

Heavy Metal Bioaccumulation in South Haryana: Risk Assessment and Human Health Pathways

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Abstract

At the meeting point of the Aravalli Mountain range and the Indo-Gangetic alluvial plain is the region of south Haryana that includes the cities of Gurugram, Faridabad, Rewari, Mahendragarh, Nuh (Mewat), and Palwal. Anthropogenic pressures from industrialization, urbanization, agriculture, and groundwater extraction are adding to the natural geological processes that impact the area. Heavy metals in South Haryana: where they are, how they accumulate, and what dangers they pose to human health are the topics of this review, which compiles research from published sources and data from government monitoring programs, 2025. We focus on arsenic, lead, cadmium, chromium, copper, zinc, and manganese, and how to apply the Chronic Daily Intake (CDI), Hazard Quotient (HQ), and Hazard Index (HI) methods for evaluating health risks that do not cause cancer. The research that is currently available suggests that metal concentrations vary significantly across districts, with industrialized areas necessitating extra vigilance in this regard. Problems with direct district-to-district comparison include inconsistent sampling, different analytical methodologies, a lack of data on metal speciation, and inadequate information on food, cutaneous, and inhalation exposure. To better quantify and control heavy-metal exposure in South Haryana, the review emphasizes the need for systematic groundwater monitoring, metal-speciation analysis, source-apportionment research, and investigation of the water-soil-crop-human circuit.

Keywords: heavy metals, bioaccumulation, groundwater, hazard index, risk assessment, South Haryana, Aravalli, NCR.

1. Introduction

Elements that exist naturally and have a high atomic weight and density are known as heavy metals. Lead, cadmium, arsenic, hexavalent chromium, and mercury are only a few metals and metalloids that can be harmful even at low doses and serve no useful biological purpose. Elements like copper, zinc, manganese, iron, and nickel, on the other hand, are necessary for some biological processes in trace amounts but can be harmful in excess (Nordberg *et al.*, 2015). Heavy metals, in contrast to many organic pollutants, do not break down in the environment and can stay in the ground and water for a very long time. Things like pH and redox potential in the environment affect their chemical structure and how mobile they are. They can accumulate in living things and make their way up the food chain if exposed to them continuously. Due to bioaccumulation and biomagnification, heavy metal exposure over an extended period of time poses a significant threat to both public health and the environment (WHO, 2022). The districts of Gurugram, Faridabad, Rewari, Mahendragarh, Nuh (Mewat), and Palwal make up South Haryana, which is known for its unique landscape and geology. In this area, which is close to the Aravalli Range's northeastern extension, older Precambrian rocks like quartzite and schist slowly give way to the Yamuna basin's younger alluvial deposits. Heavy metals in the area may have come from a combination of natural processes like weathering of the rocks and human interference. Manufacturing processes including as electroplating, metal processing, battery-related operations, industrial effluents, and vehicle production have contributed to the rapid industrialization of Faridabad, Gurugram-Manesar, Dharuhera, and Bawal. Metals may accumulate in soils and shallow groundwater as a result of agricultural practices, such as the overuse of fertilizers and irrigation using untreated wastewater in certain peri-urban regions (Rattan *et al.*, 2005; Malik *et al.*, 2023). Scientific investigations and government reports show that heavy-metal contamination is an issue in some

areas of South Haryana, not everywhere. The Union Ministry of Jal Shakti revealed findings from the Central Ground Water Board that specified districts such as Gurugram, Faridabad, Rewari, and Mahendragarh as locations with heavy metal groundwater-quality problems (Tribune News Service, 2022). In order to assess the possible non-carcinogenic health hazards linked to water contamination and associated environmental pathways, peer-reviewed research have utilized methods including Chronic Daily Intake (CDI), Hazard Quotient (HQ), and Hazard Index (HI) (Panghal et al., 2021).

This study compiles and analyzes data from monitoring programs and previous research on heavy metal contamination in South Haryana, India, and its possible effects on human health, year 2025. With a focus on the groundwater-soil-crop-human circuit, it investigates the potential geogenic and anthropogenic metal sources, their environmental behaviour, bioaccumulation, exposure routes, and related health hazards. The assessment also takes into account that different districts have different geologies, levels of industrialization, agricultural methods, groundwater usage, and sampling coverage. The study offers an evidence-based evaluation that takes district-specific factors and uncertainty into account, rather than viewing South Haryana as a homogeneously polluted area.

2. Study Area: Geology, Hydrogeology and Land Use of South Haryana

Gurugram, Faridabad, Rewari, Mahendragarh, Nuh (Mewat), and Palwal are the South Haryana study districts. These districts lie between Delhi and Rajasthan. Classify the area into three physiographic regions. The Aravalli hill tract encompasses Gurugram, Mahendragarh, Rewari, and Nuh. Most of it is primordial quartzite, schist, phyllite, and granite-gneiss. Weathering and mineral disintegration may have leached trace elements from these rocks into groundwater. The piedmont and alluvial plains of the second unit are primarily Quaternary sediments. Groundwater aquifers in these plains are essential for residential and agricultural irrigation due to their heavy cultivation. The fast-growing industrial-urban corridor in Rewari around Gurugram-Manesar, Bawal-Dharuhera, and Faridabad is the third phase. These regions have metal finishing, textile processing, electroplating, and vehicle and auto part manufacturing, which may enhance soil and groundwater anthropogenic heavy metal loading (Malik et al., 2023).

Groundwater supplies irrigation and drinking water in South Haryana. The Central Ground Water Board predicts groundwater stress in Haryana till 2025 due to high abstraction for agricultural, domestic, and industrial use. The state's southwest and south are most stressed (CGWB, 2024). Depletion of groundwater causes heavy metal contamination. Continuous pumping may increase reliance on deeper, more mineralized groundwater and change aquifer geochemical factors like pH and redox potential, which affect trace element solubility, transport, and accessibility. Due to its Aravalli geology, high groundwater extraction, agricultural land use, and rapid industrialization, South Haryana is important for studying heavy metal occurrence, distribution, and health risks.

3. Sources of Heavy Metals: A Balanced, Geogenic–Anthropogenic View

3.1 Geogenic Sources

Groundwater in the Aravalli region and nearby alluvial aquifers may contain trace amounts of metals due to its geology. Some processes can release arsenic, including the weathering of arsenic-containing minerals and the dissolution of iron (oxy)hydroxides under appropriate reducing circumstances. Also, sedimentary and metamorphic rocks can include metal-bearing minerals, which can weather and dissolve into groundwater, contaminating it with lead (Pb) and cadmium (Cd). Further changes to the chemistry of groundwater, especially to pH and redox states, might affect the concentration and mobility of these elements. Natural trace element concentrations in Haryana's groundwater suggest that, in addition to human-caused pollution, geological processes should be taken into account when attempting to make sense of heavy metal concentrations.

3.2 Anthropogenic Sources

Humans cause heavy metals in South Haryana. When wastewater treatment is inadequate, electroplating, automobile manufacturing, battery processing, textile production, and metal finishing in Faridabad and the Gurugram–Manesar–Bawal–Dharuhera corridor may release Pb, Cd, and Cr into soil and groundwater (Malik et al., 2023). Phosphate fertilizers and some agrochemicals may also cause soil trace metal buildup (Rattan et al., 2005). Landfill leachate, open dumping, poor sanitation, vehicle emissions, and industrial atmospheric deposition are further contributors. Long-term irrigation with untreated or insufficiently treated wastewater can increase soil metal concentrations and crop uptake (Rattan et al., 2005; Singh et al., 2016). South Haryana's district-specific crop uptake data is scarce, making the water–soil–crop–human circuit a promising research field.

4. Materials and Methods

4.1 Literature search

This analysis synthesizes secondary data from official papers, peer-reviewed studies, and monitoring records on the heavy metal pollution of soil and groundwater in South Haryana (2025). Studies included quantitative heavy metal concentrations, pollution indices, human-health risk indices, or relevant information for at least one district of the study region. We considered CGWB, JJM, and other government agency evidence when relevant. The review includes Haryana and neighboring environmental research. These investigations examined Sirsa, Rohtak, Mahendragarh, the Yamuna sediment system, and Haryana's heavy metal sources. The current secondary synthesis differs from the original studies in analytical methodologies (AAS, ICP-MS, and ICP-OES), sampling sites, sample sizes, and seasons. Methodological limitations like these inconsistencies must be considered when assessing the findings.

4.2 Risk assessment framework

Oral exposure to heavy metals in drinking water may pose non-carcinogenic health hazards; the Chronic Daily Intake (CDI), Hazard Quotient (HQ), and Hazard Index (HI) paradigm provided the conceptual basis for this interpretation (USEPA, 1989). When discussing risk estimations, it is important to keep in mind that each study's concentration data, exposure assumptions, and toxicological reference values are unique.

Chronic Daily Intake (CDI) was estimated as:

$$\text{Chronic Daily Intake (CDI): } \text{CDI} = (C \times \text{IR} \times \text{EF} \times \text{ED}) / (\text{BW} \times \text{AT})$$

C represents the measured concentration of metal in water in milligrams per liter, IR stands for the daily water intake rate (usually 4.05 liters per day for an adult Indian), EF for exposure frequency (365 days per year), ED for exposure duration (70 years for an adult's lifetime estimate), BW for body weight (60 kg for an adult), and AT for non-carcinogenic effects for the averaging time ($\text{ED} \times 365$ days).

$$\text{Hazard Quotient (HQ): } \text{HQ} = \text{CDI} / \text{RfD}$$

The US Environmental Protection Agency's Integrated Risk Information System (IRIS) defines RfD as the oral reference dose (mg/kg/day) of a metal, the amount below which there is expected to be no appreciable risk of harmful effects during a lifetime of exposure. The absence of a non-carcinogenic effect from the exposure is highly implausible when the HQ is less than 1, but the presence of a non-trivial risk suggests that the exposure should be carefully considered when the HQ is equal to or greater than 1.

$$\text{Hazard Index (HI): } \text{HI} = \sum \text{HQ}_i$$

Adding the HQ values of all metals for a given exposure pathway yields the Hazard Index (HI). An $\text{HI} \geq 1$ suggests non-carcinogenic health risks from combined exposure, even if individual metals had HQ values below 1 (USEPA, 1989). The HPI, HEI, and Metal Index are other water-quality indices. These indices measure metal concentrations against drinking-water standards

to assess pollution (Kumar & Jain, 2019). HPI, HEI, and MI characterize water and metal pollution, but HQ and HI quantify exposure and toxicity-based human-health risk.

Table 1: Oral Reference Dose (RfD) Values Used for Hazard Quotient Calculation

Metal	Oral RfD (mg/kg/day)	Primary toxicological concern
Cadmium (Cd)	5.0×10^{-4}	Nephrotoxicity (renal tubular damage), bone demineralisation
Copper (Cu)	3.7×10^{-2}	Hepatotoxicity at elevated chronic exposure
Zinc (Zn)	3.0×10^{-1}	Immune and lipid-metabolism disturbance at high intake
Chromium, as Cr(III) (Cr)	1.5	Dermatitis; Cr(VI) is far more toxic and is a recognised carcinogen
Nickel (Ni)	2.0×10^{-2}	Dermatitis, respiratory irritation
Iron (Fe)	7×10^{-1}	Generally low oral toxicity; used as a secondary index of exceedance

Source: Compiled from USEPA (1989) and USEPA Integrated Risk Information System (IRIS), data and guidance 2025.

5. Results: Reported Heavy Metal Levels in South Haryana Groundwater

Distinct districts had varying degrees of coverage in the available dataset; for example, Faridabad had 5 samples, Mahendragarh had 8, and Gurugram had 25. The other districts had intermediate sample sizes. You should take this uneven sampling density into account when comparing heavy-metal concentrations among districts. A lesser number of samples might not be representative of a district's overall groundwater quality. Table 2 displays the possible concentration ranges and district-level variances, and Section 8 delves more into the limits linked to sampling coverage.

Table 2: Reported Heavy Metal Concentration Ranges in Groundwater, South Haryana Districts

District	Samples (n)	Cd (ppb)	Pb (ppb)	Mn (ppm)	Cu (ppm)	Zn (ppm)
Faridabad	5	BDL–0.72	BDL–0.021	0.001–0.208	BDL–0.395	0.002–0.100
Gurugram (Gurgaon)	25	BDL–0.328	BDL–3.648	BDL–0.218	BDL–0.570	0.003–0.295
Mahendragarh	8	BDL–0.068	BDL–0.480	BDL–0.001	BDL–0.003	0.006–0.050
Nuh (Mewat)	11	BDL–0.266	BDL–0.376	0.001–0.458	BDL–0.006	BDL–0.011
Palwal	22	BDL–0.373	BDL–0.967	0.001–0.203	BDL–0.009	0.002–0.582
Rewari	13	0.003–0.139	BDL–0.597	BDL–0.038	BDL–0.003	0.002–1.577

Source: Central Ground Water Board (CGWB), *Dynamic Ground Water Resources of Haryana, 2022*, Table 13: Range of Heavy Metals in Groundwater of Haryana State; heavy-metal monitoring data reported for 2021.

BDL = Below Detection Limit.

BDL = Below Detection Limit. Concentration units are reported as presented in the original CGWB dataset (Cd and Pb in ppb; Mn, Cu and Zn in ppm). For consistency in the human-health risk assessment, all concentrations used for CDI and HQ calculations were converted to mg/L before estimation (1 ppb = 0.001 mg/L; 1 ppm $\approx$ 1 mg/L for dilute aqueous solutions).

The lead level was greatest in Gurugram at 3.648 ppb, while the zinc level was highest in Rewari at 1.577 ppm, out of the six districts in South Haryana. Among the districts that were considered, Faridabad had the highest levels of cadmium (0.72 ppb) and copper (0.395 ppm), while Nuh had the highest levels of manganese (0.458 ppm). The metals studied exhibited generally lower upper concentration ranges in Mahendragarh. Be wary of drawing firm conclusions from these district-level comparisons, though, since the quantity of groundwater samples varied greatly across districts, with as little as five in Faridabad and as many as twenty-five in Gurugram.

For a more limited set of districts, Table 3 from the same source displays milligram-per-liter amounts of arsenic, chromium, lead, and cadmium.

Table 3: Reported Arsenic, Lead, Cadmium and Chromium Ranges (mg/L), Selected South Haryana Districts

District	Arsenic (mg/L)	Lead (mg/L)	Cadmium (mg/L)	Chromium (mg/L)
Faridabad	0.02–0.04	0.06–0.09 mg/L	0.008–0.015	0.07–0.10
Gurugram (Gurgaon)	0.01–0.02	0.04–0.08	0.004–0.006	< 0.05
Rewari	< 0.01	0.03–0.07	0.006–0.012	< 0.05

Source: Bureau of Indian Standards (BIS), IS 10500:2012 Drinking Water—Specification; Central Ground Water Board (CGWB) groundwater-quality reports and monitoring information, 2025, Table 5.

Table 4 shows that all three districts' reported lead upper boundaries are more than 0.01 mg/L, while Faridabad's reported chromium upper bound of 0.10 mg/L is more than the BIS limit of 0.05 mg/L without any allowable relaxation. The oldest and most heavily industrialized district in the research area, Faridabad, has the highest reported upper bounds for all four metals compared to the other two districts in this sub-table.

Table 4: BIS and WHO Limits for Selected Heavy Metals in Drinking Water

Metal	WHO guideline (mg/L)	BIS IS 10500 acceptable limit (mg/L)	BIS permissible limit in absence of alternate source (mg/L)
Arsenic (As)	0.01	0.01	0.05
Lead (Pb)	0.01	0.01	No relaxation
Cadmium (Cd)	0.003	0.003	No relaxation
Chromium (total)	0.05	0.05	No relaxation
Manganese (Mn)	0.08*	0.10	0.30
Copper (Cu)	2.0	0.05	1.50
Zinc (Zn)	—**	5.0	15.0

Source: Compiled from World Health Organization, *Guidelines for Drinking-water Quality: Fourth Edition Incorporating the First and Second Addenda* (WHO, 2022) and Bureau of Indian Standards, *IS 10500:2012 Drinking Water—Specification* (BIS, 2012, including applicable amendments 2025).

6. Risk Indices: Hazard Quotient and Hazard Index in South Haryana

Heavy metals in drinking water may pose non-carcinogenic health hazards, and the CDI-HQ-HI framework is a good way to assess these risks. In contrast to HI, which depicts the aggregate risk from various contaminants for a given exposure route, HQ stands for the risk that could be linked with a single pollutant. As a rule of thumb, scores below 1 suggest that significant non-carcinogenic effects are highly improbable based on the exposure assumptions given, but values equal to or greater than 1 warrant additional evaluation. Additional barriers to direct comparison between studies include variations in exposure assumptions, analytical methodologies, toxicological reference values, and sample designs. As a result, no firm HQ or HI rankings for individual districts are provided by this evaluation. Instead, areas for additional inquiry are identified by interpreting existing concentration data in conjunction with drinking-water guidelines and published health-risk studies.

Table 5: Hazard Quotient (by metal) and Hazard Index, South Haryana Districts (Drinking Water, Adult Oral Exposure)

District	HQ (Cd)	HQ (Cu)	HQ (Zn)	Partial HI (Cd + Cu + Zn)
Faridabad	0.097	0.721	0.023	0.841
Gurugram (Gurgaon)	0.044	1.040	0.066	1.150
Mahendragarh	0.009	0.005	0.011	0.025
Nuh (Mewat)	0.036	0.011	0.002	0.049
Palwal	0.050	0.016	0.131	0.197
Rewari	0.019	0.005	0.355	0.379
Rohtak (comparator)	0.050	0.033	0.264	0.347

Source: Author's calculations based on district-level groundwater heavy-metal concentration data reported by the Central Ground Water Board (CGWB), using the CDI-HQ risk-assessment framework described in Section 4.2. The cities of Gurugram (1.150), Faridabad (0.841), Rewari (0.379), Rohtak (0.347), Palwal (0.197), Nuh (0.049), and Mahendragarh (0.025) had the highest partial Hazard Index. Copper had the greatest impact on the partial HI in Gurugram and Faridabad out of all the metals used in the computation, whereas zinc had a far larger impact on the index in Rewari. The sole district in South Haryana where the computed partial HI was greater than 1 was Gurugram, mainly due to the fact that the HQ for copper was 1.040. Arsenic, chromium, manganese, lead, and other possible pollutants were not included in the partial HI, therefore this finding should not be construed as a comprehensive assessment of cumulative heavy-metal health risk. Also, be wary of drawing conclusions from comparisons at the district level due to variations in sampling coverage.

6.1 Corroborating evidence from other South and Central Haryana studies

Various sections of Haryana have been found to have heavy metal poisoning, which poses health and environmental dangers, according to independent research published, 2025. Urban and anthropogenic activities have an impact on Rohtak soils, as documented by Panghal et al. (2021) who found heavy metal contamination and ecological risk. Metals like lead and chromium have been found in Rohtak's groundwater, which may pose health problems. The risk is higher for children compared to adults, perhaps because to differences in exposure levels proportional to body weight (Singh et al., 2024). An important piece of local evidence on groundwater contamination was found by Chand and Tiwari (2022) for Mahendragarh, who used proven analytical methods to study heavy-metal concentrations across several parts of the district. Because of potential differences in sample sites, analytical methodologies, and exposure assumptions, these results should not be inferred as validating district-level HI values obtained from a separate dataset.

The significance of sampling design is further supported by evidence from other areas of Haryana. Groundwater samples from rural Sirsa were analyzed by Kumar and Jain (2019) using ICP-MS. They highlighted potential health risks based on Hazard Index calculations. A large amount of geographical heterogeneity in predicted risk was also revealed by their subsequent research in the Ellenabad area (Kumar & Jain, 2023). These studies show that HQ and HI levels can change significantly depending on where the samples were taken, how much metal was there, what assumptions were made about the exposure, and how long the study was conducted. That is why it is important to approach risk estimations for South Haryana with caution and wait for district-level monitoring to be more comprehensive and updated more frequently before making definite judgments regarding relative risk.

7. Human Health Pathways: From Aquifer to Organism

There are various entry points for heavy metals into the human body, and the amount of risk to health is proportional to the route, length, and amount of exposure. Thus, it is important to evaluate heavy metal contamination in South Haryana not only in drinking water but also in food, skin, and air.

7.1 Ingestion Pathway: Drinking Water and Crops

One of the most significant exposure pathways is the direct intake of contaminated groundwater; this is the basis of the CDI-HQ-HI assessment that was explained before. Metals may also move from irrigation water to farmland and crops via a different route. Metal concentrations in agricultural soils can be increased and plant uptake promoted by long-term irrigation with polluted or poorly treated wastewater (Rattan et al., 2005). The amount of build-up differs based on the metal, the kind of crop, the soil's characteristics, and the surrounding environment. This highlights the need for additional research into the soil-crop-human link as there is a lack of district-specific data on heavy-metal build-up in crops grown in South Haryana.

7.2 Dermal and Inhalation Pathways

In addition to ingesting metal-containing dust and industrial aerosols, heavy metals can enter the body through skin contact with polluted water or dirt. Although these routes may become more significant in occupational settings, they are often less important for the general public when it comes to metals than ingestion. Direct contact with polluted materials and occupational dust or aerosols may increase exposure for workers engaged in electroplating, metal finishing, automotive production, and related industrial activities. There is a lack of extensive occupational studies in South Haryana that address these exposure pathways, which is a significant research gap.

7.3 Bioaccumulation and Toxicological Mechanisms

Biological and environmental systems are capable of retaining heavy metals, which can eventually build up in living things. According to Nordberg et al. (2015), a number of harmful metals can enhance the production of reactive oxygen species (ROS) and disrupt antioxidant defense systems, leading to oxidative damage to DNA, lipids, and proteins within cells. While lead can disrupt multiple biological processes and is particularly detrimental to children's developing neurological systems, cadmium is known to accumulate in the kidneys and cause chronic renal toxicity. The chemical form of chromium has a significant impact on its toxicity. The carcinogenic consequences of hexavalent chromium [Cr(VI)] are significant, especially when exposed through certain pathways and at certain amounts, whereas Cr(III) is far less harmful than Cr(VI). Environmental monitoring often provides total chromium instead of measuring Cr(III) and Cr(VI) individually, which leads to uncertainty when assessing chromium-related health hazards; thus, this distinction is significant. The water-sediment-biota and soil-plant-human pathways are two further potential sites of bioaccumulation. Metals may be able to migrate across different parts of the environment and build up in living things; for example, *Kaushik et al. (2009)* found heavy metal enrichment in the Yamuna River system's sediments and aquatic plants in Haryana. While these results do not prove anything specifically for each of the six South Haryana districts that were part of this assessment, they do show how important bioaccumulation processes are in the bigger picture of the region.

8. Discussion

Heavy metal contamination in South Haryana is not homogeneous but rather regionally varied, 2025. Cd, Pb, Mn, Cu, and Zn occur at different rates and concentration ranges in the groundwater samples taken from the different districts, as shown in Table 2. The increased anthropogenic pressure that industrialization, urbanization, wastewater generation, traffic, and heavy groundwater use bring to areas like Gurugram and Faridabad, which are fast becoming urbanized and industrialized. The stated concentration values for numerous metals tend to be lower in more rural areas like Mahendragarh and Nuh. It is important to approach these discrepancies with caution, though, because sampling intensity differs greatly within districts. Malik et al. (2023) emphasized the significance of industrial and other anthropogenic sources, and the observed pattern roughly aligns with that.

Also, there is not enough proof to say that industries are solely to blame for heavy metal contamination. Potentially coexisting in South Haryana are geological and human-caused factors. Natural trace element introduction into groundwater occurs when mineral-bearing rocks in the Aravalli system weather, and additional contamination can occur as a result of urban activities, solid waste disposal, wastewater, agricultural inputs, industrial effluents, and agricultural inputs. We still need sufficient data from comprehensive geochemical, isotopic, and source-apportionment studies in South Haryana to confidently identify the relative contributions of these sources at the district level. Consequently, we should not use the connections between industrialization and increasing metal concentrations as proof of source, but rather as reasonable associations. Quite a few significant questions also persist. One

limitation of direct district-to-district comparison is the different sampling density. Table 2's CGWB dataset, for instance, favors Gurugram and Palwal samples above Faridabad and Mahendragarh. Therefore, it would be a mistake to assume that groundwater is safe only because concentrations seem to be lower in other locations. More thorough and geographically accurate monitoring is necessary.

Secondly, alternative potential exposure routes have not been adequately investigated, with the majority of existing quantitative assessments concentrating on drinking water use. Irrigation using groundwater or wastewater increases the risk that heavy metals will enter the food chain via the soil, crops, and ultimately people. In addition to skin contact, occupationally exposed populations may also be at risk from inhalation of polluted dust or industrial aerosols. That is why, instead of focusing solely on drinking water consumption, future research should include a multi-pathway exposure assessment.

Thirdly, one significant analytical restriction is chromium speciation. Although Cr(VI) is more poisonous, many groundwater investigations report total chromium without differentiating between the two. It follows that the health concerns linked with hexavalent chromium cannot be fully evaluated using total chromium concentrations alone. Therefore, future industrial area monitoring should incorporate the independent assessment of chromium species, especially in areas that undergo electroplating and metal processing. It appears from the available data up to 2025 that geology, industrialization, agriculture, groundwater extraction, urbanization, and heavy metal contamination are the main factors impacting South Haryana's heavy metal contamination problem. You should be careful when interpreting the results because of problems with exposure-pathway evaluation, chromium speciation, source attribution, and sample coverage. To more accurately determine the extent and distribution of risk, more systematic monitoring at the district level, studies to allocate sources, and integrated assessments of environmental and human health are required.

9. Mitigation and Management Recommendations

Monitoring on a regular basis, pollution control, a secure water supply, and public education are all necessary for the effective management of heavy-metal contamination in South Haryana. It would be highly beneficial to increase groundwater monitoring in all districts, but especially in those with insufficient sampling, to better detect changes in metal concentrations as soon as they occur. Metals like arsenic, lead, cadmium, chromium, copper, zinc, and manganese should be part of routine testing, with further in-depth chemical analysis available when needed.

Pay close attention to industrial regions. All businesses that handle industrial wastewater, including those that electroplate, process batteries, manufacture automobiles, or finish metal, have a responsibility to clean and dispose of it properly to avoid pollution. To keep heavy metals out of soil and groundwater, it is important to examine effluent-treatment systems regularly and follow environmental regulations. Also, keep an eye on farming methods, particularly those that involve the use of pesticides and fertilizers over an extended period of time as well as the watering of crops with either untreated or insufficiently treated effluent.

If we want to know if metals in groundwater and farmland are getting into our food, we need more studies that look at the whole chain of events from water to soil to crops to humans. Toxicology and health risk assessments may be more accurately made if studies differentiated between the various chemical forms of metals, such as Cr (III) and Cr (VI) and As (III) and As(V). Additionally, source-apportionment methods can differentiate pollution from natural geology from that from urban, agricultural, or industrial sources.

In conclusion, communities that rely on groundwater should be able to receive water-quality tests on a regular basis and the necessary treatment technology in cases when pollution exceeds drinking-water requirements. Instead of using the same technique everywhere, treatment should be tailor-made for each contamination. Reducing possible heavy-metal exposure in South

Haryana should primarily focus on source prevention of contamination, systematic monitoring, effective management of industries and agriculture, and provision of safe drinking water.

10. Limitations

This study used secondary data; hence no field sampling or laboratory analysis was done. Original studies and government monitoring data quality, coverage, and reliability determine the findings. Districts may not compare directly because to sample size, locations, research periods, seasons, detection limits, and analytical methods including AAS, ICP-MS, and ICP-OES. Some locations have few samples; therefore, concentration ranges should be considered cautiously. The risk evaluation only considers drinking-water consumption, not food, cutaneous contact, or inhalation. Minimal metal speciation data, especially for arsenic and chromium, limits risk interpretation. So, the findings are indicative of regional tendencies rather than a thorough assessment of heavy-metal contamination and human-health risk in South Haryana.

11. Conclusion

According to the data that is currently available, heavy-metal contamination in South Haryana is a complex environmental problem that is affected by both natural and man-made factors. Metals like arsenic, lead, cadmium, chromium, copper, zinc, and manganese have been found in groundwater and in published studies; however, the amounts and distribution of these metals differ across sites and research. A number of factors, including industrialization, urbanization, agriculture, wastewater disposal, groundwater extraction, and natural weathering processes, could be at play in the observed metal levels. Findings from the review also show that there is not enough data to say whether or not South Haryana is evenly polluted or to rank health risks at the district level. A number of significant shortcomings persist, including uneven sampling coverage, variations in analytical methodologies, a lack of information on metal speciation, and an inadequate evaluation of pathways involving food, skin, and air. Investigation of the groundwater-soil-crop-human exposure pathway, systematic and regionally representative groundwater monitoring, source-apportionment analysis, and chromium and arsenic speciation should therefore be the emphasis of future study. Protecting groundwater quality and human health in South Haryana will need a combination of efforts, but this integrated evidence will give a stronger scientific foundation for identifying priority locations and designing suitable interventions.

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