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Heavy Metal Accumulation in Agricultural Soils: Environmental Risk Assessment and Remediation Strategies

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Abstract

Heavy metal enrichment in agricultural soils raises severe environmental as well as health issues, especially where there is industrial activity alongside intensive agriculture. This study assessed the level of heavy metal contamination in five agricultural soil samples from Ludhiana District, Punjab, India. Cadmium (Cd), lead (Pb), arsenic (As), chromium (Cr), nickel (Ni), copper (Cu), and zinc (Zn) in soil samples were analyzed by inductively coupled plasma mass spectrometry (ICP-MS). Levels of pollution were measured in terms of contamination factor (CF), enrichment factor (EF), geo-accumulation index (I_geo), and ecological risk index (RI). The risks to human health were estimated using United States Environmental Protection Agency (USEPA) models based on ingestion, dermal contact, and inhalation exposure routes. The contents of Cd (1.2–3.4 mg/kg) and Pb (45.7–112.3 mg/kg) were higher than the WHO/FAO permissible limits in 60% of the sites. RI values were maximum at Sahnewal (355) and Doraha (312), showing significant ecological risk, with cadmium accounting for about 70% of the cumulative RI. High EF values for Cd, Pb, and Zn validated severe anthropogenic impact, mainly from industrial effluent and agrochemical application. Non-carcinogenic health risk assessment showed that children were exposed to greater non-carcinogenic risks (HI > 1), especially in the vicinity of industrial areas. Multivariate statistical analysis ascribed heavy metals to both industrial pollution and overuse of fertilizers and pesticides. Results confirm the immediate requirement for site-specific treatments like phytoremediation and organic amendments combined with regulatory actions for controlling pollution sources, maintaining soil health, and food safety.

Keywords: *Heavy metals, Agricultural soils, Environmental risk assessment, Human health risk, Soil remediation strategies.*

1. INTRODUCTION

Public health, ecological resilience, and sustainable food systems all depend on the health and productivity of agricultural soils (Rashid et al., 2023). Soil quality is a global problem due to the introduction of persistent pollutants, primarily heavy metals. Cd, Pb, As, Cr, Ni, Cu, Zn, and other heavy metals are continuously increasing in agricultural settings where intensive agriculture and industry coexist (Yang et al., 2019). Unlike organic contaminants, heavy metals provide long-term risks to human health, agricultural security, and terrestrial habitats since they are not biodegradable and can accumulate over time. Although soil minerals naturally contain minor amounts of heavy metals, human activity is mostly to blame for the current elevated levels (Angon et al., 2024). Because untreated or insufficiently treated industrial effluent is released into the environment, farming lands close to industrialized regions are more likely to be contaminated. It has been discovered that significant amounts of heavy metals are released during the processes of metal fabrication, electroplating, textile dyeing, and chemical manufacturing (Wan et al., 2024). These metals then build up in the nearby soils by air deposition or wastewater discharge (Luo et al., 2009). Additionally, this issue has been made worse by the overuse and careless use of chemical pesticides and fertilizers high in phosphate in modern agriculture (Khatun et al., 2022). With every farming season, these agrochemicals, which are often contaminants like lead, arsenic, and cadmium, enter the soil profile. Furthermore, sewage or Municipal wastewater that has not been treated is frequently utilized for irrigation in the majority of peri-urban and semi-urban areas, contributing to soil contamination (Alengebawy et al., 2021).

The heavy metal genre buildup in soils has serious environmental repercussions. High concentrations of harmful metals disrupt microbial activity in the soil, alter enzymatic activity, and diminish physicochemical processes necessary for the breakdown of nutrients and organic matter (Munir et al., 2021). These changes gradually reduce agricultural production potential and soil fertility. The bioavailability of these metals makes them more likely to be absorbed by plants, which is important for food safety. Metal levels in the edible plants' roots, stems, leaves, and fruits grown in contaminated soils are often higher than those considered acceptable by international standards. There are serious health risks associated with consuming certain foods, especially if exposures are continuous and come from a variety of dietary sources (Tóth et al., 2016).

There are established hazards to one's health from prolonged exposure to heavy metals (Naujokas et al., 2013). Lead exposure affects an adult's or child's cardiovascular and cognitive development; cadmium damages the kidneys and can result in renal failure. A known carcinogen is arsenic, which has been connected to bladder, lung, and skin cancer (Järup, 2003). These toxicities are particularly important in agricultural areas where people directly use soil and water resources and consume locally grown food (Jomova et al., 2025). The danger is higher for vulnerable groups, such as youngsters and expectant mothers, and symptoms don't show up until irreparable harm has been done. Therefore, comprehending the mechanisms underlying heavy metal accumulation in farmland soils is not only important for the environment but also for human health (Deng et al., 2020). Despite these well-established hazards, comprehensive country-level evaluations are still absent, particularly in developing nations where soil quality monitoring and regulatory oversight are frequently dispersed or non-existent. The majority of research tends to confine itself to the use of concentration measures alone, without incorporating environmental and health assessments or considering risk implications. In addition, the geographical representation of pollution hotspots and statistical approaches towards detecting the sources of pollution are often neglected. Targeted repair planning and proper risk abatement are hindered by these shortcomings (Mai et al., 2025).

The development of environmental risk assessment tools that quantify the extent and type of soil pollution, and subsequently overcome these limitations. A measure of the extent and origin of the contamination is given by the CF, EF, I_geo, and potential ecological RI (Ferreira et al., 2022). They are used to identify ecologically meaningful locations and distinguish between human and geogenic origins (Kowalska et al., 2018). Estimation of carcinogenic and non-carcinogenic risk is also possible using health risk assessments, for example, those based on USEPA models, with consideration of several exposure routes, including ingestion, dermal absorption, and inhalation. Together, such frameworks provide a solid foundation for a comprehensive understanding of the entire gamut of hazards associated with heavy metal pollution (Marrugo-Negrete et al., 2017).

The remediation issue is still contextual and complicated. Even if effective, traditional options like chemical immobilization and excavation are unsustainable because they are expensive and ecologically invasive. More modern options, such as microbial-assisted degradation, phytoremediation, and organic amendments like biochar, are increasingly supported as they are cost-effective. These methods enhance soil fertility as well as decrease the bioavailability of heavy metals. Such methods are reliant largely on factors specific to the site, such as the type and level of metals, soil properties, and land use.

The primary object of this study is to assess the environmental and human health risks, as well as the buildup of heavy metals in Punjab agro-soils in the Ludhiana District. Using common indicators like the enrichment factor, pollution factor, and ecological risk index, it analyzes the degree of pollution and displays measurable values for cadmium, lead, arsenic, chromium, nickel, copper, and zinc at typical sites. By using USEPA models for adults and children, it can also determine the carcinogenic and non-carcinogenic hazards associated with different exposure pathways. In order to support sustainable land use planning and preserve the integrity of the ecosystem and public health, it also uses multivariate statistical approaches to identify possible sources of pollution and offers practical remediation procedures tailored to each site.

2. MATERIALS AND METHODS

2.1 Study Area Design

The research was carried out over 3,767 km² in the Indo-Gangetic Plains in the Ludhiana District of Punjab, India (30°33′N–31°01′N, 75°25′E–76°28′E). With temperatures ranging from 4°C to 42°C and 600–700 mm of annual rainfall, the region has a sub-tropical monsoon climate. The majority of the soils are silt loam to loamy sand, penetrative alluvium, and have a pH between 7.2 and 8.5. The predominant rice-wheat crop system, which is maintained by groundwater and canal irrigation, suggests intensive farming. Heavy metals are likely to originate from industrial complexes around Ludhiana city, Doraha, and Sahnewal through air deposition and effluents. Additionally, the risk of soil contamination is increased by the regular use of chemical pesticides, fertilizers, and organic manure. Ludhiana is a good place to assess heavy metal deposition, ecological risk, and remediation needs because of its extensive farming and industrial components.

2.2 Sampling and Analytical Procedures

A grid design was used to sample soil from selected agricultural fields. Five subsamples from each location within the depth range of 0 to 20 cm were combined to form a single representative sample (about 1 kilogram), which was then taken to the laboratory after being sealed in plastic bags. Before passing through a 2-mm screen and being partially crushed for examination, the samples were allowed to air dry in the lab. Acid digestion of 0.5 g of soil was performed using a 5:1:1 combination of HNO_3–$HClO_4$–H_2SO_4. Deionized water was used to dilute and filter the digests. ICP-MS calibrated with approved standards was employed to measure heavy metals (Cd, Pb, As, Ni, Cu, Zn, and Cr). Procedural blanks, duplicates, and recoveries within permissible limits were all part of quality control.

2.3 Pollution Index Calculations

Several pollution indicators were computed to assess the degree of contamination:

Contamination Factor (CF)

The CF for every metal was determined by dividing its soil concentration by its baseline or background value:

$$CF = \frac{C_{\text{sample}}}{C_{\text{background}}}$$

Where C_{sample} is the measured concentration and $C_{\text{background}}$ is the regional background level.

Enrichment Factor (EF)

Iron (Fe) was utilized as a reference element to distinguish between natural and man-made sources, utilizing EF:

$$EF = \left(\frac{C_{\text{metal}}}{C_{Fe}}\right)_{\text{sample}} \div \left(\frac{C_{\text{metal}}}{C_{Fe}}\right)_{\text{background}}$$

Geo-accumulation Index (I_geo)

The I_geo was computed to quantify the pollution intensity using:

$$I_{\text{geo}} = \log_2\left(\frac{C_{\text{sample}}}{1.5 \times C_{\text{background}}}\right)$$

Potential Ecological Risk Index (PERI)

Using Hakanson's technique, the ecological risk for each metal (Er) and the total risk index (RI) were assessed:

$$E_r = T_r \times CF, RI = \sum E_r$$

Where T_r is the response factor for each metal (e.g., Cd = 30, Pb = 5, As = 10, etc.)

2.4 Human Health Risk Assessment

Utilizing the USEPA risk assessment, the danger to human health was quantified standard (USEPA, 2001). Three methods were used to assess the carcinogenic and non-carcinogenic risks: exposure routes: eating, skin contact, and breathing of particulate dirt. The average dosage per day was determined using standard exposure formulas (ADD) for each route, accounting for factors such as body weight, averaging time, frequency of exposure, length of exposure, and soil ingestion rate. To ascertain non-carcinogenic hazards, the Hazard Quotient (HQ) and Hazard Index (HI) were calculated:

$$HQ = \frac{ADD}{RfD}, HI = \sum HQ$$

Where R *f* D is the reference dose. A Value of HI>1 indicates health concerns.

For carcinogenic risk (CR), the lifetime cancer risk was calculated using:

$$CR = ADD \times SF$$

Where *SF* is the slope factor for each carcinogen. Acceptable cancer risk ranges were set between 1×10^{-6} and 1×10^{-4}.

2.5 Statistical and Geospatial Analysis

A descriptive statistical study was conducted on all of the analytical data. Pearson correlation coefficient analysis was employed to determine the connections between metal concentrations. To identify possible pollution sources and group patterns, Principal Component Analysis (PCA) and Hierarchical Cluster Analysis (HCA) were employed. Maps illustrating the distribution of heavy metals in the research region were created using standard Kriging interpolation and geo-referenced sampling locations.

3. RESULTS

3.1 Heavy Metal Concentrations in Soils

Several heavy metals (Cd, Pb, As, Cr, Ni, Cu, and Zn) had varying concentrations in several Ludhiana District sample locations. At locations close to industrial regions, levels of lead and cadmium were consistently elevated; Pb (45.7–112.3 mg/kg) and Cd (1.2–3.4 mg/kg) were both significantly higher than WHO/FAO acceptable limits (0.8 mg/kg for Cd and 85 mg/kg for Pb). Arsenic was below the threshold limit at most sites; however, it varied from 3.1 to 9.6 mg/kg at different locations. Although they showed isolated maxima along waste-discharge canals, chromium and nickel were largely beneath tolerance limits. Despite being good micronutrients, copper and zinc also reached elevated levels in some crops with excessive fertilizer application, with Zn occasionally surpassing 300 mg/kg. The measured amounts (mg/kg) of the major heavy metals at five representative agricultural locations are shown in Table 1. Sahnewal and Doraha have the highest amounts of Cd and Pb, above WHO/FAO safety criteria, indicating industrial effects. Fertilized crops also have noticeably higher zinc contents.

Table 1. Heavy Metal Concentrations in Soil Samples Across Ludhiana District

Site	Cd (mg/kg)	Pb (mg/kg)	As (mg/kg)	Cr (mg/kg)	Ni (mg/kg)	Cu (mg/kg)	Zn (mg/kg)
S1 (Sahnewal)	3.4	112.3	9.6	72.1	45.6	58.7	310.2
S2 (Doraha)	2.8	98.5	7.2	69.4	41.3	52.4	288.7
S3 (Ludhiana Outskirts)	2.5	76.4	5.4	61.3	37.8	47.5	264.1
S4 (Peripheral Village)	1.2	45.7	3.1	55.7	29.4	34.6	188.5
S5 (Canal Zone)	1.6	68.2	4.5	58.6	32.5	41.2	230.3

3.2 Contamination and Risk Indices

Moderate to severe pollution was confirmed by pollution Factor (CF) values for Pb (CF > 2) and Cd (CF > 3 in 60% of samples). Significant anthropogenic impact, especially from agrochemicals and industry emissions, was shown by Enrichment Factors (EF) for Cd, Pb, and Zn being more than 5 at numerous sites. For both Pb and Cd, the Geo-accumulation Index (I_geo) showed moderate to severe pollution, ranging from Class 1 to Class 3. Cadmium's heavy toxic reaction coefficient (Tr = 30) contributed to its highest Ecological Risk Index (RI), which made up almost 70% of the overall RI. As a "considerable ecological risk," RI > 300 was primarily found in the vicinity of industrial discharge regions. Table 2 lists the (I_geo), (CF), (EF), and overall ecological risk index (RI) for zinc, lead, and cadmium for each of the five locations. With RI > 300, S1 and S2 exhibit the largest ecological concerns, suggesting significant pollution.

Table 2. Pollution Indices by Site

Site	CF_Cd	CF_Pb	EF_Zn	I_geo_Cd	RI_Total
S1	4.25	2.5	5.6	2.1	355
S2	3.50	2.2	4.8	1.8	312
S3	3.10	1.8	4.3	1.6	270
S4	1.40	1.1	2.9	0.5	134
S5	2.00	1.6	3.5	0.9	190

The overall ecological risk score for each of the five sample locations is shown in Figure 1. Significant ecological concern was indicated by the highest RI values at S1 and S2, which were mostly caused by excessive cadmium levels close to industrial discharge zones.

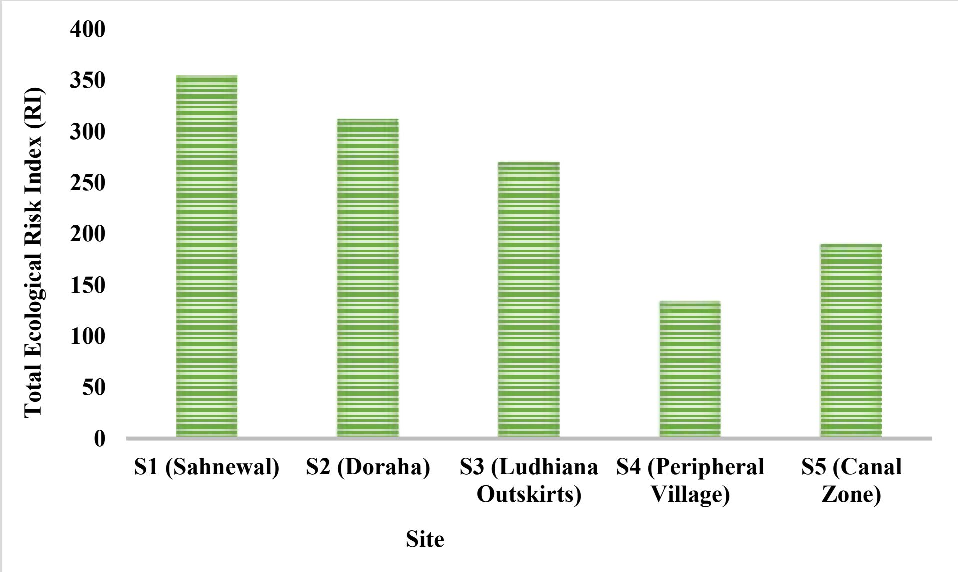

Figure 1. Total Ecological Risk Index (RI) Across Sites

3.3 Correlation and Multivariate Patterns

Excellent positive correlations were also found by Pearson correlation analysis between Pb–Cd ($r = 0.78$), Cd–Zn ($r = 0.72$), and Cu–Zn ($r = 0.65$). These connections were suggested to be mutually anthropogenic, most likely as a result of fertilizer and pesticide applications. Two important components were identified via Principal Component Analysis (PCA). The first group, Cd, Pb, and Zn, was probably caused by human activity. It accounted for 52% of the overall variation. The second component (23% variance) was composed of Cr and Ni, which may have been related to sewage irrigation or natural lithogenic origin. The heavy metal content summary figures for each research location are shown in Table 3. The biggest coefficients of variation were found for arsenic and cadmium, suggesting geographical heterogeneity.

Table 3. Descriptive Statistics of Heavy Metal Concentrations in Agricultural Soils (n = 5)

Parameter	Mean (mg/kg)	Min	Max	Standard Deviation	Coefficient of Variation (%)
Cd	2.3	1.2	3.4	0.86	37.4
Pb	80.2	45.7	112.3	25.9	32.3
As	6.0	3.1	9.6	2.28	38.0
Cr	63.4	55.7	72.1	6.44	10.2
Ni	37.3	29.4	45.6	6.32	16.9
Cu	46.9	34.6	58.7	8.35	17.8
Zn	256.4	188.5	310.2	46.3	18.1

3.4 Findings on Human Health Risk

High Hazard Index (HI) values were found in 40% of the investigated regions according to non-carcinogenic risk assessment, especially for children, whose lower body weight and higher rates of consumption made them more susceptible. The majority of the overall HI was caused by cadmium and lead, with average values in numerous urban-close fields above the threshold of 1. Arsenic and nickel carcinogenic risk (CR) values were generally below acceptable ranges, although in several samples they were near the highest safety limit (1×10^{-4}). After oral consumption, cutaneous exposure had the highest CR. There was little risk of inhalation. Sahnewal and the southern Ludhiana blocks were identified by integrative risk mapping as priority areas for immediate mitigation based on the cumulative ecological and health threats. The CR and HI values for adults and children are shown in Table 4. Children's HI levels at S1 and S2 were higher above the safety threshold (HI > 1), suggesting a possible non-carcinogenic danger.

Table 4. Health Risk Assessment by Site

Site	HI (Children)	HI (Adults)	CR_As (Children)	CR_As (Adults)
S1	1.7	0.9	1.1×10^{-4}	7.6×10^{-5}
S2	1.5	0.8	9.3×10^{-5}	6.4×10^{-5}
S3	1.2	0.7	7.2×10^{-5}	5.1×10^{-5}
S4	0.8	0.4	4.1×10^{-5}	2.9×10^{-5}
S5	1.0	0.6	5.3×10^{-5}	3.7×10^{-5}

Children's non-carcinogenic risk (HI) is displayed for each sample site in Figure 2. At S1 and S2, values greater than 1 suggest possible long-term health hazards, mostly from increased levels of lead and cadmium.

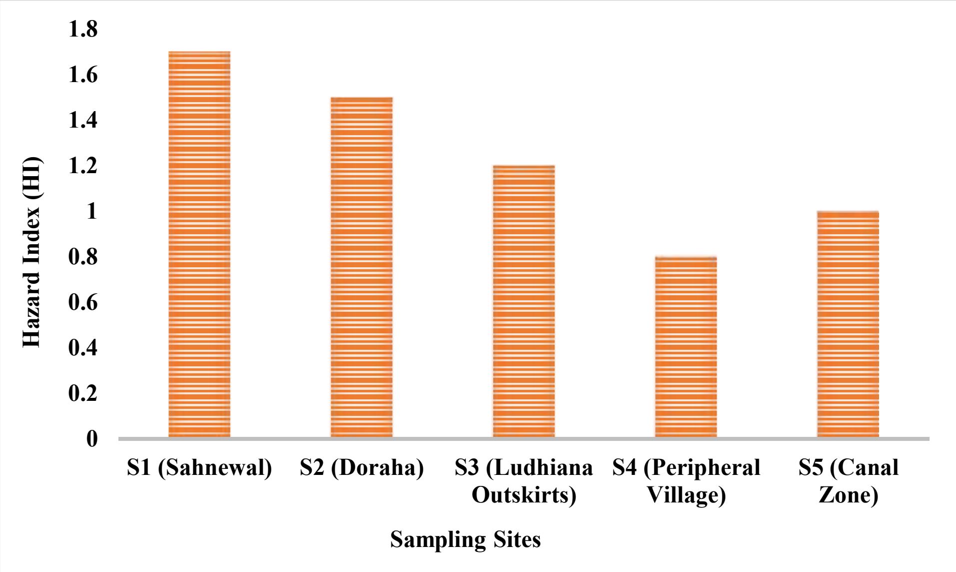

Figure 2. Non-Carcinogenic Risk (HI) for Children Across Sites

4. DISCUSSION

The interpretation of contamination indices, such as the ecological risk index RI (I_geo), EF, and CF, indicates moderate to high pollution in locations near industrial and peri-urban regions. The much higher CF and EF readings for cadmium (CF > 3 in Sahnewal and Doraha) suggest a human source, most likely from industrial effluent and fertilizer use. This finding is also supported by the I_geo categorization of lead and cadmium, which shows a moderate to high degree of pollution, particularly in locations where aerial deposition has taken place and wastewater without treatment has been applied (Ahamad et al., 2024). It's an incredibly high hazardous reaction factor, cadmium is frequently identified as the primary source of inferred ecological risks by ecological risk index (RI) values more than 300.

These patterns are consistent with data from other high-risk agricultural regions worldwide. Previous data have described spatial heterogeneity in the metal content of soils that have similar frequency in the industrial belts of eastern China, central Poland, and the Nile Delta. This is usually attributed to proximity to manufacturing plants, vehicle traffic, and prior industrial use with residual contamination (Santos et al., 2025). Cadmium and lead are often priority contaminants in such environments because they are toxic, bioaccumulate, and migrate. The Cd and Pb values of the study, especially for Ludhiana's urban fringe, are either at or above the upper limits of those in several studies worldwide, highlighting the severity of pollution in India. In addition, 40% of the samples also contained children's hazard index (HI) greater than unity, in line with trends observed in other peri-urban agricultural zones in Bangladesh and Nigeria, where children's exposure via dust or crop contamination is a considerable public health issue (Paz-Ferreiro et al., 2014). Metal enrichment is revealed to be significantly affected by farm activities. Because cadmium is an impurity in phosphate rocks, the widespread application of phosphate-based fertilizers in Ludhiana, owing to rice-wheat rotation systems with high yields, most likely leads to a high concentration of cadmium (Ali et al., 2020). Also, the regular use of pesticides, sometimes without proper regulation or in excess, may cause trace metals like copper and arsenic to enter the soil (Dheri et al., 2007). The condition is often made worse by irrigation techniques. The geographical concentration of high-risk locations can be explained by the fact that the fields of Sahnewal and other southern communities often rely on wastewater flows that contain industrial effluents. The frequent recycling of such water, which plants then access, leads to metal accumulation in the soil profile over time.

These findings have direct effects on the food chain in addition to environmental contamination. This region has a long history of heavy metal soil-to-plant transfer; previous research has indicated that the levels of lead and cadmium in leafy greens and grains exceed WHO/FAO safety guidelines. Long-term health risks, including renal, neurological, and developmental disorders, are posed by repeated exposure to such contaminated foods, particularly among people engaged in subsistence farming. The study validates these concerns and provides quantitative evidence of exposure risk via many pathways. Children are more vulnerable due to their greater rates of soil ingestion and smaller body weights, which increase their exposure load (Eid et al., 2024). Monitoring soil metals is therefore not just of agricultural relevance but also a crucial component of public health management. In terms of regulation, these results suggest that waste management, irrigation techniques, and the use of pesticides and fertilizers ought to be better regulated. Untreated wastewater irrigation in peri-urban agriculture is currently not heavily regulated. Integrating soil monitoring within the agricultural extension program would help prevent long-term harm by detecting pollution early. Furthermore, it should be promoted to use subsidies or incentive schemes to promote certified, low-contaminant agrochemicals. The reduction of long-term pollution transfer may also be achieved by land use planning and buffer rules between agricultural and industrial zones (Banerjee et al., 2017).

There are certain restrictions to be aware of. Despite its representativeness, the sample is limited to a certain geographic area within the Ludhiana District. This study did not account for seasonal dynamics; metal levels would fluctuate in response to varying irrigation cycles, rainfall, and fertilizers and pesticides used throughout the year. Furthermore, the research was done on total metal concentrations rather than bioavailable fractions, which would have provided a more accurate assessment of ecological exposure and plant absorption (Rehman et al., 2018). The risk modeling might be further enhanced by adding soil physicochemical characteristics such as cation exchange capability and organic matter concentration. Thus, the study confirms that the combined weight of industrial forces and intensive agriculture is putting Ludhiana's agricultural soils at greater danger of heavy metal buildup. Policymakers, agricultural organizations, and environmental regulators must act quickly in response to the high ecological and health risk factors that have been found. In order to support targeted, evidence-driven remediation and land management strategies, Future studies ought to concentrate on seasonal surveillance, larger-scale sampling, and crop-based risk assessments, even if the current technique provides a legitimate foundation for the evaluation of contamination.

5. CONCLUSION

An extensive analysis of contamination by heavy metals in Ludhiana District's agricultural soils is presented in this article, with an emphasis on the anthropogenic stress-related health and environmental risks that arise. Systematic sampling revealed high levels of cadmium, lead, and zinc, particularly in agricultural fields near industrial regions. These findings were confirmed by pollution indices like the ecological RI, CF, and EF. Cadmium's extreme toxicity and widespread presence make it the most dangerous element for the environment. Patterns of contamination were linked by multivariate analysis to wastewater irrigation techniques, pesticide use, and industrial effluent outflow. Hazard indices were higher than permitted in many areas, and Children had an increased chance of developing non-carcinogenic illnesses, according to a health risk assessment. Risk of arsenic-induced cancer estimates were close to or exceeding acceptable levels, emphasizing the urgency of action. These indicate how agricultural practices, soil contamination, and public health are linked, especially in high-cultivation areas. Restricting the application of untreated wastewater irrigation, enhancing sustainable soil management, and controlling the agrochemical quality are all essential measures towards avoiding these risks. Implementation of site-specific remediation strategies, including organic soil amendment and phytoremediation, can ensure the restoration of soil quality while sustaining production. Creating buffer strips between farms and industry and incorporating soil contamination measurements in regular agricultural valuations are fundamental policy measures. A priority should also be placed on educating farmers and enhancing public awareness of the use of safe inputs. To better comprehend mechanisms of exposure, additional research must examine food-chain transfer, metal bioavailability, and seasonal fluctuations. Incorporating crop and water testing and increased geographic coverage will enhance risk assessment models and enable evidence-based environmental management.

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