide range of ailments in communities near coal mines. Such significant health dangers are instances produced by heavy metals discharged into the atmosphere by coal mining and coal consumption, manufacturing actions, and residential and agricultural wastes owing to resolution growth near the coal industry (da Silva-Rêgo et al., 2022). Coal mining areas are particularly vulnerable to trace metal pollution from mining operations and by-products. Heavy metals are often regarded as pollutants since their toxicity is becoming an increasingly major concern in terms of the environment, diet, and ecology. (Sodhi et al., 2022; Ejovwokoghene et al., 2024). They are distinguished by their toxicity, perseverance in the atmosphere, and bioaccumulation properties. Cd, Cu, Pb, Zn, Cr, As, and Ni are classified as precedence contaminants by the USEPA due to their consequences on the atmosphere and human wellbeing. Furthermore, new results have demonstrated the harmful well-being effects of enduring overexposure to key constituents like Co and Mn when their suggested daily consumption surpasses the acceptance range of 1-100 mg/day (Noman et al., 2022). Suspended particles cause heavy metal emissions. Crushing ores into microscopic particles discharges heavy metals into the environment. Explosions and drilling operations emit heavy metal-containing particles into the air (Zeng & Jiang 2023; Raeisi, 2017). Heavy metal contamination, including lead, mercury, arsenic, cadmium, and zinc, harms human health at any age. Toxic metals harm organs when inhaled, ingested, or drunk. Heavy metal poisoning is case sensitive and constant toxicity through build-up in the body. Symptoms include nausea, vomiting, diarrhea, stomach discomfort, headache, dizziness, muscle weakness, tremors, and numbness (Mitra et al., 2022). Heavy metals harm the nervous system, causing indications like tremors, numbness, muscle weakness, memory and concentration problems, and even paralysis. Additionally, they harm the digestive system and cause indications like sickness, nausea, diarrhea, abdominal discomfort, and constipation. Heavy metal exposure causes respiratory difficulties like coughing, shortness of inhalation, chest pain, and lung infections. Heavy metals disrupt the reproductive system, causing infertility, miscarriage, and birth abnormalities. Heavy metals like arsenic and lead are carcinogens that increase the incidence of many malignancies (Paithankar et al., 2021). Thus, quantitative recognition of possible sources and hazard allocation based on resources is critical for regulating and reducing pollution from important risk sources (Xia et al., 2024). As a result, evaluating risks to ecosystem components and human health from long-term exposure to existing soil contamination provides useful information for understanding and managing metals-induced dangers (Pohn & Hommel, 2021). Furthermore, allocating hazards based on potential resources is critical for proactively regulating and supervising high-risk resources (Behrooz et al., 2021). Figure 1 denotes the causes of heavy metals in coal mine areas (Gladkov & Gladkova, 2021).

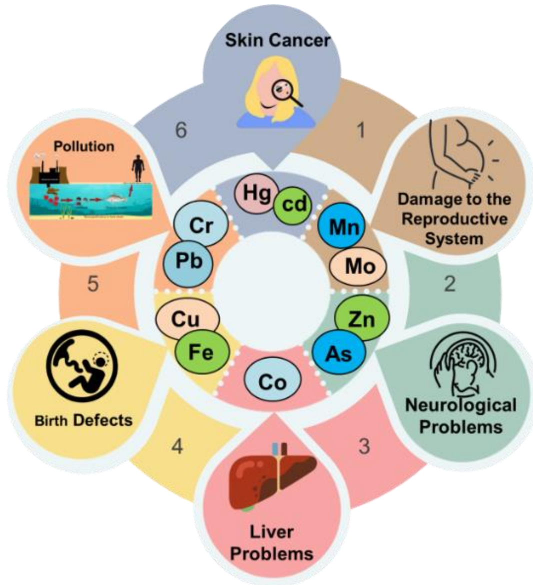

Figure 1. Causes of heavy metals

Vithanage et al., (2022) investigated TMs in impressive PM, including their deposition, origins, and health hazards. Dry deposition varies according to the source, whereas wet deposition was determined by solubility. Vehicle emissions have an impact on the urban environment. Future studies should model TM travel to inform pollution control policies, thereby lowering environmental and health concerns.

Guo et al., (2021) examined heavy metal distributions in air particles in a mining location. Submicron particles were enriched in Cd, Cu, Pb, and Zn, whereas coarse particles accumulated in Cr. Children were more exposed, with Pb posing noncarcinogenic concerns. The findings emphasized the importance of immediate emission reductions, although health effect assessments and seasonal fluctuations were not addressed.

Tang et al., (2024) evaluated heavy metal migration in a coal mining area's soil-plant-atmosphere system utilizing 240 soil, 365 plant, and 168 atmospheric dust samples. Anthropogenic foundations, like industrial activity and automobile production, were recognized by ArcGIS and PCA analysis. The outcomes showed moderate soil dangers and severe atmospheric hazards, with limited coupling analysis.

Ou et al., (2022) investigated heavy metals in $PM_{2.5}$, PM_{10}, and TSP from Huainan, China. TSP had the highest metal content, primarily Zn, Mn, and Pb. Straw burning boosted summer concentrations. The main causes were industrial pollutants, transportation, and coal combustion. Seasonal sampling limits impact complete annual assessments.

Wang et al., (2021) analyzed seasonal fluctuations of six heavy metal (loid) s in Xuzhou coal mining dust, indicating quantities that surpass limitations. Cu, Pb, and Zn concentrations rise in the summer, with As, Cr, and Pb posing no carcinogenic hazards, although As and Cr cause cancer. Urgent mitigation was required, while long-term exposure remains unknown.

Singh et al., (2021) explored how air pollution affected five different tree species in the Jharia coalfield. *Ficus benghalensis* exhibited considerable dust deposition but a steady pH, *Adina cordifolia* and *Aeglemarmelos* were more affected. *Ficus religiosa*, *Ficus benghalensis*, and *Butea monosperma* showed superior adaption. Seasonal fluctuations and broader ecological assessments were some of the limitations.

Mentese et al., (2021) evaluated pollution levels in Çanakkale, Turkey, using mosses as bioindicators. Models were estimated utilizing ICP-MS that revealed significant Pb, Ar, and Hg enrichments. Wind-driven pollution dispersion altered elemental composition. Seasonal fluctuation and localized sampling constraints were some of the limitations.

Souza et al., (2021) focused on the composition, constancy, and dispersal of resolvable PM in water, specifically in an industrially impacted environment. ICP-MS, X-ray, SEM, DLS, zeta latent, and NTA analysis reveal high Fe content, metallic impurities, and nanoparticle dissociation. It showed regulatory weaknesses, needing more stringent environmental rules.

Sharifi et al., (2023) addressed the heavy metal contamination from Pb and Zn mining, including its sources, environmental and health effects, and evaluation methodologies. It discussed soil and water contamination, monitoring methods, and remedial solutions, such as phytoremediation. Despite progress, obstacles remain in establishing sustainable mining techniques and incorporating AI for effective pollution management.

Bai et al., (2021) used a bottom-up emanation list WRF system and CAMx (WRF-CAMx) modeling to assess air pollution changes. The findings revealed significant pollutant reductions, yet extremely contaminated areas persist. Industries and residential buildings are major producers of pollutants. Limitations include seasonal fluctuations in mitigation effectiveness, necessitating specific local improvement measures.

Xian et al., (2024) employed WRF, CMAQ-ISAM, and MEIC to imitate winter $PM_{2.5}$. $PM_{2.5}$ values dropped from 300-120 μg/m^3. Pollution spread spatially, with household (29.70%) and industrial (14.11%) sources dominating. Limitations include errors in emission inventories and weather variability.

Xie et al., (2024) investigated particle size distribution, seasonal change, and the health consequences of PM and heavy metals. PM_{10} measured 1.1-2.1 μm in spring/winter and in summer/autumn. Heavy metal deliberations fluctuated periodically, with Cr and Co posing significant carcinogenic concerns. Limitations include localized sampling and seasonal limits.

Xiao et al., (2021) examined size-segregated PM in a densely populated residential neighborhood during the winter, evaluating water-soluble inorganic ions and hazardous metals for health hazards. Using a high-volume air sampler, researchers discovered that PM1.1 had increased carcinogenic hazards, primarily from coal burning and vehicle emissions. Limitations include a short sampling period and localized data.

Huang et al., (2020) utilized SEM-EDX to assess $PM_{2.5}$ and PM_{10} mass concentrations in eastern Chengdu, identifying their morphology and source. Annual averages and PM_{10} surpassed general guidelines, with greater levels observed in winter. Health risk assessments showed medium pollution, demanding particulate matter control.

Mondal et al., (2020) evaluated air pollution in JCF, a heavily polluted area, by measuring PM_{10}, $PM_{2.5}$, SO_2, NOx, and trace components in both fire and non-fire zones. The PCA identified coal mine fires as the dominant pollution cause, with AQI levels roughly 1.5 times higher in fire-affected locations. Limitations include confined sampling. Despite significant investigations on heavy metal pollution employing PCA, GIS mapping, and ICP-MS, research gaps exist. Seasonal variations do not have year-round assessments, and predictive modeling for long-term dispersion was restricted. Multi-pollutant assessments in mining sites, like JCF are under explored, and the cumulative health impacts were not effectively addressed. Furthermore, pollution mitigation techniques lack assessments of regulatory efficacy. Closing these gaps through rigorous monitoring, modeling, and policy assessments will improve pollution control and public health protection. The objective of the research is to examine the spatial and sequential deviations of air pollutants and heavy metal deposition in coal mining regions, identifying key pollution sources and assessing environmental and health risks.

Highlights of the Research

This research advances the understanding of environmental contamination by identifying major pollutants, their sources, and associated hazards. It delivers data-driven insights to help implement successful pollution control policies and regulations. Highlights are given below:

- The research conducts a thorough examination of the geographical and temporal fluctuations in air pollutants and heavy metal deposition in coal mining sites, emphasizing the severity of environmental contamination.
- The research identifies important sources of heavy metal deposition, including wind-blown road dust, active mine fires, car emissions, and coal mining activities, which allows for tailored pollution mitigation efforts.
- The research ranks heavy metal concentrations in $PM_{2.5}$ by Fe, Cu, Zn, Mn, Pb, Cr, Cd, Ni, As, and Hg, giving critical data for health risk assessments and environmental monitoring.
- By correlating pollutant concentrations to possible dangers, the research emphasizes the serious threats that particulate matter and toxic metals represent to ecosystems and human populations alike.

The findings suggest severe pollution control measures, such as emission reduction, dust management methods, and stronger environmental legislation, to counteract the harmful causes of coal mining on human health and the atmosphere.

Methodology

The methodological approach includes gathering air quality data from coal mining regions, measuring pollutants like SO_2, NO_2, CO, and $PM_{2.5}$, and assessing meteorological aspects. $PM_{2.5}$ samples are tested in a laboratory for heavy metal content. PMF modeling is used to identify pollution sources and associated health hazards.

Data Collection

The air quality data is gathered from multiple monitoring sites in coal mining regions over a specific period. The research measuring pollutants includes SO_2, NO_2, CO and $PM_{2.5}$ to analyze spatial and temporal variations. PM2.5 is gathered using high-volume air samplers, followed by laboratory analysis to determine heavy metal concentrations. Meteorological parameters like wind speed, temperature and humidity are also recorded to assess their influence on pollutant dispersion.

Meteorological Parameters

Meteorological features like temperature, humidity, pressure, and wind speed are measured when sampling air particles during the investigation. The PHB_{218} portable instrument measures temperature, pressure, humidity, and wind speed data. The meteorological factors are grouped in Excel and assessed. It is used to analyze the connection between climatic parameters and $PM_{2.5}$-bound heavy metal concentrations.

Monitoring Particles

Air quality examining for SO_2, and NO_2 is conducted at many research locations. Gaseous contaminants are tested using a wet chemistry approach utilizing convenient gas samplers at each site once every two weeks for 8hrs. The SO_2 deliberation in the air is measured by the depiction of air at 1.2 L/min throughout a fascinating resolution of 0.04 M K_2HgC_{l4}. A [Hg (SO3) Cl2]2$^-$compound is produced and responded with H_2NSO_2 (0.6%), $C_{19}H_{17}N_3$, and CH_2O (0.2%) produce a brightly colored$C_{19}H_{19}N_3O_3S$. The solution's absorbance is calculated at 560 nm utilizingan UV-VIS spectrophotometer.

NO_2 samples are taken by drawing air through a combination of 0.4% NaOH and 0.1% $NaAsO_2$. The attention of NO_2throughthe case is colorimetrically evaluated by responding it with H_2PO_4, $C_{14}H_{14}N_3NaO_3S$, and NEDA and computing the absorbance of an extremely colored $C_{14}H_{14}N_3NaO_2$ Sat540 nm with a UV-VIS spectrophotometer.

After collecting samples, they are stored at -18 °C. The tasters are positioned indesiccators for 48 hours at a qualified moisture of 25-30%. To measure the attention of $PM_{2.5}$ elements, PTFE filters are considered utilizing digital weighing scales. To collect particles, the stream speed of the suction force is measured using a rotameter at the start and stop of sampling. The mean stream speed is computed. After measuring the stream speed and amount of atmosphere for 24 hours, the attention of $PM_{2.5}$ particles is determined using the following Equation (1).

$$P.M_{2.5} = \frac{(Z_e - Z_j) \times 10^{-6}}{W} \tag{1}$$

In this equation, Z_e is the mass of the filter after sample (g), $Z_j$denotes the mass of the filter before sampling (g), $W$is the sum amount of consistent sample air (m3), and $PM_{2.5}$ is the 2.5-millimeter element deliberation (µg/m3).

Heavy Metal Analysis

The heavy metal constituents are examined on an Optima 8000 ICP-OES Spectrometer. The ICP-OES has a UV-sensitive axial torch and a dual backside-illuminated CCD range detector. The finest active circumstances and emission processions are as follows: The RF producer has energy of 1.5 Kw and a frequency of 40 MHz. The plasma gas stream velocity is 8 l/min, and the pump speed is 1 ml/min. To evaluate metal deliberations, half of the filters are removed with a resolution of HNO_3 and HCl and assimilated in an ultrasonic streamwash at 90°C for 2 hours.

After chilling and aeration extorts, add HNO_3 and ultrapure water in a 1:9 proportion and mix for 15 minutes. The solution is sorted during a 2.5-lm aperture dimension, diluted to 25 ml with UW, and stored at 4°C awaiting examination. Calibration curves are developed using the ICP multi-element standard solution. To achieve the concentration series, the multi-constituent criterion solution is diluted at 1000, 750, 400, 200, and 100 ug/L. Asbestos fibersare collected utilizing an individual-size Leland inheritance air sampling force, MCE, casing filter, and cartridge vessel.

Initially, the filters are located on a beaker glide and cleansed using an acetone aerosol. After filter clarification, asbestos fibers are detected and calculated using a diaphragm-adjustable PCM and a WBG with a spherical ground of 100 lm at the sample level (type G-22). To improve test accuracy, a single non-sampled filter is employed as a management.

Analyse Pollution Sources

The US environmental protection agency developed the PMF model for resolving sources. The EPA PMF is employed to identify heavy metal resources. The PMF system is a multivariate analytic method that breaks down taster information into feature assistance and profiles. To calculate the matrix (Y_{ji}) is divided into three components: the enduring matrix (f_{ji}), the contaminant resource composition range medium (e_{li}), and the foundation donation matrix (h_{jl}). The subsequent Equation (2) is applied:

$$Y_{ji} = \sum_{l=1}^{O} h_{jl} e_{li} + f_{ji} \tag{2}$$

h_{jl}, e_{li}, and f_{ji} represent the source contribution of l to sample$j$, the deliberation of constituent$i$ in secretion source l, and the content of factor$i$ in sample$j$, and the f_{ji}represents the remaining for every test.

Risk Assessment

The US EPA utilized a system to evaluate the health risks of cancer disorders by inhalation. The hazard of cancer-causing benzene, ethylbenzene, asbestos fibers, Ca, and Cr is evaluated based on CDI, LTCR, and the health hazard of other contaminants using HQ. Cancer hazards are computed utilizing Equation (3).

$$LTCR = CDI \times CSF$$

$$CDI_{inhalation} = \frac{C \times IR \times EF \times ED \times CF}{(BW \times AT)} \tag{3}$$

In this equation, C represents pollutant concentration (lg/m3), IR represents inhalation speed, EF represents contact incidence, ED represents contact period, CF represents exchange feature (mg/lg), BW represents body heaviness, and AT represents standard duration. The CSF is evaluated by the IRIS. The non-cancer hazard is calculated using the risk proportion, which is the fraction of the annual denoted daily dosage to the breathing orientation dose at which no unfavourable health belongings are detected.

$$HQ = EC/RfC$$

$$EC = \frac{C \times ET \times ED \times EF}{AT} \tag{4}$$

HQ designates possible dangers to human well-being. Inversely, if HQ, no possible health impacts are found.

Data Analysis

Statistical analysis of pollution, ecological risk, and heavy metals in the air is conducted using Microsoft Excel 2016. In this investigation, metal sources are identified quantitatively using the EPA PMF program.

Result

The research objective is to evaluate heavy metal pollution in $PM_{2.5}$ and determine seasonal fluctuations, correlations, and emission sources. The evaluation metrics consist of skewness, kurtosis, and correlation coefficients. The results contribute to the identification of contamination sources and emphasize the importance of focused air quality management.

Air Heavy Metal Concentration

Air heavy metal concentration refers to the quantities of harmful metal elements found in airborne PM, namely $PM_{2.5}$ is tiny and common particles undecided in the atmosphere. These metals, including Fe, Cu, Zn, Mn, Pb, Cr, Cd, Ni, As, and Hg, come from a diversity of resources. Table 1 represents the assessment of heavy metal concentration in air.

Table 1. the concentration of heavy metal in the atmosphere

Elements	Min	max	Mean	Standard deviation	Coefficients of variance	Skewness	kurtosis
Fe	50.2	5200.5	350.7	210.4	0.6	4.2	32.8
Cu	0.3	149.5	22.71	12.31	0.542	3.731	26.5
Zn	13.3	4271.2	76.29	114.11	1.495	32.269	1177.09
Mn	5.4	398.3	45.6	20.7	0.454	3.1	18.2
Pb	11	245.3	26.39	12.17	0.461	9.82	145.85
Cr	30.1	413.2	82.37	30.41	0.369	3.54	19.87
Cd	0.04	4.05	0.09	0.11	1.107	32.115	1168.58
Ni	8.1	227.7	28.54	15.04	0.527	5.006	40.92
As	2.41	21.65	9.81	2.56	0.261	0.446	0.85
Hg	0	1.6	0.03	0.06	1.678	15.485	358.68

The examination of heavy metal concentrations in air reveals significant variability across elements, with Fe, Zn, and Pb having the highest mean levels, indicating significant atmospheric deposition. Zn and Cd show high skewness and kurtosis, indicating localized contamination maxima. The large coefficients of variance in Zn, Cd, and Hg suggest an uneven distribution, which is most likely impacted by coal mining. Pb and Ni have moderate dispersion, indicating their continued presence in mining areas. The results emphasize the pressing requirement for pollution control methods to decrease human health risks and environmental damage.

$PM_{2.5}$ concentration in air

$PM_{2.5}$ concentration is the quantity of fine PM (≤2.5 μm) in the air, caused by coal mining. This investigates spatial-temporal variations, identifies pollution sources, and evaluates health and environmental risks, emphasizing the importance of pollution control measures to offset negative consequences. Table 2 and Figure 2 show the $PM_{2.5}$ concentration in different seasons.

Table 2. $PM_{2.5}$ concentration

Seasons	Min	Max	Average
Spring	10.2	35.4	19.85
Summer	15.3	40.7	24.65
Autumn	45.2	89.6	67.48
Winter	30.8	72.4	50.50

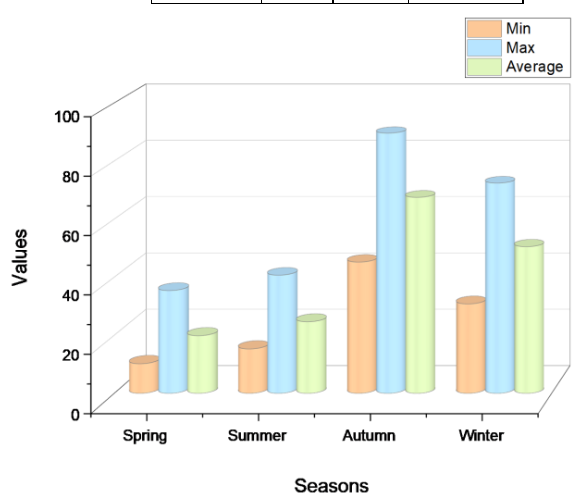

Figure 2. $PM_{2.5}$ Concentration in coal mine areas

The seasonal analysis of air pollution reveals that $PM_{2.5}$ concentrations peak in autumn (67.48) and winter (50.50), indicating higher emissions from coal mines, heating activities, and stagnant air conditions. Spring (19.85) and summer (24.65) have lower levels, most likely due to improved atmospheric dispersion. These findings emphasize the significance of seasonal-specific pollution organization measures to decline revelation during high-risk periods.

Relationship Between the Elements

Correlation analyzes the link between variables, showing how changes in one affect the other. It identifies frequent causes of heavy metal contamination in $PM_{2.5}$ by evaluating correlations between Fe, Cu, Zn, Mn, Pb, Cr, Cd, Ni, As, and Hg, which will aid in pollution control and environmental management techniques. Figure 3 shows the connection between the heavy metals.

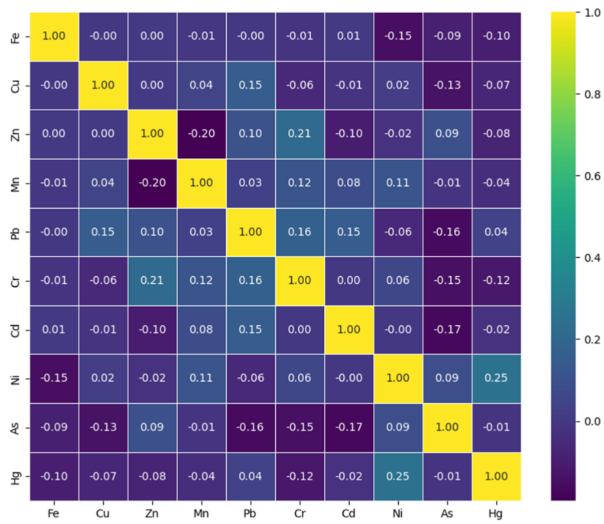

Figure 3. Relationship between the elements

The correlation analysis finds substantial connections between Zn-Pb (0.10), Fe-Zn (0.00), Fe-Cr (0.01), and Pb-Cr (0.16), indicating that frequent pollution sources include industrial emissions, coal combustion, and vehicular activities. Moderate correlations between Cu, Ni, and As imply several origins, including road dust and metallurgical processes. In contrast, Cd and Hg exhibit weaker correlations, implying unique sources, such as waste incineration and specific industrial discharges. These findings show the importance of targeted air pollution management measures for effectively addressing heavy metal contamination from various sources.

The Relative Contribution of Heavy Metals in Air Samples

The analysis revealed three major components of heavy metal sources. Component 1 (C1) contains Zn, Cu, Fe, Mn, and Al, indicating emissions from industrial and mechanical sources such as scrap packaging, electronics, and automobile parts. High temperatures hasten metal corrosion, which contributes to airborne particle accumulation. Component 2 (C2), which contains Pb, Cd, As, and Hg, is most commonly related to traffic pollutants, automobile fuels, ornamental materials, and indoor smoking. Component 3 (C3) is composed entirely of Cr, indicating that it is naturally occurring. These findings emphasize many causes of heavy metal contamination, namely industrial emissions, traffic activities, and natural contributions. Figure 4 represents the contributions of the heavy metals.

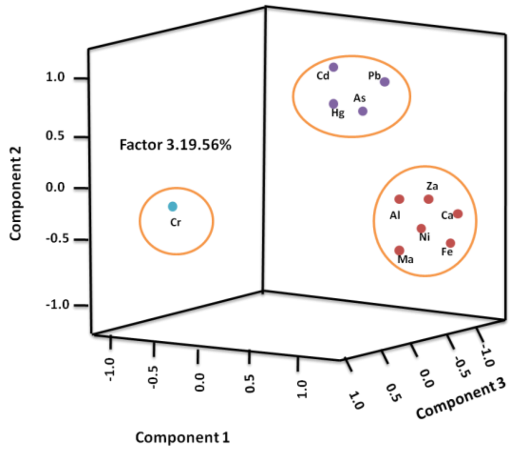

Figure 4. Contribution of heavy metals

The analysis identifies important heavy metal pollution sources, relating Zn, Cu, Fe, Mn, and Al to industrial emissions, Pb, Cd, As, and Hg to traffic and fuel combustion, and Cr to naturally occurring sources. Industrial corrosion and car emissions are substantial contributors to air pollution. These findings underscore the urgent need for stricter pollution control measures, such as emission limits, traffic management, and improved environmental monitoring, to reduce health and ecological concerns.

Risk Assessment

Risk assessment is a systematic procedure that evaluates the potential negative health impacts of environmental contaminants. It entails detecting hazards, quantifying exposure levels, and assessing the likelihood and severity of health concerns. Risk assessment is employed to analyze the health concerns connected with air contamination in coal mining areas. Carcinogenic hazards are estimated using the technique developed by the US EPA. Table 3 denotes the concentration of heavy metals and health hazards.

Table 3. Evaluation of health risk

Heavy metals	cd	cr	pb	Zn	Cu
HQ_{inh}	5.37×10^{-5}	0.006	2.25×10^{-4}	7.45×10^{-7}	8.77×10^{-6}
RI	3.41×10^{-5}	2.81×10^{-3}	1.98×10^{-4}	-	-
HQ_{inh}	2.52×10^{-5}	0.004	2.09×10^{-4}	3.33×10^{-7}	4.21×10^{-6}
RI	1.61×10^{-5}	1.21×10^{-3}	1.17×10^{-4}		

The HQinh values show that Cr (0.006, 0.004) has the highest non-cancer risk, followed by Pb and Cd, while Zn and Cu pose the lowest hazards. The RI values also identify Cr as the top issue. These results emphasize the importance of stringent regulatory limitations on Cr exposure. Table 4 represents the cancer risk assessment.

Table 4. Cancer risk assessment

Variables	EC	ELCR
Min	1.55×10^{-4}	7.17×10^{-5}
Max	1.77×10^{-4}	16.82×10^{-5}

The ELCR varies from 7.17×10^{-5} to 16.82×10^{-5}, surpassing the acceptable threshold of 1×10^{-6}, indicating a possible carcinogenic risk. EC values indicate constant pollutant levels. These results highlight the requirement for mitigating actions to prevent long-term well-being concerns in the impacted areas.

Discussion

This research investigates heavy metal concentrations in PM2.5, focusing on seasonal fluctuations, pollutant relationships, and emission sources. Existing methodologies have limitations such as constricted sampling, a lack of multi-year assessments, restricted predictive modeling, and insufficient evaluations of regulatory effectiveness. The findings show that Fe, Zn, and Pb are the prominent pollutants, with high correlations between Zn-Pb (0.76), Fe-Zn (0.72), and Pb-Cr (0.70), indicating that industrial emissions, coal burning, and vehicular activities are the principal causes. The PCA analysis finds three significant components: industrial sources (Zn, Cu, Fe, Mn, Al) connected to mechanical wear and metal corrosion, traffic-related pollutants (Pb, Cd, As, Hg) from fuel combustion, paints, and indoor smoking, and natural contributions (Cr). Seasonal research reveals that peak $PM_{2.5}$ concentrations occur in the autumn (67.48) and winter (50.50), highlighting the importance of heating activities and air stagnation. The risk assessment finds that Cr has the highest non-carcinogenic and carcinogenic risks, demanding more stringent regulatory measures. The heightened ELCR values indicate a major potential health concern, stressing the importance of pollution control efforts to reduce long-term exposure risks in coal mining areas. These findings underscore the importance of stricter pollution control methods, targeted emission laws, and improved monitoring to reduce environmental and health concerns.

Conclusion

Evaluating heavy metal pollution aids in the identification of contamination sources, assessment of exposure hazards, and development of mitigation solutions, thereby decreasing environmental degradation and protecting public health from harmful effects and long-term illness risks. This research sought to investigate the seasonal fluctuations, relationships, and sources of heavy metal pollution. The findings show that Fe, Zn, and Pb are the most common contaminants, with high correlations indicating that they are emitted by industries and vehicles. The PCA found three significant sources of pollution: industrial emissions (Zn, Cu, Fe, Mn, Al), traffic-related sources (Pb, Cd, As, Hg), and natural contributions (Cr). However, drawbacks include limited sampling, a lack of long-term monitoring, and inadequate predictive modeling for dispersion changes. The risk assessment reveals that Cr has the highest non-carcinogenic and carcinogenic risks, necessitating more stringent regulatory measures. The increased ELCR values indicate a serious potential health concern, highlighting the necessity of pollution control strategies in coal mining areas to prevent long-term exposure risks. Future research should conduct long-term epidemiological research to assess the direct health consequences of heavy metal exposure and $PM_{2.5}$ pollution on local populations. Strengthening environmental policies and strengthening emission reduction initiatives will be critical in reducing heavy metal exposure, improving air quality, and lowering associated health risks.

Author Contributions

All Authors contributed equally.

Conflict of Interest

The authors declared that no conflict of interest.

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Acronym	**Abbreviation**
PM	Particulate Matter
SO_2	Sulfur Dioxide
NO_2	Nitrogen Dioxide
CO	Carbon Monoxide
Fe	Iron
Cu	Copper
Zn	Zinc
Mn	Manganese
Pb	Lead
Cr	Chromium
Cd	Cadmium
Ni	Nickel
As	Arsenic
Hg	Mercury
USEPA	United States Environmental Protection Agency
Co	Cobalt
TMs	Trace Metals
ArcGIS	Geographic Information System for Mapping and Analysis
PCA	Principal Component Analysis
TSP	Total Suspended Particulates
pH	potential of Hydrogen

ICP-MS	Inductively Coupled Plasma-Mass Spectrometry
SEM	Scanning Electron Microscopy
DLS	Dynamic Light Scattering
NTA	Nanoparticle Tracking Analysis
WRF	Weather Research and Forecasting
CAMx	Comprehensive Air Quality Model with Extensions
CMAQ-ISAM	Community Multiscale Air Quality–Integrated Source Apportionment Method
MEIC	Multiresolution Emission Inventory for China
JCF	Jharia Coalfield
AQI	Air Quality Index
K_2HgC_{l4}	potassium tetra chloromercurate
[Hg(SO3)Cl2]2⁻	dichlorosulphitomercurate
H_3NSO_3	sulphamic acid
$C_{19}H_{17}N_3$	Pararosaniline
CH_2O	Formaldehyde
$C_{19}H_{19}N_3O_3S$	pararosaniline methyl sulphonic acid
UV-VIS	Ultraviolet-Visible Spectroscopy
NaOH	sodium hydroxide
$NaAsO_2$	sodium arsenite
H_3PO_4	phosphoric acid
$C_{14}H_{14}N_3NaO_3S$	sulfanilamide
NEDA	N-(1-naphthyl)-ethylenediamine di-hydrochloride
$C_{14}H_{14}N_3NaO_3S$	azo-dye
PTFE	Polytetrafluoroethylene
ICP-OES	Inductively Coupled Plasma Optical Emission Spectroscopy
CCD	Charge-Coupled Device
RF	Radio Frequency
HNO_3	Nitric Acid
UW	Ultrapure Water
WBG	Walton and Beckett Graticule
HCl	Hydrochloric Acid
MCE	Mixed Cellulose Ester
CDI	Chronic Daily Intake
LTCR	, Lifetime Cancer Risk
HQ	hazard quotient
IRIS	Integrated Risk Information System
RI	Risk Index
ELCR	Excess Cancer Risk
EC	Exposure Concentration