

# Integrated Spatial and Probabilistic Human Health Risk Assessment of Heavy-Metal Contamination in Canal Waters of Semi-Arid Region, India

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## Research Article

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*Running title: Heavy-Metal Risks in Semiarid region Canal Waters*

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## Title Page

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## **Abstract**

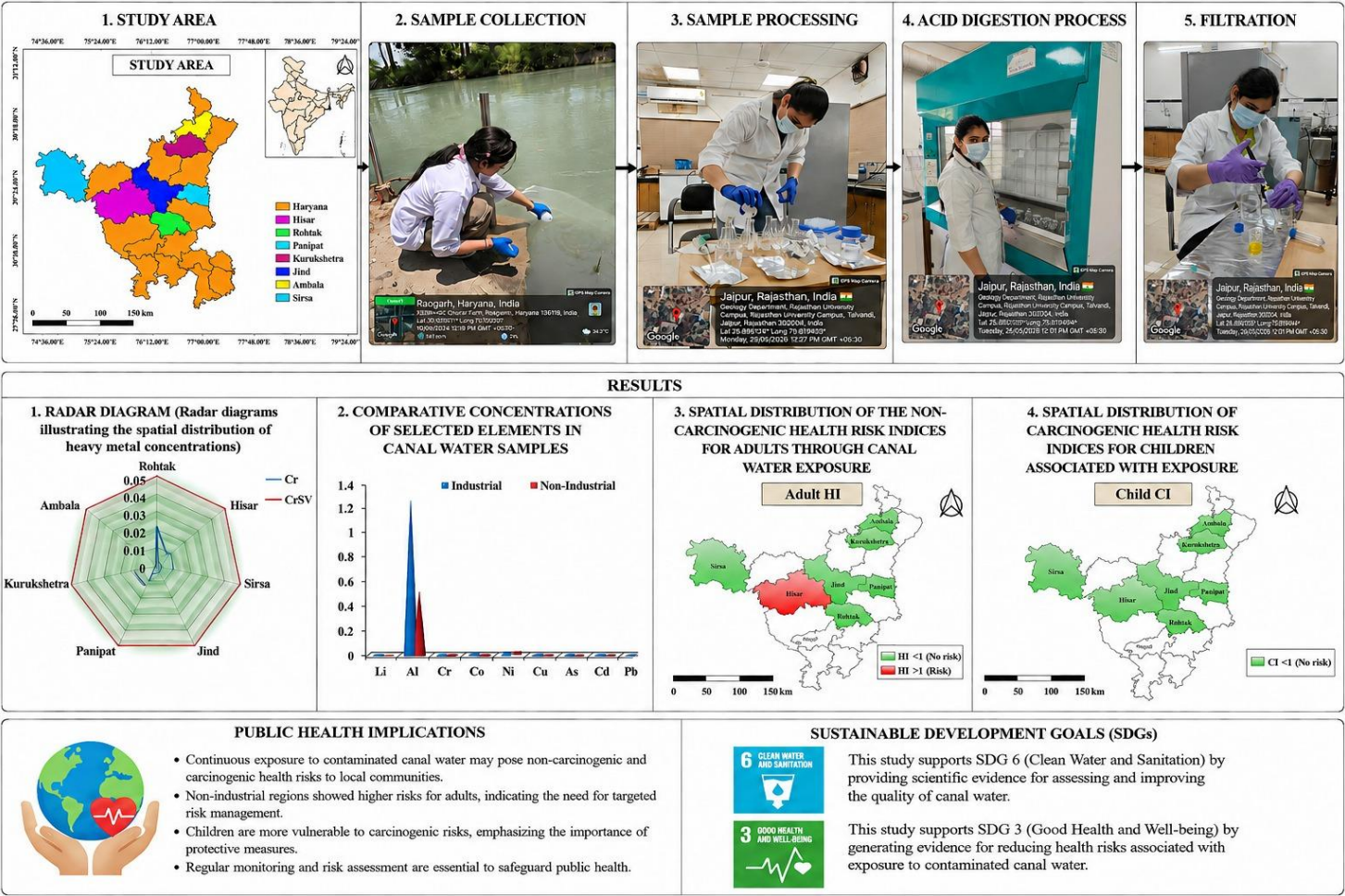
Canal water is being used for irrigation and domestic use in semiarid regions of India. The possible greater spatial distribution of different heavy metals in this region may initiate noncarcinogenic and carcinogenic risk in the inhabitants of this region. In this study, 42 canal water samples were collected from semiarid regions of India. Heavy metal concentrations (Li-lithium; Al-aluminium; Cr-chromium; Co-cobalt; Ni-nickel; Cu-copper; As-arsenic; Cd-cadmium; and Pb-lead) were determined using ICP-MS. The results revealed considerable spatial variability, with Cu, Cd, and Pb within permissible limits across all districts, whereas As remained compliant but reached the threshold level in Hisar (0.01 ppm). Ni was relatively high in Rohtak (0.008 ppm) and Hisar (0.010 ppm); Li exceeded the permissible limits throughout. Multivariate statistical analysis revealed dominant anthropogenic factors with partial geogenic control. A noncarcinogenic risk assessment revealed that adults were within safe limits, whereas children exhibited relatively higher risk, with some values exceeding the threshold. The carcinogenic risk estimates remained within acceptable limits, with As and Cr representing the predominant contributors. Nevertheless, the occurrence of localized hotspots characterized by elevated heavy metal concentrations, together with the increased associated risks observed among children, underscore the importance of continuous monitoring and the implementation of effective management strategies. These findings provide baseline information for heavy metal surveillance, human health risk assessment, and the sustainable management of canal water resources utilized for domestic purposes. Moreover, this study aligns with Sustainable Development Goal (SDG) 6 (Clean Water and Sanitation) and SDG 3 (Good Health and Well-being) by providing evidence to support informed strategies for improving water quality and safeguarding public health.

105 **Keywords: Keywords:** Anthropogenic factors; Carcinogenic risk; ICP–MS;  
106 Noncarcinogenic risk; Sustainable development goals; Spatial distribution

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Graphical Abstract



### **Highlights**

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114 • Heavy metals showed distinct spatial patterns across Haryana's canal network.

115 • Li was widespread, while Al and Ni varied across sampling locations.

116 • Ingestion was the main exposure route, with children more susceptible.

117 • Hisar, Rohtak and Panipat emerged as priority areas for targeted monitoring.

118 • Integrated risk assessment supports sustainable canal-water management.

## Statement of Significance

Heavy-metal contamination of canal networks presents a critical water-quality and human-health challenge in rapidly industrializing and agriculturally intensive semi-arid regions. Yet, assessments commonly focus on metal concentrations at limited locations, providing insufficient resolution of spatial variability, source contributions, regional industrial influence, and population-specific health risks. This study addresses these gaps through an integrated assessment of canal water across seven districts of Haryana, India, encompassing industrial and non-industrial regions and paired sampling locations. By combining multi-metal characterization, spatial and suitability assessment, pollution indices, multivariate source evaluation, industrial-non-industrial comparison, and probabilistic health-risk assessment, this study links contaminant occurrence with potential human exposure. The analysis further resolves age- and pathway-specific risks by evaluating adults and children through ingestion and dermal exposure, including both non-carcinogenic and carcinogenic endpoints. The results identify localized contamination and health-risk hotspots, demonstrate a predominantly ingestion-driven exposure pattern, and reveal greater vulnerability among children despite generally acceptable cumulative regional risks.

The study therefore advances canal-water assessment from concentration-based characterization toward an integrated source-exposure-risk framework, providing a transferable basis for risk-based monitoring and targeted pollution control in semi-arid canal systems. Its findings support evidence-based water-quality management and contribute to protecting human health and freshwater resources under increasing industrial and agricultural pressures.

## 1 Introduction

Freshwater scarcity has emerged as a defining environmental challenge of the twenty-first century. Although water covers nearly three-quarters of the Earth's surface, only a small fraction is accessible for human consumption, and this limited resource faces mounting pressure from population growth, urbanization, industrial expansion, and agricultural intensification [1,2]. Compounding the demand-side crisis, anthropogenic contamination has progressively degraded surface water quality, making the protection of safe water supplies a global public health and environmental priority [3]. Canal systems are critical yet comparatively understudied components of surface freshwater resources in developing countries [4]. Beyond agricultural applications, canal water is extensively used for domestic purposes, including drinking, cooking, bathing, washing, and livestock rearing, particularly in rural and peri-urban communities where access to alternative water sources is limited [5]. India operates one of the world's largest canal irrigation networks. In the semiarid state of Haryana, where groundwater is frequently compromised by salinity and overexploitation, canal water plays an even more central role in domestic supply [6]. Safeguarding its chemical quality is therefore essential for both environmental sustainability and public health protection [7].

Rapid industrialization, urban expansion, agricultural intensification, and inadequate wastewater management have exposed canal systems to multiple, often overlapping, contamination pathways, including industrial effluents, municipal sewage, agrochemical runoff, road runoff, atmospheric deposition, and geogenic weathering [8]. Heavy metals are of particular concern within this contaminant mixture: unlike many conventional pollutants, they are nonbiodegradable, environmentally persistent, and governed by complex dissolution, adsorption,

precipitation, and sediment–water partitioning processes that render them difficult to remove once introduced into aquatic systems [9]. Canals traversing industrially developed and agriculturally intensive corridors therefore tend to integrate the cumulative signatures of both natural and anthropogenic sources. Potentially toxic elements such as lithium (Li), aluminum (Al), arsenic (As), cadmium (Cd), chromium (Cr), cobalt (Co), nickel (Ni), and lead (Pb) enter canal systems *via* industrial discharge, metallurgical and mining activity, fertilizer application, municipal wastewater, atmospheric fallout, and weathering of parent rock [4]. While trace elements such as copper (Cu) and Co are physiologically essential at low concentrations, arsenic, cadmium, chromium, and lead are high-priority contaminants because they are toxic even at trace concentrations. Chronic exposure has been linked to neurological, renal, hepatic, cardiovascular, endocrine, developmental, immunological, and reproductive disorders, as well as carcinogenesis, with bioaccumulation and food-chain biomagnification further amplifying long-term human exposure [10].

Where canal water is used directly for domestic purposes, human exposure occurs primarily through oral ingestion and dermal contact during routine household activities [5]. Children are disproportionately vulnerable owing to their lower body weight, higher water intake relative to body mass, and physiological immaturity. Robust contamination assessment must therefore extend beyond elemental quantification to include quantitative human health risk assessment that can resolve exposure differences across population subgroups [11]. Human health risks associated with potentially toxic elements (PTEs) in water are typically evaluated using the United States Environmental Protection Agency (USEPA) risk assessment framework, which includes the estimation of the average daily dose (ADD), hazard quotient (HQ),

201 hazard index (HI), and carcinogenic risk (CR) [12,13]. In parallel, multivariate  
202 statistical approaches, such as principal component analysis (PCA), hierarchical  
203 cluster analysis (HCA), and correlation analysis, are widely applied to identify  
204 potential contaminant sources, distinguish geogenic influences from anthropogenic  
205 influences, and characterize spatial variability in water quality [14]. Integrating health  
206 risk assessment with multivariate statistical analyses and contamination indices  
207 provides a comprehensive framework for interpreting contaminant distribution, source  
208 apportionment, and associated environmental and human health risks, thereby  
209 supporting evidence-based water quality management [15]. Despite extensive  
210 literature on heavy metal contamination in rivers, lakes, reservoirs, and groundwater,  
211 canal water resources remain relatively underexamined despite their intensive  
212 domestic use across much of India [12]. Existing canal-focused studies have  
213 predominantly addressed irrigation suitability or general physicochemical  
214 characteristics, often at isolated sites, leaving an integrated assessment combining  
215 spatial metal distribution, source apportionment, contamination indexing, and  
216 probabilistic human health risk assessment largely absent from the literature. This gap  
217 constrains the development of targeted, evidence-based management strategies for  
218 canal-dependent populations [16]. A comparative overview of previous studies on  
219 heavy metal contamination in canal and surface waters, together with the key  
220 methodological and analytical advances of the present study over existing research, is  
221 presented in Table 1. Haryana provides an especially instructive setting for addressing  
222 this gap. The state combines intensive agriculture, rapid industrial growth, and dense  
223 urban settlement with an extensive canal network [17]. Major industrial cluster-metal  
224 processing, textiles, petrochemicals, electroplating, engineering, and thermal power  
225 generation operations occur alongside highly fertilized and pesticide-intensive

agricultural zones, creating substantial potential for heavy metal loading via industrial discharge, wastewater, and diffuse agricultural runoff [18]. Canals traversing industrial versus nonindustrial districts would therefore be expected to exhibit distinct contamination signatures, underscoring the value of comparative spatial assessment across contrasting land use regimes [19].

Characterizing spatial contamination patterns alone, however, is insufficient without linking them to human exposure [10]. Because canal water used for drinking, cooking, bathing, and washing represents a potential source of chronic exposure—particularly for rural communities lacking alternative supplies—embedding human health risk assessment within water quality monitoring substantially increases its practical and regulatory relevance, enabling the identification of vulnerable groups, priority contaminants, and geographic hotspots requiring intervention [20,21]. Recent advances in environmental risk assessment favour integrated frameworks that couple high-precision instrumental analysis with multivariate statistics and quantitative risk modelling [22]. Inductively coupled plasma–mass spectrometry (ICP–MS) enables simultaneous, high-sensitivity quantification of trace metals [16], while its integration with contamination indices, correlation analysis, PCA, and HCA facilitates robust source identification [23]. Probabilistic human health risk assessment further improves the realism of exposure characterization by explicitly accounting for population variability and dataset uncertainty, strengthening confidence in the resulting risk estimates [24].

This investigation also aligns with global sustainability priorities: SDG 6 calls for universal access to safe water through improved quality management and pollution reduction. Moreover, SDG 3 emphasizes minimizing the environmental determinants of poor health [25]. Evidence from integrated contamination and health

251 risk assessments therefore contributes not only to regional water management but also  
252 to broader national and international policy objectives [4]. In this context, the present  
253 study evaluates the distribution of selected heavy metals in canal water across  
254 industrial and nonindustrial districts of Haryana, India, using high-resolution ICP–MS  
255 analysis. Specific objectives were to (i) quantify spatial variability in metal  
256 concentrations, (ii) identify probable contamination sources through multivariate  
257 statistical analysis, (iii) compare pollution characteristics between industrial and  
258 nonindustrial land use regimes, and (iv) conduct probabilistic human health risk  
259 assessments for both adults and children *via* oral ingestion and dermal exposure  
260 pathways, including noncarcinogenic risk and carcinogenic risk estimation for  
261 different heavy metals. By integrating environmental chemistry, statistical source  
262 apportionment, contamination indexing, and quantitative health risk analysis within a  
263 single analytical framework, this study establishes a scientific baseline for canal water  
264 monitoring in semiarid regions of India. It offers a transferable methodological model  
265 for assessing heavy metal contamination and associated human health risks in canal  
266 systems of other rapidly industrializing, agriculturally intensive regions worldwide.

**Table 1.** Overview of recent studies investigating heavy metal concentrations in Canal water and comparisons with the present study

| References | Country    | Water body<br>(Canal & Surface) | Heavy metal Concentrations                                                                                                                                           | Analytical techniques                     | Superiority of our work                                                                                                                                                                                                                                                    |
|------------|------------|---------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| [26]       | Bangladesh | Canal water                     | Zn (0.01-0.20), Cu (0.008-0.032), Pb (0.09-0.61), Cd (0.09-0.13) mg/L in Tejgaon canal; Zn (0-0.15), Cu (0-0.032), Pb (0-0.60), Cd (0.13-0.31) mg/L in Rampura canal | Atomic Absorption Spectrophotometer (AAS) | The present study provides a broader spatial assessment across seven Haryana districts with 42 canal-water samples and extends beyond metal concentrations to industrial-non-industrial comparison, source identification, and probabilistic human-health risk assessment. |
| [27]       | India      | Canal water                     | Cr (0-0.791), Pb (0-0.308), Hg (0-0.008), Zn (0.171-1.084), Mn (0-1.066), Mg (2.171-31.217), Fe (0.148-2.847) mg/L                                                   | Flame AAS                                 | Characterized multiple metals in canal water using AAS. Present study advances this concentration-based approach through seven-district spatial comparison, source identification, and simultaneous assessment of adult and child exposure and health risks.               |
| [28]       | India      | Canal water                     | As (0.96), Cr (1.56), Cu (2.24), Mn (7.91), Ni (1.94), Pb (3.66), Zn (5.26) mg/L                                                                                     | ICP-OES                                   | Reported metal concentrations in canal water using ICP-OES. Present study goes beyond elemental characterization by distinguishing industrial and non-industrial regions and linking metal occurrence with exposure pathways and carcinogenic/non-carcinogenic risks.      |

|      |                                         |               |                                                                                                                                                           |         |                                                                                                                                                                                                                                                                                    |
|------|-----------------------------------------|---------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------|---------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| [29] | India                                   | Canal water   | Hg (0.00084-0.00206), Pb (0.00334-0.00583), Fe (0.140-0.580), Cu (0.00255-0.00707), Zn (0.00793-0.01023), Cd (0.00188-0.00577), Ni (0.00622-0.00854) mg/L | AAS     | Investigated multiple heavy metals in canal water using AAS. Present study provides greater spatial resolution across seven Haryana districts and additionally evaluates contamination patterns, potential sources, and population-specific health risks.                          |
| [30] | Republic of Macedonia (North Macedonia) | Surface water | (0.00698) mg/L                                                                                                                                            | ICP-MS  | Focused on the occurrence of Li in surface water. Present study places Li within a multi-metal framework, enabling comparison with other potentially toxic elements and assessment of their spatial distribution and associated health implications.                               |
| [31] | India                                   | Canal water   | Cd (0.001-0.016), Cr (0.020-0.074), Cu (0.008-0.077), Mn (0.011-0.042), Ni (0.023-0.122) mg/L                                                             | AAS     | Examined heavy-metal contamination in canal water in relation to industrial influence. Present study expands the industrial perspective to a systematic industrial-non-industrial comparison across seven districts and further quantifies adult- and child-specific health risks. |
| [32] | Pakistan                                | Canal water   | Al (134.04), Cr (0.17), Cu (0.58), Fe (29.31), Mn (0.45), Ni (0.27), P (14.89), Zn (1.66) mg/L                                                            | ICP-OES | Characterized several metals in canal water using ICP-OES. Present study adds spatially resolved pollution assessment, multivariate source interpretation, and probabilistic health-risk characterization to elemental monitoring                                                  |

|      |            |             |                                                                                                                                          |         |                                                                                                                                                                                                                                                                                            |
|------|------------|-------------|------------------------------------------------------------------------------------------------------------------------------------------|---------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| [33] | Bangladesh | Canal water | As (0.59), Ca (47.50), Cd (0.13), Co (0.41), Cr (5.27), Cu (0.44), Fe (4.68), K (37.99), Mn (0.52), Ni (0.33), Pb (0.81), Zn (0.70) mg/L | AAS     | Assessed a broad suite of metals in canal water using AAS. Present study combines multi-element characterization with district-wise spatial analysis, industrial-non-industrial differentiation, and integrated human-health risk assessment.                                              |
| [34] | Egypt      | Canal water | Al (2.69), Cd (0.00045), Cu (0.007), Fe (0.57), Mn (0.113), Ni (0.010), Pb (0.018), Zn (0.015) mg/L                                      | AAS     | Quantified multiple heavy metals in canal water using AAS. Present study extends elemental assessment to a geographically broader seven-district design and evaluates both environmental contamination and potential human-health consequences.                                            |
| [4]  | India      | Canal water | Al (1.272), Cr (0.025), Cu (0.079), Fe (1.193), Pb (0.048), Zn (0.350) mg/L                                                              | ICP-OES | Reported selected heavy-metal concentrations in Indian canal water using ICP-OES. Present study provides a more comprehensive spatial framework by comparing industrial and non-industrial regions and integrating source analysis with carcinogenic and non-carcinogenic risk assessment. |
| [35] | India      | Canal water | Cr (0.006-0.012), Cu (1.04-1.34), Fe (0.23-1.75), Pb (0.013-0.035), Zn (0.125-1.6) mg/L                                                  | ICP-MS  | Investigated heavy metals in canal water using ICP-MS. Present study builds on high-sensitivity elemental analysis by incorporating spatial risk mapping, source evaluation, exposure-pathway analysis, and age-specific health-risk assessment.                                           |
| [36] | India      | Canal water | Cr (0.02-0.21) mg/L                                                                                                                      | AAS     | Focused primarily on Cr contamination in canal water. Present study expands the assessment from a single-metal perspective to a multi-element evaluation across                                                                                                                            |

|      |       |             |    |                        |     |                                                                                                                                                                                                                                                                               |
|------|-------|-------------|----|------------------------|-----|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| [37] | India | Canal water | Pb | (0.185-0.198),         | AAS | seven districts, including source identification and comprehensive health-risk characterization.                                                                                                                                                                              |
|      |       |             | Cr | (0.160-0.177),         |     | Investigated several heavy metals in canal water using AAS. Present study extends this assessment through seven-district spatial characterization and integrates contamination status with source interpretation, exposure pathways, and carcinogenic/non-carcinogenic risks. |
|      |       |             | Ni | (0.091-0.099),         |     |                                                                                                                                                                                                                                                                               |
|      |       |             | Cu | (0.088-0.089),         |     |                                                                                                                                                                                                                                                                               |
|      |       |             | As | (0.070-0.075)<br>mg/L. |     |                                                                                                                                                                                                                                                                               |

268 **Note:** Metal concentrations are reported in the units specified by the respective studies (mg/L) and represent the reported concentration ranges or  
 269 mean values. The “Superiority of our work” column summarizes the major methodological and analytical advances of the present study relative  
 270 to previous investigations, particularly regarding spatial coverage, industrial-non-industrial comparison, source identification, and integrated  
 271 human-health risk assessment. Comparative statements are based on the scope and parameters reported in the cited studies. AAS: Atomic  
 272 Absorption Spectrophotometry; Al: Aluminium; As: Arsenic; Cd: Cadmium; Co: Cobalt; Cr: Chromium; Cu: Copper; Fe: Iron; Hg: Mercury;  
 273 ICP-OES: Inductively Coupled Plasma-Optical Emission Spectrometry; ICP-MS: Inductively Coupled Plasma-Mass Spectrometry; K:  
 274 Potassium; Li: Lithium; Mg: Magnesium; Mn: Manganese; Ni: Nickel; P: Phosphorus; Pb: Lead; Zn: Zinc

## 2 Study area

The present study was conducted in the state of Haryana, which is located in northwestern India between 27°39'N and 30°55'N and between 74°28'E and 77°36'E, covering approximately 44,212 km<sup>2</sup>. Punjab borders the state to the north and west; Himachal Pradesh and Uttarakhand border it to the northeast; Uttar Pradesh borders it to the east; and Rajasthan borders it to the south and southwest. Haryana forms an important part of the Indo-Gangetic alluvial plains. It has undergone rapid agricultural, industrial, and urban development over the past few decades, resulting in increasing pressure on its surface water resources [38].

Haryana experiences a semiarid to subhumid climate characterized by pronounced seasonal variability. Summers (April–June) are hot and dry, with maximum temperatures frequently exceeding 45°C, whereas winters (December–February) are cold, with temperatures occasionally falling below 5°C [39]. The annual rainfall ranges from approximately 300 mm in the southwestern districts to nearly 1000 mm in the northeastern region, with nearly 75–80% of the precipitation occurring during the southwest monsoon season [40]. Seasonal fluctuations in rainfall and temperature strongly influence surface water availability; dilution capacity; and the transport, mobilization, and accumulation of dissolved contaminants, including heavy metals, within canal systems [41]. Hydrologically, Haryana is primarily drained by the Yamuna and Ghaggar River systems and has one of the largest canal networks in India. Major canal systems include the Western Yamuna Canal, Bhakra Main Line Canal, Sirsa Canal, Gurgaon Canal, and Hansi-Butana Canal, together with numerous distributaries and minor canals. Beyond supporting agriculture, these canal systems also provide water for drinking, household needs, livestock, and other domestic uses,

particularly in rural and peri-urban areas. Groundwater extracted through tube wells and bore wells further supplements domestic water demand across the state [42].

Haryana's geology is dominated by Quaternary alluvial deposits of the Indo-Gangetic Plains, consisting mainly of unconsolidated sediments deposited by the Yamuna and Ghaggar River systems [42]. These alluvial formations facilitate interactions between surface water and groundwater and influence the transport, mobility, and distribution of dissolved contaminants, including potentially toxic elements [43]. Although agriculture remains an important economic activity in Haryana, rapid industrialization, urban expansion, increasing population density, and inadequate management of municipal and industrial wastewater have substantially altered surface water quality [39]. Industrial effluents, domestic sewage, urban runoff, and agricultural runoff carrying fertilizers and pesticides collectively introduce potentially toxic elements into canal systems [44]. Consequently, the contamination of canal water has become an important environmental and public health concern, particularly where these water resources are utilized for drinking, household activities, and livestock consumption [8]. Seven districts were strategically selected to evaluate the spatial distribution of heavy metals in canal water under different anthropogenic settings across Haryana. The sampling design enabled comparisons between industrially influenced regions and predominantly nonindustrial regions, thereby providing representative spatial coverage of the major environmental conditions prevailing within the state.

### ***2.1 Industrial districts***

Four districts, Panipat, Hisar, Rohtak, and Ambala, were classified as industrially significant because of their extensive industrial activities and documented history of environmental pollution. Panipat is one of India's largest textile processing and dyeing

centers, where industrial discharge may contain synthetic dyes, heavy metals, and other hazardous chemicals [45]. Hisar is an important center for steel manufacturing, fertilizer production, and chemical industries. Rohtak hosts pharmaceutical, food-processing, and automobile-related industries, whereas Ambala is well known for scientific instrument manufacturing and associated chemical industries. Canal systems passing through these districts may be affected by industrial effluents, municipal wastewater, and urban runoff, making them suitable locations for investigating heavy metal contamination [46] in water intended for domestic use [47,48].

## ***2.2 Nonindustrial districts***

Three districts—Sirsa, Jind, and Kurukshetra—were selected to represent predominantly nonindustrial regions where anthropogenic influences arise mainly from agricultural runoff, domestic wastewater, and rural settlements rather than intensive industrial activities [49]. Sirsa is situated in the semiarid southwestern part of Haryana and depends extensively on canal water for domestic and agricultural purposes. Jind is an agriculturally important district traversed by an extensive canal distribution network, whereas Kurukshetra is characterized by moderate urban development and intensive agricultural activities with comparatively limited industrialization [50]. These districts provide an appropriate baseline for evaluating heavy metal concentrations in areas with relatively low industrial influence.

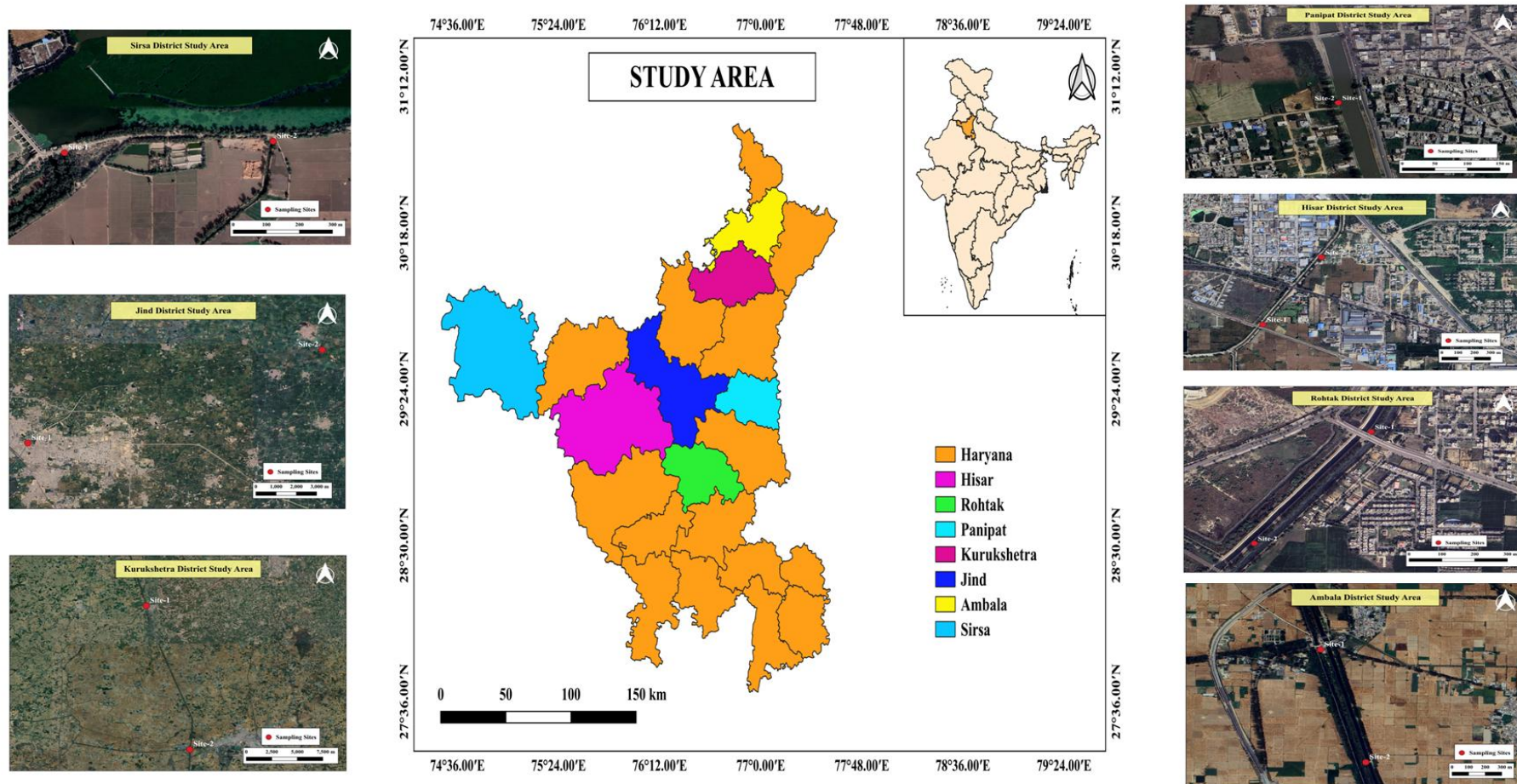
The comparative selection of industrial and nonindustrial districts enabled a comprehensive assessment of the spatial distribution of heavy metals in canal water across Haryana. It facilitates the evaluation of the influence of different anthropogenic activities on water quality [49]. The selected districts collectively represent a broad gradient of industrial, agricultural, and urban pressures, providing a robust framework for assessing heavy metal contamination in canal water used for drinking, household

activities, and livestock consumption, as well as the associated implications for domestic water quality and public health [51].

### **3 Materials and Methods**

#### ***3.1 Sampling locations***

A stratified sampling approach was employed to achieve a comprehensive spatial representation of canal water quality across the selected districts of Haryana. One major representative canal was selected from each of the seven study districts on the basis of its environmental significance, level of anthropogenic influence, and year-round accessibility for systematic sampling. Within each selected canal, two sampling sites were designated, namely, an upstream location (Site 1) and a downstream location (Site 2), to evaluate spatial variability and longitudinal changes in water quality associated with cumulative anthropogenic inputs along the canal. Table 2 presents the geographical coordinates and detailed characteristics of all the sampling locations.



363 **Fig. 1.** Location map of the study area showing the selected districts of Haryana (Rohtak, Hisar, Panipat, Ambala, Jind, Kurukshetra, and Sirsa)  
 364 and the canal water sampling locations (Sites 1 and 2) included in the study

365 **Table 2.** Geographical coordinates of the canal water sampling locations across the selected districts of Haryana, where Site-1 and Site-2 denote  
366 the upstream and downstream sampling points, respectively

| Sl. No. | Districts   | Sites  | Latitude     | Longitude    | Nearby Industries                                 | Nearby Hospitals                                                      | Nearby Schools/Colleges                                  | Nearby Temples/Mosques                         | Nearby Roads/Highways                                       |
|---------|-------------|--------|--------------|--------------|---------------------------------------------------|-----------------------------------------------------------------------|----------------------------------------------------------|------------------------------------------------|-------------------------------------------------------------|
| 1.      | Rohtak      | Site-1 | 28.868573°E  | 76.625787°N  | Aditi Ind, 2.2 km, Industrial Model Twp, - 6.4 km | Holy Heart Hospital - 2.3 km                                          | MDU - 3.1 km                                             | Shiv Mandir - 0.7 km                           | 0.2 km                                                      |
|         |             | Site-2 | 28.864152° E | 76.622127° N | 2.9 km                                            | 2.7 km, and Titiksha Ayurveda Panchakarma & Psoriasis Center - 1.3 km | 3.9 km                                                   | Shiv Mandir - 1.1 km                           | Nirbhay Pilonia's Bridge Area - 0.4 km and Highway - 1.1 km |
| 2.      | Panipat     | Site-1 | 29.384607° E | 76.94619° N  | R.D Steel Industries - 1.5 km                     | Ravindra Hospital - 2.2 km                                            | Bal Vikash School - 0.8 km, Arya College - 3.8 km        | Khatu Shyam, Mandir - 1.1 km                   | Panipat NH44 - 3.6 km                                       |
|         |             | Site-2 | 29.384601° E | 76.94618° N  | Magnatic Lubricants- .55 km                       | D. S hospital - .55 km                                                | Bhagwan Parshuram College of Education - 1.7 km          | Radha Raman Mandir - 0.5 km                    | 3.5 km                                                      |
| 3.      | Ambala      | Site-1 | 30.207398° E | 76.708985° N | A. J Industries - 7 km                            | Shree Ram Hospital - 2.8 km                                           | Primary School - 8.7 km and Govt College Chammu - 9.9 km | Shiva Temple - 8.3 km                          | Kaithal - Ambala Highway - 0.9 km                           |
|         |             | Site-2 | 30.19917° E  | 76.711825° N | Bansal Agro Industriel - 7.1 km                   | Hospital - 4 km                                                       | Govt College Chammu - 10.9 km                            | Masjid - 6.9 km                                | Ambala Hisar Marg - 1.9 km                                  |
| 4.      | Jind        | Site-1 | 29.323039° E | 76.307181° N | Rama Industries - 1.3 km                          | Sood Hospital - 1.1 km                                                | Jat Sr. School - 0.8 km, CR Kisan ITI - 0.8 km           | Shri Jayanti Devi Temple And Museum - 70 meter | Patiala Road - 10 meter                                     |
|         |             | Site-2 | 29.374311° E | 76.457018° N | Gotam Metal Industry - 6.3 km                     | Shyamji Hospital - 4.8 km                                             | GSSS - 1 km, Chetna Nursing Collge - 3.1 km              | Devi Mandir - 1.5 km                           | Ambala- Narnaul Expresway - 2.6 km                          |
| 5.      | Kurukshetra | Site-1 | 30.117455° E | 76.736452° N | Gupta Metal Industry - 9.4 km                     | Govt. Medical Hospital - 0.4 km                                       | MS Sr. School - 750 meter, LCM College - 1.5 km          | Mandir - 35 meter                              | Jhansa Road - 50 meter and Above on Canal                   |
|         |             | Site-2 | 29.95978° E  | 76.78068° N  | Cosmetic Industry -4.5 km                         | LNJP Hospital - 5.3 km                                                | Hotel Mangment Collge - 2.2 km                           | Shiv Mandir - 900 meter                        | Kurukshetra - Pehowa Marg - 20 meter                        |
| 6.      | Hisar       | Site-1 | 29.119889° E | 75.795242° N | Bharat Metal Ind.                                 | Sukhda Hospital - 2.8 km                                              | Imperial College - 6.7 km,                               | Hanuman Temple -                               | OP Jindal Marg -                                            |

|    |       |        |              |              |                                                              |                                                        |                                                |                                                |                                             |
|----|-------|--------|--------------|--------------|--------------------------------------------------------------|--------------------------------------------------------|------------------------------------------------|------------------------------------------------|---------------------------------------------|
| 7. | Sirsa | Site-2 | 29.125439° E | 75.798946° N | - 1.1 km<br>Vikash Steel Ind. - 1.4 km                       | Sukhda Hospital - 1.7 km<br>and Jindal Hospital - 6 km | Sanik School - 3.2 km<br>Skill Collge - 5.6 km | 750 meter<br>Devi Temple - 650 meter           | 400 meter<br>Hisar Southren Byp - 350 meter |
|    |       | Site-1 | 29.487422° E | 74.894362° N | Vinayak Industries - 1.8 km                                  | Dhulara Singh Hospital - 1.8 km                        | Guru Nanak School - 4.2 km                     | Salasar Dham - 7 km,<br>Peer Majid - 500 meter | Sirsa Raniya Marg - 10 meter                |
|    |       | Site-2 | 29.487807° E | 74.90087° N  | Vinayak Industries - 1.8 km<br>and Shri Balaji Agro - 3.1 km | Dhulara Singh Hospital - 1.2 km                        | Genius Sr. School - 7.4 km,                    | Peer Majid - 1.1km                             | Sirsa Raniya Marg - 10 meter                |

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367 **Note:** Distances are expressed in kilometers (km), unless otherwise stated. Geographic coordinates were recorded using a Global Positioning

368 System (GPS). Site-1 and Site-2 denote the upstream and downstream sampling locations, respectively. byp: Bypass; CR: Chhotu Ram; °E:

369 Degree East; Govt.: Government; GSSS: Government Senior Secondary School; ITI: Industrial Training Institute; LNJP: Lok Nayak Jai Prakash

370 Hospital; MDU: Maharshi Dayanand University; °N: Degree North; NH: National Highway; OP: Om Parkash; Sr.: Senior; Twp: Town Park

At each sampling location, water samples were collected in triplicate to minimize analytical uncertainty and improve the reliability of the results. Accordingly, the sampling design included 7 districts  $\times$  1 canal  $\times$  2 sampling sites  $\times$  3 replicates, resulting in 42 water samples being collected during each sampling campaign. The geographic coordinates of all the sampling locations were recorded using a handheld global positioning system (GPS) device to ensure accurate geospatial reference and reproducibility.

### ***3.2 Inclusion and Exclusion Criteria***

The inclusion and exclusion criteria were established to ensure representative canal water samples and maintain consistency in heavy metal analysis. The sampling sites were selected on the basis of year-round accessibility, continuous water availability, and active canal flow. Canal water samples were collected from the designated sampling sites that had sufficient volume and no visible contamination introduced during sampling for subsequent analysis.

Sampling sites with stagnant water, temporary flow obstructions, excessive floating debris, or substantial anthropogenic disturbance that could compromise sample representativeness were excluded. In addition, samples were excluded if accidental contamination occurred during collection, preservation, or transport; if the collected volume was insufficient for heavy metal analysis; or if transport exceeded the recommended holding time. These criteria ensured the accuracy, reliability, and comparability of the analytical results

### ***3.3 Canal Water Collection and Processing***

A total of 42 canal water samples were collected from the seven selected districts of Haryana, with six samples collected from each district. In each district, sampling was conducted at two locations, and three replicate samples were collected from each

location to ensure representative sampling. Sampling was performed during the premonsoon season to minimize the influence of rainfall-induced dilution on heavy metal concentrations. The selected sampling locations represented areas subjected to varying degrees of anthropogenic influence, including industrial activities and residential settlements. Water samples were collected in precleaned high-density polyethylene (HDPE) narrow-mouth bottles. Before sample collection, each bottle was rinsed three times with water from the respective sampling location to minimize the potential for cross-contamination. The geographic coordinates (latitude and longitude) of each sampling location were recorded using a handheld global positioning system (GPS) device to ensure accurate geospatial referencing and reproducibility of the sampling locations

Immediately after collection, all water samples were preserved by acidification with 69% analytical reagent-grade nitric acid ( $\text{HNO}_3$ ) to maintain a  $\text{pH} \leq 2$ , following the preservation procedure described by [52]. Acidification prevented dissolved heavy metals from adsorbing onto the walls of the sample containers and suppressed biological activity that could alter the elemental composition during storage and transport. The preserved samples were transported to the laboratory in insulated, ice-filled containers and stored at  $4^\circ\text{C}$  until analysis. All analyses were completed within the recommended holding period for trace metal determination. Before heavy metal determination, the preserved water samples were digested following the standard procedure for trace metal analysis [53]. Briefly, 50 mL of a well-mixed water sample was transferred into an acid-washed digestion conical flask, followed by the addition of 5 mL of concentrated  $\text{HNO}_3$  (69%, trace metal grade). The conical flask was allowed to stand for 30 min at room temperature under a fume hood to facilitate initial oxidation and then heated in a hot air oven at  $70^\circ\text{C}$  for 25 min. After cooling, 2 mL of

HClO<sub>4</sub> was added, the mixture was returned to the hot air oven and heated at 135°C for 25 min. Next, 2 mL of HClO<sub>4</sub> and 2 mL of HNO<sub>3</sub> were added, and the mixture was heated in the hot air oven at 135°C for another 25 min. Thereafter, 2 mL of HNO<sub>3</sub> and 5 mL of HCl were added, and the digestion mixture was allowed to cool to room temperature. The digest was then filtered through Whatman No. 42 filter paper, followed by a 0.2 µm nylon syringe filter into a sterile 50 mL Falcon tube, and the final volume was adjusted to 50 mL with ultrapure deionized water. The overall workflow encompassing canal water sampling, preservation, acid digestion, filtration, and preparation for elemental analysis by ICP–MS is illustrated in Supplementary Fig. F1. The heavy metal concentrations of the digested samples were subsequently analysed using inductively coupled plasma–mass spectrometry (ICP–MS) [54].

### ***3.4 Evaluation of Heavy Metals in Collected Canal Water***

The collected water samples were filtered through Whatman No. 42 filter paper, followed by a 0.2 µm nylon syringe filter, to remove suspended particulate matter before elemental analysis. The concentrations of Li, Al, As, Cd, Cr, Co, Cu, Ni, and Pb were determined using inductively coupled plasma–mass spectrometry (ICP–MS) in accordance with the Standard Methods for the Examination of Water and Wastewater [55,56] because of its high sensitivity, multielement detection capability, and low detection limits, enabling accurate and reliable determination of trace heavy metals in water samples [19].

#### ***3.4.1 Instrumental conditions***

The elemental composition was quantified using inductively coupled plasma–mass spectrometry (ICP–MS) under optimized instrumental conditions to ensure analytical sensitivity, precision, and reproducibility. Selected isotopes (<sup>7</sup>Li, <sup>27</sup>Al, <sup>52</sup>Cr, <sup>59</sup>Co, <sup>60</sup>Ni, <sup>63</sup>Cu, <sup>75</sup>As, <sup>111</sup>Cd, and <sup>208</sup>Pb) were analysed with a dwell time of 0.01 s and a nebulizer

flow rate of 14 mL min<sup>-1</sup>. The working concentration range was maintained at 1–100 µg mL<sup>-1</sup>, with an optimized detection range of 0.01–500 µg mL<sup>-1</sup> and an instrumental sensitivity of 0.5 µg mL<sup>-1</sup>. Certified reference materials (CRMs; 100 mg mL<sup>-1</sup>) were used for calibration and quality assurance to ensure accurate elemental quantification and minimize analytical deviation, as presented in Table 3 [56,57].

**Table 3.** Instrumental operating conditions and analytical parameters used for elemental quantification by ICP-MS

| Sl. No. | Element | Isotops | Dwell Time | Nebulizer rate (mL min <sup>-1</sup> ) | Optimum working range (µg mL <sup>-1</sup> ) | Standard working range (µg mL <sup>-1</sup> ) | Sensitivity (µg mL <sup>-1</sup> ) | CRM values (mg mL <sup>-1</sup> ) |
|---------|---------|---------|------------|----------------------------------------|----------------------------------------------|-----------------------------------------------|------------------------------------|-----------------------------------|
| 1.      | Li      | 7       | 0.01       | 14                                     | 0.01 to 500                                  | 1 to 100                                      | 0.5                                | 100                               |
| 2.      | Al      | 27      | 0.01       | 14                                     | 0.01 to 500                                  | 1 to 100                                      | 0.5                                | 100                               |
| 3.      | Cr      | 52      | 0.01       | 14                                     | 0.01 to 500                                  | 1 to 100                                      | 0.5                                | 100                               |
| 4.      | Co      | 59      | 0.01       | 14                                     | 0.01 to 500                                  | 1 to 100                                      | 0.5                                | 100                               |
| 5.      | Ni      | 60      | 0.01       | 14                                     | 0.01 to 500                                  | 1 to 100                                      | 0.5                                | 100                               |
| 6.      | Cu      | 63      | 0.01       | 14                                     | 0.01 to 500                                  | 1 to 100                                      | 0.5                                | 100                               |
| 7.      | As      | 75      | 0.01       | 14                                     | 0.01 to 500                                  | 1 to 100                                      | 0.5                                | 100                               |
| 8.      | Cd      | 111     | 0.01       | 14                                     | 0.01 to 500                                  | 1 to 100                                      | 0.5                                | 100                               |
| 9.      | Pb      | 208     | 0.01       | 14                                     | 0.01 to 500                                  | 1 to 100                                      | 0.5                                | 100                               |

**Note:** Dwell time is expressed in seconds (s), nebulizer rate in millilitres per minute (mL min<sup>-1</sup>), and the optimum, standard, and sensitivity working ranges in micrograms per millilitre (µg mL<sup>-1</sup>). CRM: Certified Reference Material; Al: Aluminium; As: Arsenic; Cd: Cadmium; Co: Cobalt; Cr: Chromium; Cu: Copper; Li: Lithium; Ni: Nickel; Pb: Lead

#### 3.4.2 Quality Assurance and Quality Control (QA/QC)

Stringent quality assurance and quality control (QA/QC) procedures were implemented throughout sample collection, preservation, preparation, and instrumental analysis to ensure accurate, precise, and reliable analytical results. Procedural blanks prepared with ultrapure deionized water and subjected to the same sample preparation and analytical procedures as the canal water samples were analysed at regular intervals to monitor potential background contamination. Certified

reference materials (CRMs) for water analysis were analysed alongside the samples to verify analytical accuracy.

Instrument calibration was performed using multielement calibration standards prepared from certified stock solutions over concentration ranges encompassing the expected concentrations in the water samples. The calibration curves exhibited excellent linearity, with correlation coefficients ( $r^2$ )  $\geq 0.999$  throughout the analytical runs. Rhodium (Rh) and indium (In) were employed as internal standards and added to all the calibration standards, procedural blanks, and samples to compensate for instrumental drift and matrix effects. Duplicate analyses were performed for at least 10% of the total samples, and the relative percent difference (RPD) between duplicate measurements was maintained within  $\pm 5\%$ , confirming satisfactory analytical reproducibility. The method detection limit (MDL) for each heavy metal was calculated as three times the standard deviation of ten replicate measurements of the procedural blank. In contrast, the limit of quantification (LOQ) was established as ten times the corresponding standard deviation. Table 4 presents the LOD, LOQ, and recovery values for the analysed heavy metals. All reported heavy metal concentrations exceeded their respective LOQ values.

**Table 4.** Analytical performance characteristics of the ICP-MS method for the determination of heavy metals in canal water samples

| Sl. No. | Attributes | Li          | Al      | Cr      | Co      | Ni      | Cu      | As      | Cd      | Pb      |
|---------|------------|-------------|---------|---------|---------|---------|---------|---------|---------|---------|
| 1.      | LOD (ppm)  | 8.18606E-05 | 5.4E-07 | 7E-10   | 4.1E-10 | 3.4E-08 | 1.7E-08 | 1.6E-08 | 2.3E-10 | 2.2E-10 |
| 2.      | LOQ (ppm)  | 1.57656E-06 | 1.8E-06 | 2.3E-09 | 1.4E-09 | 1.1E-07 | 5.7E-08 | 5.2E-08 | 7.5E-10 | 7.2E-10 |
| 3.      | Recovery%  | -           | 106.628 | 92.41   | 94.09   | 108.728 | 94.306  | 109.01  | 96.076  | 107.712 |

**Note:** LOD (Limit of Detection) and LOQ (Limit of Quantification) represent the analytical sensitivity of the ICP-MS method and are expressed in parts per million (ppm). Recovery (%) indicates the analytical accuracy of the method. Abbreviations: Al: Aluminium; As: Arsenic; Cd: Cadmium; Co: Cobalt; Cr: Chromium; Cu: Copper;

Li: Lithium; LOD: Limit of Detection; LOQ: Limit of Quantification; Ni: Nickel; Pb: Lead; ppm, Parts per million

### ***3.4.3 Calculation of Health Risk Assessment***

The human health risks associated with heavy metals in canal water were assessed using the methodology recommended by the United States Environmental Protection Agency [58]. Human exposure was evaluated through two primary pathways: direct ingestion of canal water and dermal absorption during domestic use. The assessments were performed separately for adults and children to account for age-specific differences in exposure parameters and physiological characteristics.

The exposure doses through ingestion ( $Exp_{ing}$ ) and dermal absorption ( $Exp_{derm}$ ) for each heavy metal were estimated using the standard exposure equations recommended by the USEPA. On the basis of the estimated exposure doses, the noncarcinogenic health risk was evaluated by calculating the hazard quotient (HQ) for individual heavy metals and the hazard index (HI) for combined exposure. The carcinogenic risk (CR) was estimated for heavy metals with established carcinogenic slope factors following the USEPA risk assessment framework. The assessment considered potential human exposure through the domestic use of canal water, including drinking water and household activities.

### ***3.4.4 Assessment of the noncarcinogenic health risk of children and adults***

#### ***3.4.1 Contamination factor (CF)***

The contamination factor (CF) was used to quantify the extent of heavy metal contamination in the canal water by comparing the measured concentration of each metal with its corresponding guideline value. This index provides a quantitative measure of the relative enrichment of individual heavy metals and serves as a useful indicator for evaluating contamination severity in aquatic systems [58,59]. The contamination factor was calculated using Equation (1):

$$CF = \frac{C_i}{C_b} \dots\dots\dots(1)$$

where  $C_i$  is the average measured concentration of the  $i^{th}$  heavy metal and  $C_b$  is the reference value or standard permissible value of the heavy metal in Equation (1) [60].

### 3.4.2 Degree of contamination (DOC)

The degree of contamination (DOC) was calculated as the cumulative sum of the individual contamination factors (CFs) to provide an integrated assessment of heavy metal contamination in canal water [61]. The DOC was calculated using Equation (2):

$$DOC = \sum_n CF \dots\dots\dots (2)$$

where DOC represents the degree of contamination, CF is the contamination factor of the  $i^{th}$  heavy metal, and  $n$  denotes the total number of heavy metals included in the assessment. On the basis of the calculated DOC values, contamination levels were classified as low ( $DOC < 1$ ), moderate ( $DOC = 1-3$ ), or high ( $DOC > 3$ ) according to [61] (Table 10).

### 3.4.3 Pollution load index (PLI)

The pollution load index (PLI) was calculated to evaluate the overall level of heavy metal pollution in canal water by integrating the contamination factors (CFs) of the investigated heavy metals into a single index. The PLI was calculated as the  $n$ th root of the product of the individual contamination factors, where  $n$  represents the total number of heavy metals included in the assessment, as expressed in Equation (3) (Ogunsanwo et al., 2024):

$$PLI = \sqrt[n]{CF_1 \times CF_2 \times CF_3 \dots\dots\dots CF_n} \dots\dots\dots (3)$$

where CF is the contamination factor of an individual heavy metal and n is the total number of heavy metals included in the assessment. On the basis of the calculated PLI values, the pollution levels were classified as no pollution ( $PLI < 1$ ), moderate pollution ( $1 \leq PLI < 2$ ), heavy pollution ( $2 \leq PLI < 3$ ), and extremely high pollution ( $PLI \geq 3$ ) (Table 11).

#### 3.4.4 Average daily dose (ADD) ingestion

The average daily dose through ingestion ( $ADD_{ing}$ ) for adults and children was calculated using Equation (4) on the basis of the methodology recommended by the United States Environmental Protection Agency [58]:

$$ADD_{ing} = \frac{C_w \times IR \times EF \times ED}{BW \times AT} \dots\dots\dots (4)$$

where  $ADD_{ing}$  (mg/kg/day) is the average daily dose through ingestion of canal water,  $C_w$  is the concentration of heavy metals in canal water (mg/L), IR is the ingestion rate (L/day), EF is the exposure frequency (days/year), ED is the exposure duration (years), BW is the body weight (kg), and AT is the average time for noncarcinogenic effects (days/year).

#### 3.4.5 Average daily dose (ADD)-Dermal

The average daily dose through dermal absorption ( $ADD_{der}$ ) for adults and children was calculated using Equation (5) on the basis of the methodology recommended by the United States Environmental Protection Agency [58]:

$$ADD_{der} = \frac{C_w \times SA \times PC \times ET \times EF \times ED \times CF}{BW \times AT} \dots\dots\dots (5)$$

where  $ADD_{der}$  (mg/kg/day) is the average daily dose through dermal absorption of canal water,  $C_w$  is the concentration of heavy metals in canal water (ppm), SA is

the exposed skin surface area (cm<sup>2</sup>), PC is the dermal permeability coefficient (cm/hour), ET is the exposure time (hours/day), EF is the exposure frequency (days/year), ED is the exposure duration (years), BW is the body weight (kg), AT is the average time for noncarcinogenic effects (days), and CF is the conversion factor (1 L/1000 cm<sup>3</sup>). The average daily doses for both adults and children were calculated, and different values were used for the following parameters, as represented in Supplementary Table S1.

### 3.4.6 Hazard quotient (HQ)

The noncarcinogenic health risk associated with heavy metal exposure through canal water was evaluated by comparing the estimated average daily dose with the corresponding reference dose (RfD). The hazard quotient (HQ) for the ingestion and dermal exposure pathways was calculated using Equations (6) and (7), respectively, following the methodology recommended by the United States Environmental Protection Agency [58]:

$$HQ_{ing} = \frac{ADD_{ing}}{RfD_{ing}} \dots\dots\dots (6)$$

where HQ<sub>ing</sub> is the hazard quotient through ingestion, ADD<sub>ing</sub> is the average daily dose through ingestion (mg/kg/day), and RfD<sub>ing</sub> is the reference dose for the ingestion pathway (mg/kg/day).

$$HQ_{der} = \frac{ADD_{der}}{RfD_{der}} \dots\dots\dots (7)$$

where  $HQ_{der}$  is the hazard quotient through dermal absorption,  $ADD_{der}$  is the average daily dose through dermal absorption (mg/kg/day), and  $RfD_{der}$  is the reference dose for the dermal exposure pathway (mg/kg/day). [62,63].

### 3.4.7 Hazard Index (HI)

The hazard index (HI) was calculated to evaluate the combined noncarcinogenic health risk associated with simultaneous exposure to multiple heavy metals through ingestion and dermal absorption pathways. The HI was determined by summing the hazard quotients (HQs) of the respective exposure pathways, as expressed in Equation (8) [58]:

$$HI = HQ_{ing} + HQ_{der} \dots\dots\dots (8)$$

where HI is the hazard index,  $HQ_{ing}$  is the hazard quotient through ingestion, and  $HQ_{der}$  is the hazard quotient through dermal absorption. HQ or HI values  $< 1$  indicate that noncarcinogenic health effects are unlikely, whereas values  $\geq 1$  indicate the potential for adverse noncarcinogenic health effects (Table 5). [58].

## 3.5 Assessment of the carcinogenic health risk of children and adults

### 3.5.1 Cancer risk (CR)

The carcinogenic risk (CR) associated with heavy metal exposure was estimated to evaluate the potential for cancer development over an individual's lifetime following exposure to potential carcinogens. The carcinogenic risk was calculated using Equations (9) and (10) [58]:

$$CR_{ing} = ADD_{ing} \times CSF_{ing} \dots\dots\dots (9)$$

$$CR_{der} = ADD_{der} \times CSF_{der} \dots\dots\dots (10)$$

where  $CR_{ing}$  and  $CR_{der}$  represent the cancer risks associated with the ingestion and dermal exposure routes, respectively (unitless).  $CSF_{ing}$  and  $CSF_{der}$  denote the cancer slope factors for ingestion and dermal intake, respectively (mg/kg/day) [64–67][64–66,68], with the corresponding values provided in Supplementary Table S2.  $ADD_{ing}$  and  $ADD_{der}$  represent the average daily intakes estimated for adults and children, respectively. The acceptable cancer risk range is  $1 \times 10^{-6}$  to  $1 \times 10^{-4}$  [58]. Cancer risk values exceeding this range indicate an increased likelihood of cancer development due to lifetime exposure to the toxicants of interest, as presented in Table 5.

### 3.5.2 Cancer index (CI)

The cancer index (CI) represents the cumulative cancer risk across the individual exposure pathways, namely, ingestion and dermal absorption, and was calculated using Equation (11) [58].

$$CI = CR_{ing} + CR_{der} \quad \dots\dots\dots (11)$$

where CI denotes the cancer index and  $CR_{ing}$  and  $CR_{der}$  represent the carcinogenic risks associated with the ingestion and dermal absorption pathways, respectively. A CI value  $>1$  indicates a higher overall cancer risk, whereas a CI value  $<1$  indicates a lower overall cancer risk, as presented in Table 5 [58].

**Table 5.** Classification criteria of pollution and health risk indicators used for evaluating canal water quality and associated human health risks

| Sl. No | Parameter | Low/No Pollution | Moderate Pollution    | High Pollution | Extremely High Pollution | Reference |
|--------|-----------|------------------|-----------------------|----------------|--------------------------|-----------|
| 1.     | DOC       | $<1$             | 1–3                   | $>3$           | -                        | [61]      |
| 2.     | PLI       | $<1$             | 1–2                   | 2–3            | $>3$                     | [61]      |
| 3.     | HQ        | $<1$             | -                     | $>1$           | -                        | [58]      |
| 4.     | HI        | $<1$             | -                     | $>1$           | -                        | [58]      |
| 5.     | CR        | $<10^{-6}$       | $10^{-6}$ – $10^{-4}$ | $>10^{-4}$     | -                        | [58]      |
| 6.     | CI        | $<1$             | -                     | $>1$           | -                        | [58]      |

**Note:** DOC and PLI were classified according to Backman et al. (1998) [61], whereas HQ, HI, CR, and CI were interpreted following the health risk assessment guidelines of USEPA (2004). HQ, HI, CR, and CI are dimensionless indices. The acceptable carcinogenic risk (CR) range is  $10^{-6}$ - $10^{-4}$ , with values  $<10^{-6}$  indicating negligible risk and values  $>10^{-4}$  indicating unacceptable carcinogenic risk. The symbol (-) indicates that no specific classification category has been defined for the respective pollution indicator in the cited reference. Abbreviations: CI: Cancer Index; CR: Carcinogenic Risk; DOC: Degree of Contamination; HI: Hazard Index; HQ: Hazard Quotient; PLI: Pollution Load Index; USEPA: United States Environmental Protection Agency

### ***3.6 Statistical analysis***

The heavy metal concentration data were statistically analysed to evaluate their spatial distribution, identify variations among the selected districts, and examine the relationships among the investigated heavy metals in canal water.

#### ***3.6.1 Data standardization***

Before multivariate statistical analyses were performed, the concentrations of all investigated heavy metals were standardized to eliminate the influence of differences in measurement scales and ensure that each variable contributed equally to the statistical interpretation.

#### ***3.6.2 Statistical procedures***

Descriptive and multivariate statistical analyses were performed to characterize the heavy metal distribution patterns in the canal water. Descriptive statistics, including the mean and standard deviation (SD), were calculated to summarize the concentration levels and variability of the investigated heavy metals. One-way analysis of variance (ANOVA) was performed to evaluate significant differences in heavy metal concentrations between industrial and nonindustrial districts, followed by Tukey's honestly significant difference (HSD) post hoc test when significant differences were observed ( $p < 0.05$ ). Pearson correlation analysis was used to examine the relationships among the investigated heavy metals. All the statistical

analyses were performed using IBM SPSS Statistics version 26.0 (IBM Corp., Armonk, NY, USA).

Before principal component analysis (PCA), the suitability of the dataset for multivariate analysis was evaluated using the Kaiser–Meyer–Olkin (KMO) measure of sampling adequacy and Bartlett's test of sphericity (Table 6). The KMO value was 0.684, and Bartlett's test was statistically significant ( $\chi^2 = 1148.704$ ,  $df = 36$ ,  $p < 0.001$ ), confirming the dataset's suitability for PCA. Principal component analysis was subsequently performed to identify the major factors governing heavy metal distribution in canal water. Hierarchical cluster analysis (HCA) was conducted using standardized data, the squared Euclidean distance, and Ward's linkage method to classify the sampling locations according to similarities in heavy metal concentrations, following the methods of Giri et al. (2019) and Giri et al. (2025) [52,69].

**Table 6.** Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy and Bartlett's test of sphericity for principal component analysis

| KMO and Bartlett's Test <sup>a</sup>                                      |                    |          |
|---------------------------------------------------------------------------|--------------------|----------|
| Kaiser-Meyer-Olkin Measure of Sampling Adequacy.                          |                    | 0.684    |
| Bartlett's Test of Sphericity                                             | Approx. Chi-Square | 1148.704 |
|                                                                           | df                 | 36       |
|                                                                           | Sig.               | 0.000    |
| a. Only cases for which VAR00001 = Rohtak are used in the analysis phase. |                    |          |

**Notes:** df: degrees of freedom; KMO: Kaiser-Meyer-Olkin; Sig.: significance. The KMO measure and Bartlett's test were performed to evaluate the suitability of the dataset for principal component analysis. A significant Bartlett's test ( $p < 0.001$ ) confirmed that the dataset was suitable for multivariate analysis

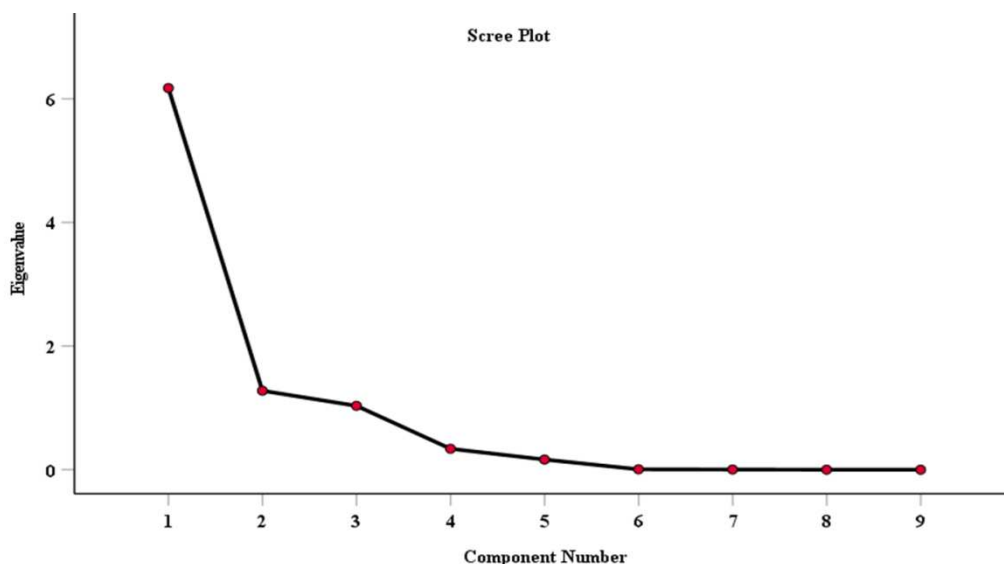


**Fig. 2.** Scree plot illustrating the eigenvalue distribution of the principal components obtained from principal component analysis (PCA). The first three principal components exhibited eigenvalues greater than 1 and explained most of the total variance, whereas the remaining components contributed relatively less to the overall variability of the dataset

## 4 Results

### 4.1 Spatial distribution of heavy metals in canal water collected from the Industrial and non-industrial region of Haryana

Spatial distribution of heavy metals in canal water collected from the seven districts of Haryana. Significant spatial variation was observed for lithium and aluminium ( $p < 0.05$ ), whereas chromium, cobalt, nickel, copper, arsenic, cadmium, and lead did not differ significantly among the districts ( $p > 0.05$ ). Li concentrations ranged from  $0.009 \pm 0.003$  ppm in Sirsa to  $0.025 \pm 0.006$  ppm in Hisar, whereas Al concentrations varied between  $0.111 \pm 0.093$  ppm in Hisar and  $2.309 \pm 0.041$  ppm in Panipat.

Among the remaining metals, Cr concentrations ranged from  $0.002 \pm 0.000$  to  $0.016 \pm 0.004$  ppm, with the highest concentration recorded in Rohtak. Co and Ni exhibited maximum concentrations in Hisar ( $0.0079 \pm 0.0078$  ppm and  $0.010 \pm 0.009$  ppm, respectively), whereas Cu was highest in Sirsa ( $0.028 \pm 0.023$  ppm). Similarly, Hisar recorded the maximum concentrations of As ( $0.012 \pm 0.009$  ppm), Cd ( $8.0E-3 \pm$

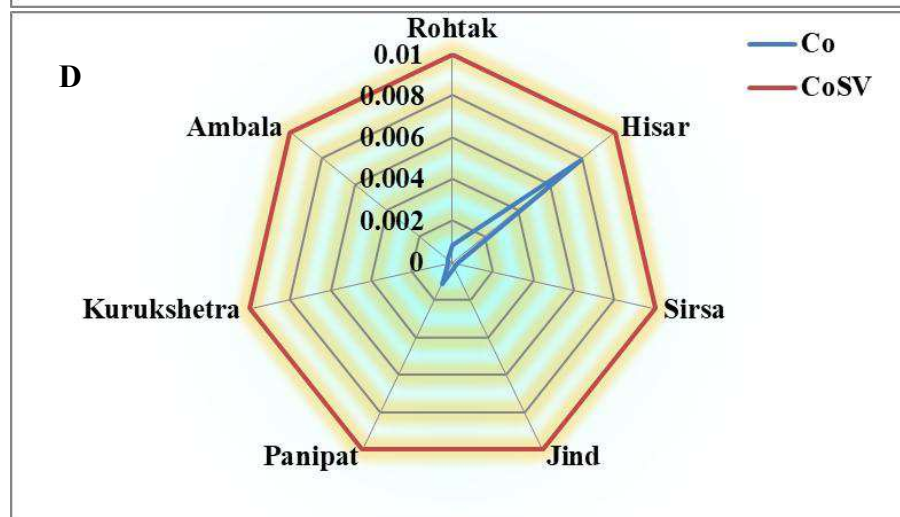
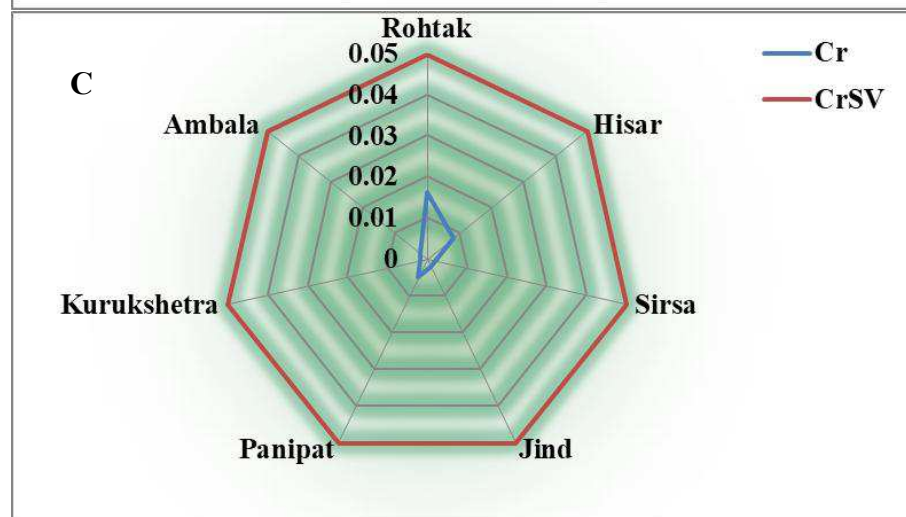
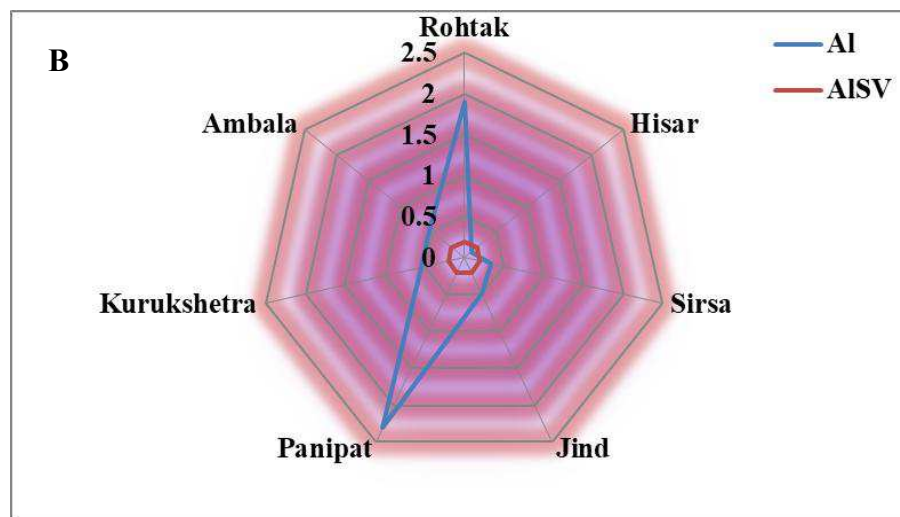
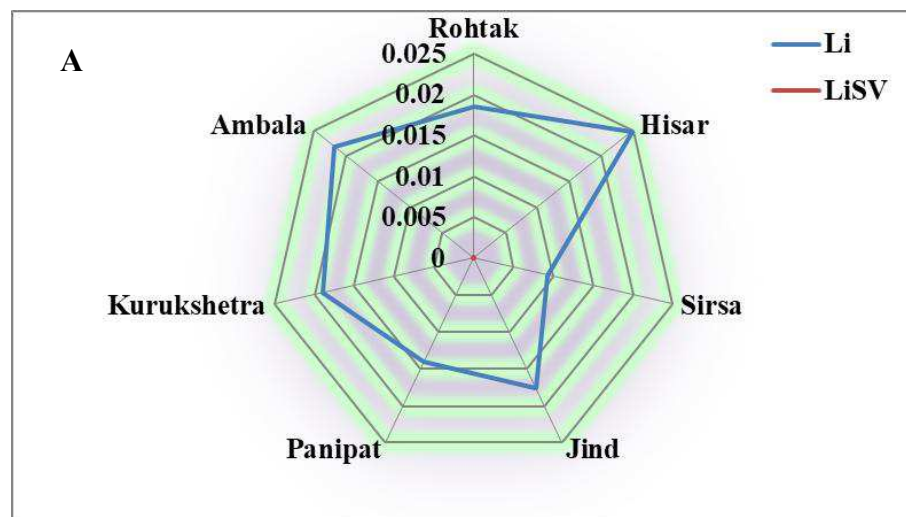
698 8.0E-3 ppm), and Pb ( $0.009 \pm 0.009$  ppm). Overall, Panipat had the highest Al  
699 concentration, Rohtak had the highest Cr concentration, and Sirsa had the highest Cu  
700 concentration. In contrast, Hisar showed relatively high concentrations of Li, Co, Ni,  
701 As, Cd, and Pb. All measured heavy metal concentrations remained below the  
702 respective standard permissible values (SVs) listed in Table 7.  
703

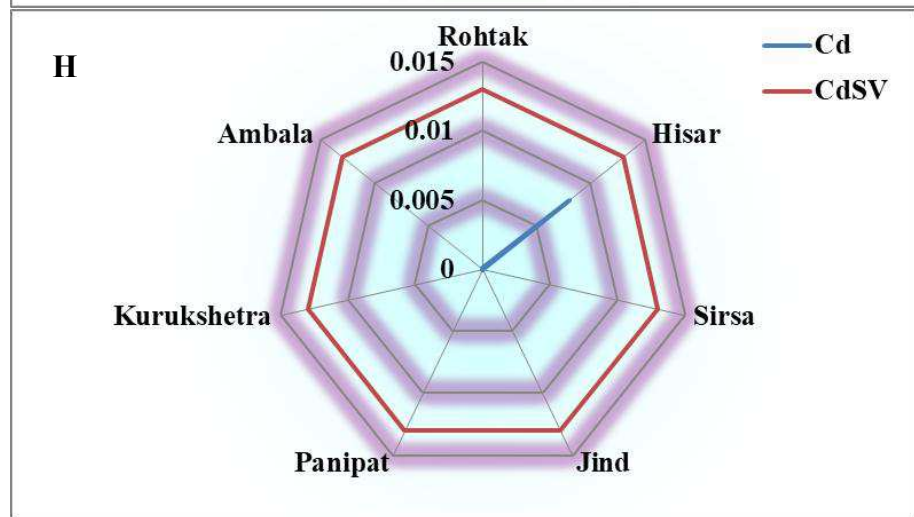
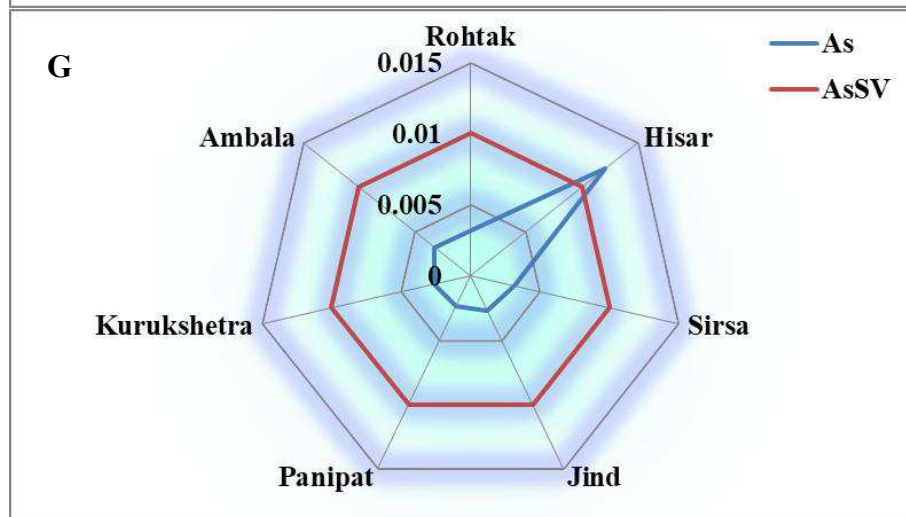
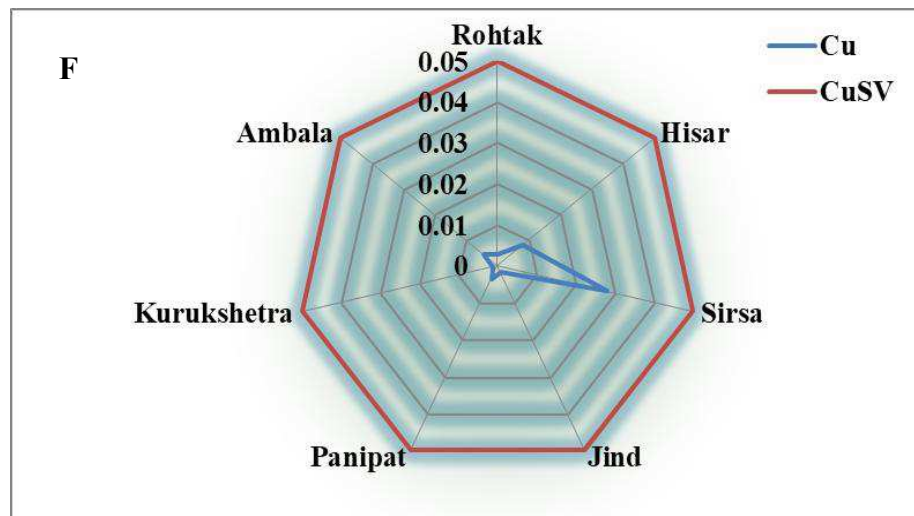
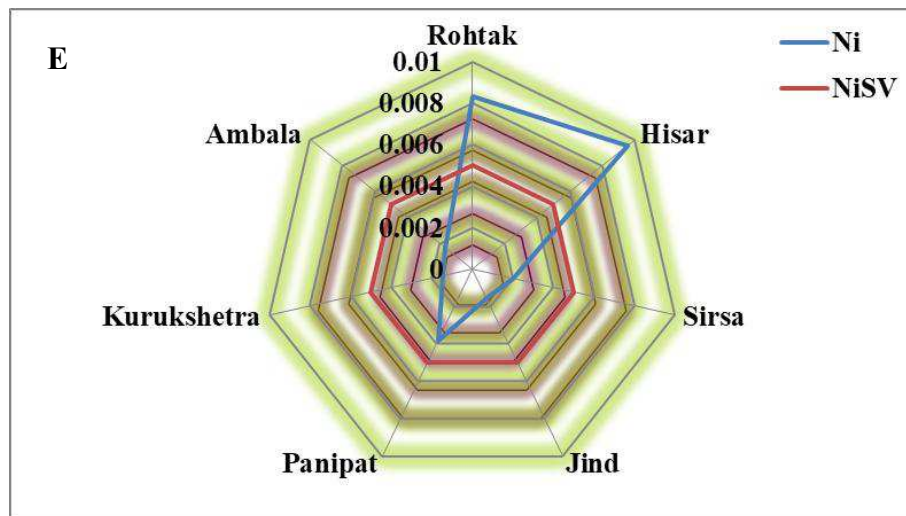
704 **Table 7.** Spatial Distribution of different heavy metals (ppm) in canal water collected from seven districts of Haryana, India

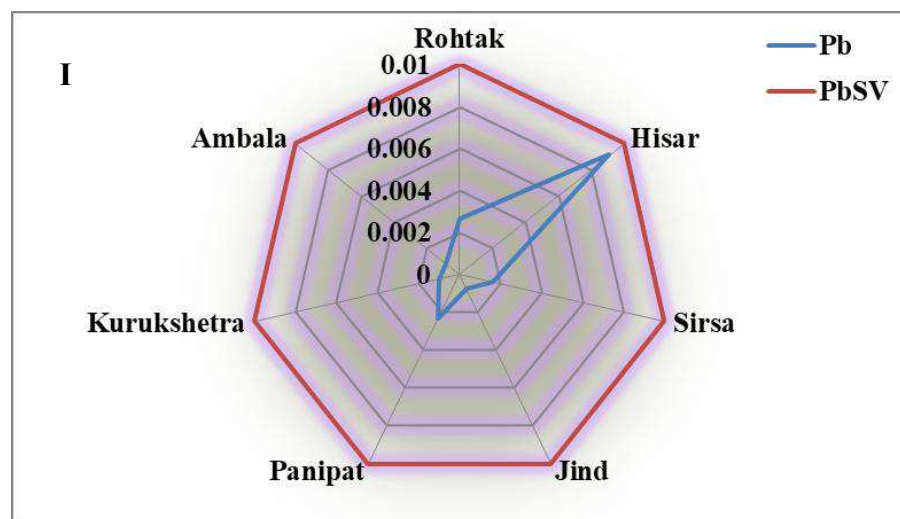
| Sl. No | Elements | Attributes | Rohtak                       | Hisar                        | Sirsa                        | Jind                         | Panipat                      | Kurukshetra                  | Ambala                       |
|--------|----------|------------|------------------------------|------------------------------|------------------------------|------------------------------|------------------------------|------------------------------|------------------------------|
| 1.     | Li       | Mean±SEM   | 0.018±0.000 <sup>bc</sup>    | 0.025±0.006 <sup>c</sup>     | 0.009±0.003 <sup>a</sup>     | 0.018±0.000 <sup>abc</sup>   | 0.014±0.000 <sup>ab</sup>    | 0.019±0.004 <sup>bc</sup>    | 0.022±0.000 <sup>bc</sup>    |
|        |          | Range      | 0.017-0.019                  | 0.017-0.054                  | 0.004-0.020                  | 0.016-0.018                  | 0.014-0.014                  | 0.000-0.023                  | 0.021-0.023                  |
|        |          | LiSV       | 0.0001 <sup>£</sup>          | 0.0001 <sup>£</sup>          | 0.0001 <sup>£</sup>          | 0.0001 <sup>£</sup>          | 0.0001 <sup>£</sup>          | 0.0001 <sup>£</sup>          | 0.0001 <sup>£</sup>          |
| 2.     | Al       | Mean±SEM   | 1.901±0.379 <sup>b</sup>     | 0.111±0.093 <sup>a</sup>     | 0.334±0.104 <sup>a</sup>     | 0.488±0.268 <sup>a</sup>     | 2.309±0.041 <sup>b</sup>     | 0.538±0.104 <sup>a</sup>     | 0.543±0.012 <sup>a</sup>     |
|        |          | Range      | 0.011-2.368                  | 0.004-0.574                  | 0.065-0.762                  | 0.070-1.777                  | 2.173-2.407                  | 0.019-0.683                  | 0.500-0.572                  |
|        |          | AlSV       | 0.2 <sup>¥</sup>             | 0.2 <sup>¥</sup>             | 0.2 <sup>¥</sup>             | 0.2 <sup>¥</sup>             | 0.2 <sup>¥</sup>             | 0.2 <sup>¥</sup>             | 0.2 <sup>¥</sup>             |
| 3.     | Cr       | Mean±SEM   | 0.016±0.004 <sup>a</sup>     | 0.008±0.008 <sup>b</sup>     | 0.002±0.000 <sup>a</sup>     | 0.002±0.000 <sup>a</sup>     | 0.005±0.000 <sup>a</sup>     | 0.002±0.000 <sup>a</sup>     | 0.002±0.000 <sup>b</sup>     |
|        |          | Range      | 0.000-0.025                  | 0.000-0.046                  | 0.002-0.003                  | 0.002-0.004                  | 0.005-0.005                  | 0.000-0.002                  | 0.002-0.002                  |
|        |          | CrSV       | 0.05 <sup>£</sup>            | 0.05 <sup>£</sup>            | 0.05 <sup>£</sup>            | 0.05 <sup>£</sup>            | 0.05 <sup>£</sup>            | 0.05 <sup>£</sup>            | 0.05 <sup>£</sup>            |
| 4.     | Co       | Mean±SEM   | 0.0008±0.0002 <sup>a</sup>   | 0.0079±0.0078 <sup>a</sup>   | 0.0002±0.0001 <sup>a</sup>   | 0.0003±0.0001 <sup>a</sup>   | 0.0011±0.0000 <sup>a</sup>   | 0.0002±0.0000 <sup>a</sup>   | 0.0003±0.0000 <sup>a</sup>   |
|        |          | Range      | 0.0000-0.0011                | 0.0000-0.0471                | 0.0001-0.0005                | 0.0001-0.0008                | 0.0011-0.0012                | 0.0000-0.0003                | 0.0003-0.0003                |
|        |          | CoSV       | 0.01 <sup>B</sup>            | 0.01 <sup>B</sup>            | 0.01 <sup>B</sup>            | 0.01 <sup>B</sup>            | 0.01 <sup>B</sup>            | 0.01 <sup>B</sup>            | 0.01 <sup>B</sup>            |
| 5.     | Ni       | Mean±SEM   | 0.008±0.002 <sup>a</sup>     | 0.010±0.009 <sup>a</sup>     | 0.002±0.000 <sup>a</sup>     | 0.002±0.000 <sup>a</sup>     | 0.004±0.000 <sup>a</sup>     | 0.001±0.000 <sup>a</sup>     | 0.002±0.000 <sup>a</sup>     |
|        |          | Range      | 0.000-0.012                  | 0.000-0.055                  | 0.001-0.002                  | 0.001-0.003                  | 0.004-0.004                  | 0.000-0.002                  | 0.002-0.002                  |
|        |          | NiSV       | 0.005 <sup>£</sup>           | 0.005 <sup>£</sup>           | 0.005 <sup>£</sup>           | 0.005 <sup>£</sup>           | 0.005 <sup>£</sup>           | 0.005 <sup>£</sup>           | 0.005 <sup>£</sup>           |
| 6.     | Cu       | Mean±SEM   | 0.003±0.001 <sup>a</sup>     | 0.008±0.008 <sup>a</sup>     | 0.028±0.023 <sup>a</sup>     | 0.002±0.000 <sup>a</sup>     | 0.004±0.000 <sup>a</sup>     | 0.001±0.000 <sup>a</sup>     | 0.004±0.003 <sup>a</sup>     |
|        |          | Range      | 0.000-0.004                  | 0.000-0.048                  | 0.002-0.141                  | 0.001-0.003                  | 0.003-0.004                  | 0.000-0.002                  | 0.001-0.020                  |
|        |          | CuSV       | 0.05 <sup>P</sup>            | 0.05 <sup>P</sup>            | 0.05 <sup>P</sup>            | 0.05 <sup>P</sup>            | 0.05 <sup>P</sup>            | 0.05 <sup>P</sup>            | 0.05 <sup>P</sup>            |
| 7.     | As       | Mean±SEM   | 0.003±0.000 <sup>a</sup>     | 0.012±0.009 <sup>a</sup>     | 0.003±0.001 <sup>a</sup>     | 0.003±0.000 <sup>a</sup>     | 0.002±0.000 <sup>a</sup>     | 0.003±0.001 <sup>a</sup>     | 0.003±0.000 <sup>a</sup>     |
|        |          | Range      | 0.003-0.004                  | 0.002-0.059                  | 0.000-0.004                  | 0.003-0.003                  | 0.002-0.002                  | 0.000-0.003                  | 0.003-0.003                  |
|        |          | AsSV       | 0.01 <sup>£</sup>            | 0.01 <sup>£</sup>            | 0.01 <sup>£</sup>            | 0.01 <sup>£</sup>            | 0.01 <sup>£</sup>            | 0.01 <sup>£</sup>            | 0.01 <sup>£</sup>            |
| 8.     | Cd       | Mean±SEM   | 6.5E-05±1.4E-05 <sup>a</sup> | 8.0E-03±8.0E-03 <sup>a</sup> | 4.8E-05±3.2E-06 <sup>a</sup> | 1.9E-05±1.6E-06 <sup>a</sup> | 4.2E-05±4.4E-06 <sup>a</sup> | 2.4E-05±4.3E-06 <sup>a</sup> | 2.0E-05±5.2E-07 <sup>a</sup> |
|        |          | Range      | 1.3E-05-1.2E-04              | 3.0E-06-4.8E-02              | 3.5E-05-5.7E-05              | 1.4E-05-2.4E-05              | 3.2E-05-6.2E-05              | 3.0E-06-3.3E-05              | 1.8E-05-2.1E-05              |
|        |          | CdSV       | 0.013 <sup>§</sup>           | 0.013 <sup>§</sup>           | 0.013 <sup>§</sup>           | 0.013 <sup>§</sup>           | 0.013 <sup>§</sup>           | 0.013 <sup>§</sup>           | 0.013 <sup>§</sup>           |
| 9.     | Pb       | Mean±SEM   | 0.003±0.001 <sup>a</sup>     | 0.009±0.009 <sup>a</sup>     | 0.002±0.001 <sup>a</sup>     | 0.001±0.000 <sup>a</sup>     | 0.002±0.000 <sup>a</sup>     | 0.001±0.000 <sup>a</sup>     | 0.001±0.000 <sup>a</sup>     |
|        |          | Range      | 0.000-0.007                  | 0.000-0.054                  | 0.001-0.005                  | 0.000-0.002                  | 0.002-0.003                  | 0.000-0.002                  | 0.001-0.001                  |
|        |          | PbSV       | 0.01 <sup>§</sup>            | 0.01 <sup>§</sup>            | 0.01 <sup>§</sup>            | 0.01 <sup>§</sup>            | 0.01 <sup>§</sup>            | 0.01 <sup>§</sup>            | 0.01 <sup>§</sup>            |

705 **Note:** Mean values are presented as Mean  $\pm$  SEM (Standard Error of the Mean). Different superscript lowercase letters (a-c) within the same row  
706 indicate statistically significant differences among districts at  $P < 0.05$  (one-way ANOVA followed by Tukey's honestly significant difference  
707 (HSD) post hoc test). Range represents the minimum and maximum concentrations (mg/L) recorded for each element. SV denotes the standard  
708 permissible value (mg/L) adopted from the respective regulatory or guideline source. Al: Aluminum; As: Arsenic; Cd: Cadmium; Co: Cobalt;  
709 Cr: Chromium; Cu: Copper; HSD: Honestly Significant Difference; Li: Lithium; Mean  $\pm$  SEM: Mean  $\pm$  Standard Error of the Mean; Ni: Nickel;  
710 Pb: Lead; Range: Minimum-Maximum concentration; SEM: Standard Error of the Mean; SV: Standard Permissible Value: £: [70] [30]; ¥: [71];  
711 €: [72]; ₰: [73]; ₧: [74]; ₣: [75]; ₤: [76,77]; §: [78,79]; \$: [77,80]

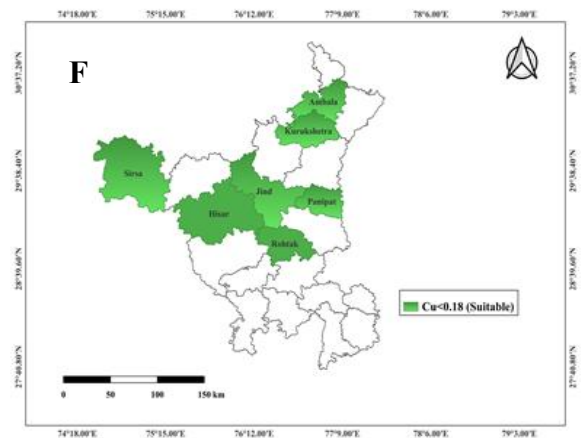
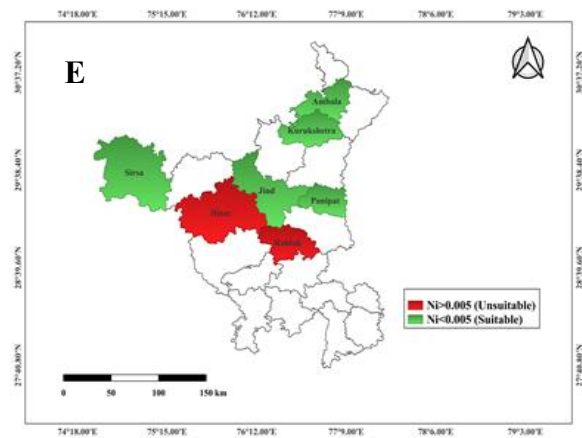
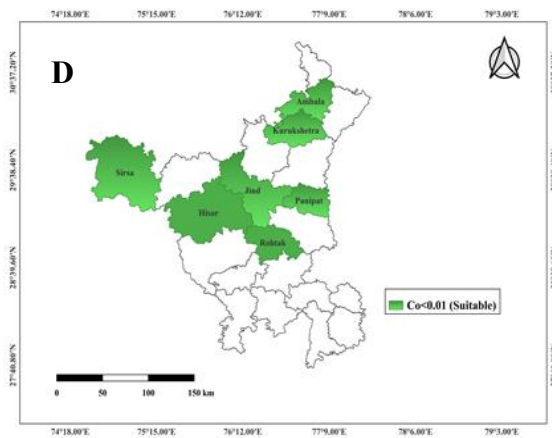
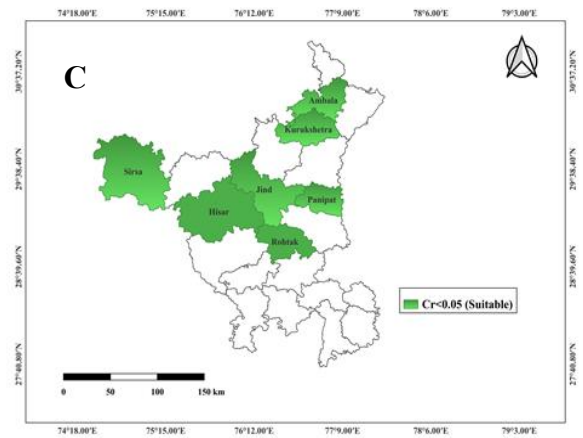
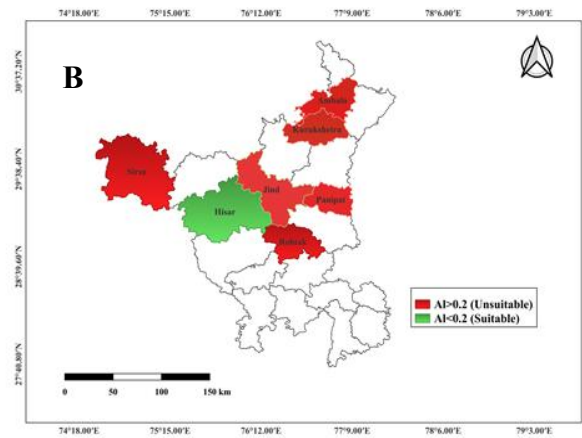
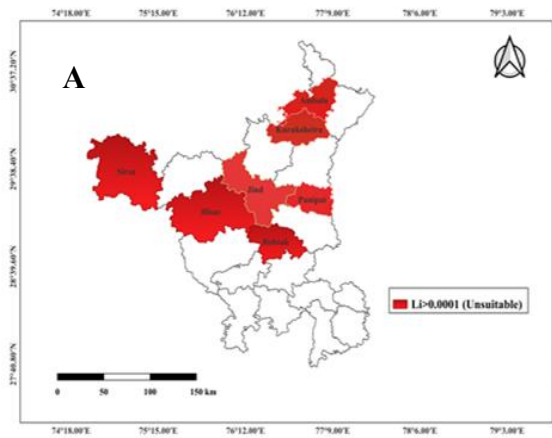
The radar plots revealed distinct spatial variations in heavy metal concentrations across the seven sampling districts, highlighting the heterogeneous distribution of trace elements in canal water (Figure 3). Lithium was present at relatively high concentrations in Hisar, followed by Rohtak and Ambala, whereas Sirsa had the lowest concentration. The elevated Li levels in these districts may reflect localized geological characteristics and enhanced mineral dissolution through water–rock interactions. Aluminium was strongly enriched in Panipat and Rohtak, suggesting the presence of localized anthropogenic inputs, particularly from industrial activities and aluminosilicate-rich suspended particulates. Chromium, cobalt, and copper concentrations remained relatively low across all the districts, indicating limited enrichment and relatively stable spatial distribution. In contrast, nickel, arsenic, cadmium, and lead showed localized maxima, predominantly in Hisar, suggesting site-specific metal mobilization that may be influenced by local hydrogeochemical conditions and diffuse anthropogenic inputs. Overall, the radar plots demonstrate that the heavy metal distribution in canal water is highly metal specific rather than uniform, reflecting the combined influence of regional geology, land use characteristics, and localized anthropogenic activities across the canal network.

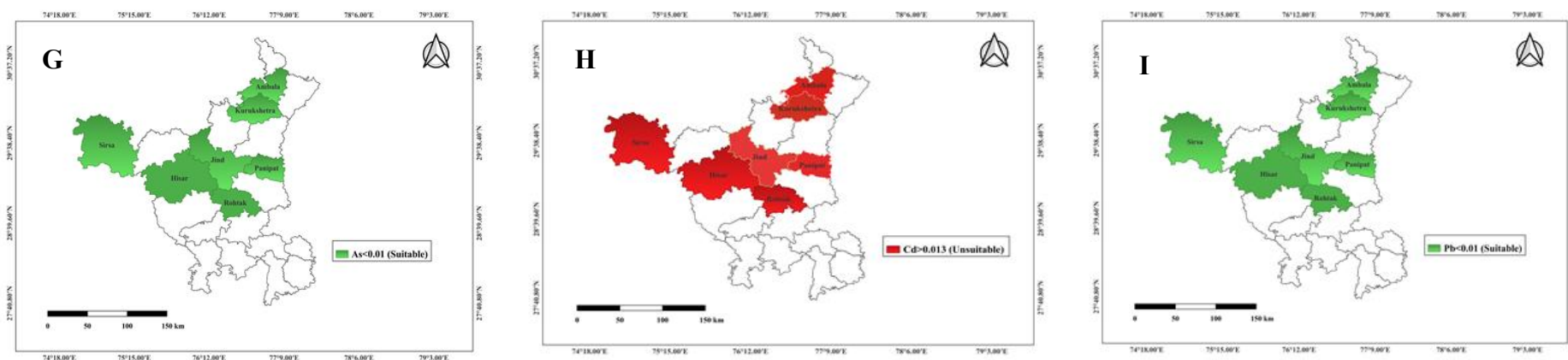






730  
 731 **Fig. 3 (A-I).** Radar diagrams illustrating the spatial distribution of heavy metal concentrations in canal water samples collected from the  
 732 industrial and non-industrial regions of Haryana, India: (A) Lithium (Li), (B) Aluminium (Al), (C) Chromium (Cr), (D) Cobalt (Co), (E) Nickel  
 733 (Ni), (F) Copper (Cu), (G) Arsenic (As), (H) Cadmium (Cd), and (I) Lead (Pb)  
 734





735 **Fig. 4 (A-I).** Spatial suitability maps of trace elements in canal water samples from the selected districts of Haryana, India, based on the  
 736 respective standard permissible values (SVs). Districts are classified as Suitable (green) or Unsuitable (red) according to the guideline limits for  
 737 (A) Lithium (Li), (B) Aluminium (Al), (C) Chromium (Cr), (D) Cobalt (Co), (E) Nickel (Ni), (F) Copper (Cu), (G) Arsenic (As), (H) Cadmium  
 738 (Cd), and (I) Lead (Pb)

The spatial distribution maps demonstrated distinct variations in the suitability status of trace elements across the selected districts of Haryana on the basis of their respective standard permissible values (Figure 4). Among the investigated trace elements, Li was classified as unsuitable in all seven districts, indicating that its concentration exceeded the recommended permissible limit throughout the study area. A similar trend was observed for Cd, which also resulted in unsuitable water quality across all investigated districts, suggesting widespread cadmium contamination relative to the prescribed guideline value. In contrast, Cr, Co, Cu, As, and Pb were uniformly distributed across all the districts, indicating that their concentrations remained below the corresponding standard permissible limits. No district exceeded the guideline values for these elements, suggesting minimal spatial variation in their suitability status. The spatial distribution of Al revealed both suitable and unsuitable zones. Rohtak, Jind, Panipat, Kurukshetra, and Ambala were classified as unsuitable, whereas Hisar and Sirsa remained within the permissible limit and were therefore categorized as suitable. This pattern indicates localized aluminium enrichment, particularly in the eastern and central parts of the study area. Similarly, Ni displayed a heterogeneous spatial pattern. Hisar, Rohtak, and Jind were classified as unsuitable, whereas Sirsa, Kurukshetra, Ambala, and Panipat remained suitable. This localized exceedance suggests that nickel contamination was confined to specific districts rather than distributed uniformly across the study region. Overall, the suitability maps indicate that Li and Cd are the most widespread trace elements in canal water, whereas Al and Ni show localized exceedances in selected districts. Conversely, Cr, Co, Cu, As, and Pb remained within the prescribed permissible limits throughout the study area, reflecting better water quality for these trace elements.

Comparative concentrations of heavy metals in canal water collected from the industrial and nonindustrial regions of Haryana. Overall, the concentrations of most of the analysed heavy metals were higher in the industrial region than in the nonindustrial region. The lithium concentration was higher in the industrial region ( $0.020 \pm 0.002$  ppm) than in the nonindustrial region ( $0.015 \pm 0.002$  ppm), although the difference was not statistically significant. In contrast, the concentration of aluminium was significantly greater in the industrial region ( $1.216 \pm 0.211$  ppm) than in the nonindustrial region ( $0.453 \pm 0.098$  ppm;  $p < 0.05$ ). Similarly, the concentrations of chromium ( $0.008 \pm 0.002$  vs  $0.002 \pm 0.000$  ppm) and nickel ( $0.006 \pm 0.002$  vs  $0.002 \pm 0.000$  ppm) significantly increased in the industrial region ( $p < 0.05$ ).

Among the remaining metals, cobalt, arsenic, cadmium, and lead also exhibited relatively higher mean concentrations in the industrial region than in the nonindustrial region. The concentrations of Co were  $0.003 \pm 0.002$  and  $0.0002 \pm 0.0000$  ppm, those of As were  $0.005 \pm 0.002$  and  $0.003 \pm 0.000$  ppm, those of Cd were  $0.002 \pm 0.002$  and  $0.00003 \pm 0.00000$  ppm, and those of Pb were  $0.004 \pm 0.002$  and  $0.001 \pm 0.000$  ppm in the industrial and nonindustrial regions, respectively. In contrast, copper was the only metal with a higher concentration in the nonindustrial region ( $0.010 \pm 0.008$  ppm) than in the industrial region ( $0.005 \pm 0.002$  ppm). Overall, the results indicate a greater heavy metal burden in the industrial region, with significant regional differences observed for Al, Cr, and Ni, as presented in Table 8 and Fig. 5

**Table 8.** Comparative results of different Heavy metals in the canal water of industrial and nonindustrial regions of Haryana

| Sl. No. | Heavy metals | Industrial Region<br>(Mean $\pm$ SEM) | Non-Industrial Region<br>(Mean $\pm$ SEM) |
|---------|--------------|---------------------------------------|-------------------------------------------|
| 1.      | Li           | 0.020 $\pm$ 0.002                     | 0.015 $\pm$ 0.002                         |
| 2.      | Al           | 1.216 $\pm$ 0.211                     | 0.453 $\pm$ 0.098*                        |
| 3.      | Cr           | 0.008 $\pm$ 0.002                     | 0.002 $\pm$ 0.000*                        |
| 4.      | Co           | 0.003 $\pm$ 0.002                     | 0.0002 $\pm$ 0.0000                       |
| 5.      | Ni           | 0.006 $\pm$ 0.002                     | 0.002 $\pm$ 0.000*                        |
| 6.      | Cu           | 0.005 $\pm$ 0.002                     | 0.010 $\pm$ 0.008                         |
| 7.      | As           | 0.005 $\pm$ 0.002                     | 0.003 $\pm$ 0.000                         |
| 8.      | Cd           | 0.002 $\pm$ 0.002                     | 0.00003 $\pm$ 0.00000                     |
| 9.      | Pb           | 0.004 $\pm$ 0.002                     | 0.001 $\pm$ 0.000                         |

**Note:** Values are presented as Mean  $\pm$  SEM (Standard Error of the Mean). Industrial values represent the mean concentrations of trace elements in canal water samples collected from the industrial districts (Rohtak, Hisar, Panipat, and Ambala), whereas non-industrial values represent the corresponding mean concentrations from the non-industrial districts (Sirsa, Jind, and Kurukshetra). An asterisk (\*) indicates a statistically significant difference between industrial and non-industrial regions at  $P < 0.05$ . Al: Aluminium, As: Arsenic, Cd: Cadmium, Co: Cobalt, Cr: Chromium, Cu: Copper, Li: Lithium, Mean  $\pm$  SEM: Mean  $\pm$  Standard Error of the Mean, Ni: Nickel, Pb: Lead, SEM: Standard Error of the Mean

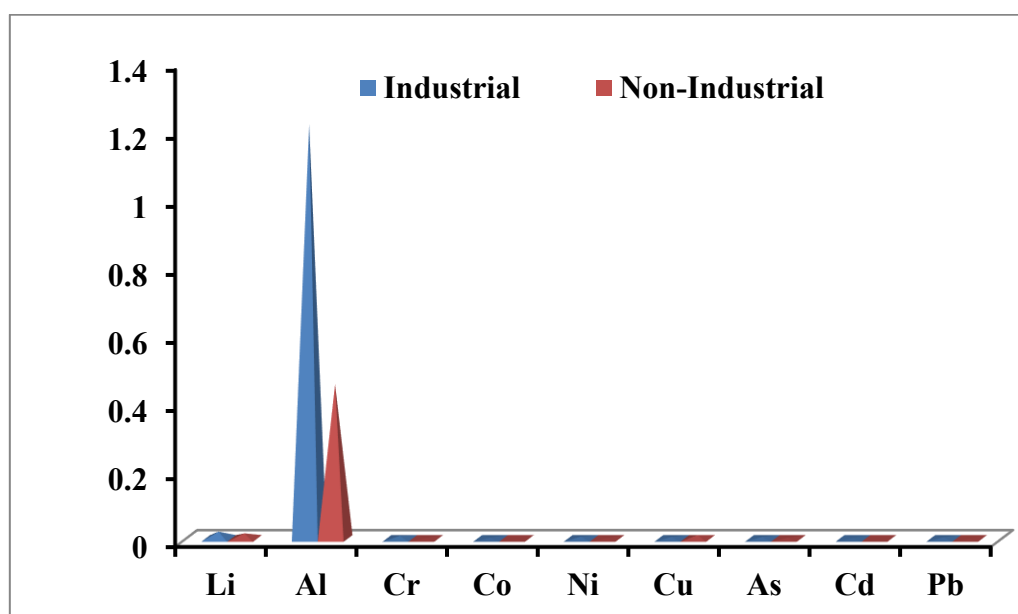


**Fig. 5.** Comparative concentrations of selected elements in canal water samples from industrial and non-industrial regions of Haryana, India. The figure illustrates the distribution of elemental concentrations across the investigated regions. Al,

Aluminium; As, Arsenic; Cd, Cadmium; Co, Cobalt; Cr, Chromium; Cu, Copper; Li, Lithium; Ni, Nickel; Pb, Lead

#### ***4.2 Uncovering the possible sources of heavy metals in canal water of Haryana***

The varimax-rotated factor loading matrix extracted three principal factors (VF1–VF3) with eigenvalues greater than 1, collectively explaining 94.30% of the total variance in heavy metal concentrations (Table 9; concentrations expressed in ppm). VF1 explained 67.07% of the total variance and exhibited strong positive loadings for As (0.979), Co (0.975), Cd (0.974), Pb (0.967), Ni (0.958), Li (0.811), and Cr (0.800). VF2 accounted for 14.37% of the total variance and was characterized by a strong positive loading for Al (0.976) and a moderate loading for Cr (0.506). VF3 explained 12.86% of the total variance and had a strong positive loading for Cu (0.963). Together, the three extracted factors accounted for 94.30% of the cumulative variance in heavy metal concentrations, as shown in Table 9

**Table 9.** Varimax-rotated R-mode factor loading matrix of heavy metals in canal water collected from different districts of Haryana, India

| Parameters                 | Component    |              |              |
|----------------------------|--------------|--------------|--------------|
|                            | VF1          | VF2          | VF3          |
| <b>Li</b>                  | <b>0.811</b> | -0.125       | -0.282       |
| <b>Al</b>                  | -0.065       | <b>0.976</b> | -0.031       |
| <b>Cr</b>                  | <b>0.800</b> | 0.506        | 0.085        |
| <b>Co</b>                  | <b>0.975</b> | -0.032       | 0.167        |
| <b>Ni</b>                  | <b>0.958</b> | 0.224        | 0.150        |
| <b>Cu</b>                  | 0.151        | -0.022       | <b>0.963</b> |
| <b>As</b>                  | <b>0.979</b> | -0.097       | 0.115        |
| <b>Cd</b>                  | <b>0.974</b> | -0.085       | 0.165        |
| <b>Pb</b>                  | <b>0.967</b> | 0.031        | 0.226        |
| <b>Eigenvalues</b>         | <b>6.04</b>  | <b>1.29</b>  | <b>1.16</b>  |
| <b>Total % of variance</b> | <b>67.07</b> | <b>14.37</b> | <b>12.86</b> |
| <b>Cumulative %</b>        | <b>67.07</b> | <b>81.44</b> | <b>94.30</b> |

**Note:** Heavy metal concentrations are expressed in ppm. Principal Component Analysis (PCA) was performed using the varimax rotation method. Only components

with eigenvalues  $> 1$  were retained. Factor loadings represent the correlation between individual trace elements and the extracted varifactors (VFs) and are dimensionless. Eigenvalues indicate the amount of variance explained by each component, whereas Total % of variance and Cumulative % represent the individual and cumulative proportions of the total variance explained by the extracted components, respectively. Al: Aluminum, As: Arsenic, Cd: Cadmium, Co: Cobalt, Cr: Chromium, Cu: Copper, Li: Lithium, Ni: Nickel, Pb: Lead, PCA: Principal Component Analysis, VF: Varifactor

### ***4.3 Possible health risk assessment due to Canal water consumption in the Haryana Semi-Arid region***

On the basis of these findings, a health risk assessment was conducted to evaluate the potential health risks associated with heavy metal contamination in canal water sources in Haryana. This section presents the estimated health risk indices, including noncarcinogenic and carcinogenic risks associated with exposure to different heavy metals through ingestion and dermal contact pathways, considering the relevant toxicological reference values.

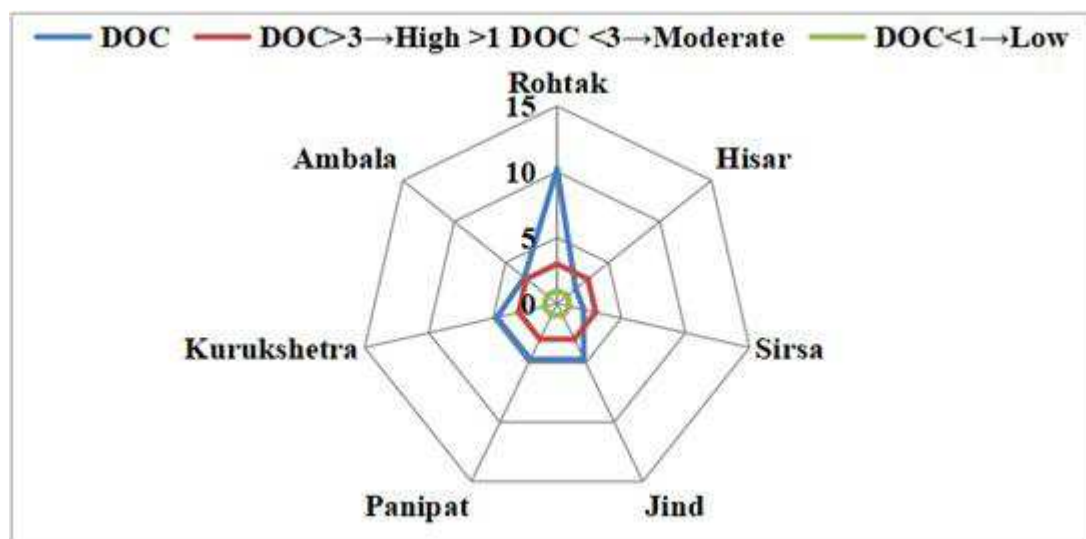
#### ***4.3.1 Degree of contamination (DOC)***

The DOC-based classification revealed marked spatial variability in canal water quality across the seven districts of Haryana. Rohtak had the highest DOC value (10.2317), followed by Jind, Panipat, Kurukshetra (4.70198 each), and Ambala (3.19041), all of which fell within the high category ( $\text{DOC} > 3$ ). In contrast, Hisar (1.80749) and Sirsa (2.06677) were classified as moderate ( $1 < \text{DOC} < 3$ ). Overall, the DOC index indicated predominantly high DOC levels across the study area, with moderate conditions observed in Hisar and Sirsa, as presented in Table 10 and Fig 6.

**Table 10.** Degree of contamination (DOC) values and contamination classification of canal water across the selected districts of Haryana

| Pollution Category    | Rohtak  | Hisar   | Sirsa   | Jind    | Panipat | Kurukshetra | Ambala  |
|-----------------------|---------|---------|---------|---------|---------|-------------|---------|
| <b>DOC</b>            | 10.2317 | 1.80749 | 2.06677 | 4.70198 | 4.70198 | 4.70198     | 3.19041 |
| <b>DOC&gt;3→High</b>  |         |         |         |         |         |             |         |
| <b>&gt;1 DOC</b>      |         |         |         |         |         |             |         |
| <b>&lt;3→Moderate</b> | 3.00    | 3.00    | 3.00    | 3.00    | 3.00    | 3.00        | 3.00    |
| <b>DOC&lt;1→Low</b>   | 1.00    | 1.00    | 1.00    | 1.00    | 1.00    | 1.00        | 1.00    |

848 **Notes:** The table presents the degree of contamination (DOC) values for canal water  
849 samples collected from the selected districts of Haryana. Contamination levels were  
850 classified as low (DOC < 1), moderate (1 ≤ DOC < 3), and high (DOC ≥ 3)  
851



852  
853 **Fig. 6.** Radar diagram showing the degree of contamination (DOC) values and  
854 contamination classification of canal water across the selected districts of Haryana.  
855 The concentric reference lines indicate the threshold values for low (DOC < 1),  
856 moderate (1 ≤ DOC < 3), and high (DOC ≥ 3) contamination levels

#### 857 **4.3.2 Pollution load index (PLI)**

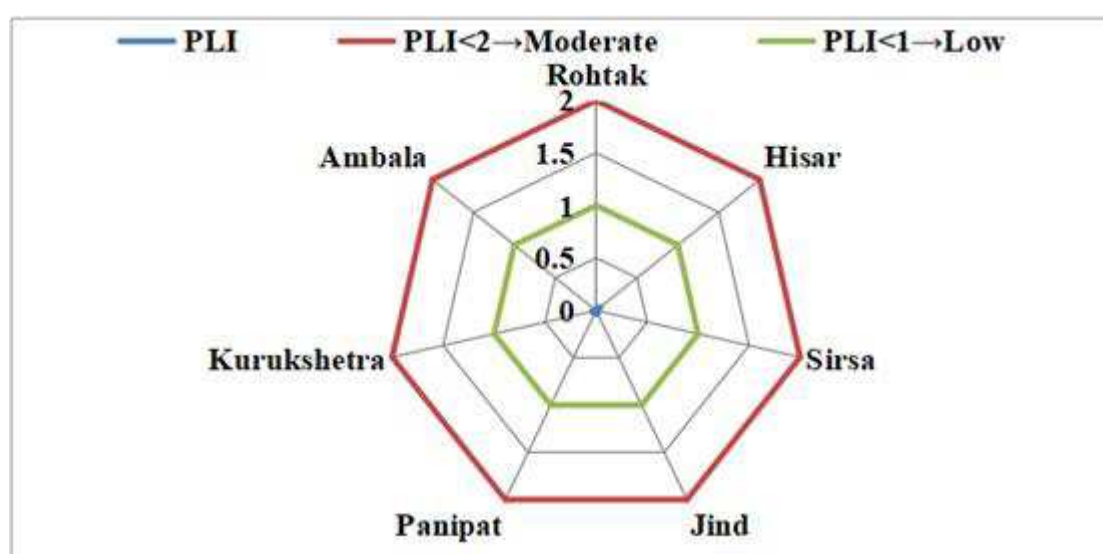
858 The pollution load index (PLI) values and corresponding classification of canal water  
859 across the seven districts of Haryana are presented in Table 11 and Fig. 7. PLI values  
860 ranged from 0.00355 in Ambala to 0.04616 in Hisar, with intermediate values  
861 recorded for Sirsa (0.00491), Rohtak (0.01303), and Jind, Panipat, and Kurukshetra  
862 (0.03489 each). All observed PLI values were less than 1, corresponding to the low-  
863 pollution category (PLI < 1). Overall, the PLI assessment indicated a consistently low  
864 pollution load in canal water across all investigated districts, although Hisar exhibited  
865 the comparatively highest PLI value.

866 **Table 11.** Pollution Load Index (PLI) values and pollution classification of canal  
867 water samples from the selected districts of Haryana, India

| Pollution Category | Rohtak  | Hisar   | Sirsa   | Jind    | Panipat | Kurukshetra | Ambala  |
|--------------------|---------|---------|---------|---------|---------|-------------|---------|
| PLI                | 0.01303 | 0.04616 | 0.00491 | 0.03489 | 0.03489 | 0.03489     | 0.00355 |
| PLI<2→Moderate     | 2.00    | 2.00    | 2.00    | 2.00    | 2.00    | 2.00        | 2.00    |
| PLI<1→Low          | 1.00    | 1.00    | 1.00    | 1.00    | 1.00    | 1.00        | 1.00    |

868 **Notes:** The table presents the pollution load index (PLI) values for canal water  
869 samples collected from the selected districts of Haryana. Pollution levels were  
870 classified as low ( $PLI < 1$ ), moderate ( $1 \leq PLI < 2$ ), heavy ( $2 \leq PLI < 3$ ), and  
871 extremely high ( $PLI \geq 3$ )

872



873

874 **Fig. 7.** Radar diagram showing the pollution load index (PLI) values and the  
875 corresponding pollution classification of canal water across the selected districts of  
876 Haryana. The concentric reference lines indicate the threshold values for low ( $PLI <$   
877 1) and moderate ( $1 \leq PLI < 2$ ) pollution levels

**4.3.3 District-wise statistical assessment of heavy metal exposure through ingestion and dermal contact with canal water among adults and children in Haryana**

Districtwise statistical assessment revealed considerable variation in heavy metal exposure through ingestion and dermal contact with canal water among adults. As presented in Table 12, ingestion-related exposure to Li was highest in Hisar ( $7.07\text{E-}04$ ), whereas the lowest value was observed in Sirsa ( $2.66\text{E-}04$ ). Al exposure was relatively high in Panipat ( $6.60\text{E-}02$ ) and Rohtak ( $5.43\text{E-}02$ ), whereas Cr exposure was greatest in Rohtak ( $4.66\text{E-}04$ ). Co, Ni, As, Cd, and Pb generally presented relatively high ingestion-related exposure in Hisar, with values of  $2.26\text{E-}04$ ,  $2.72\text{E-}04$ ,  $3.45\text{E-}04$ ,  $2.29\text{E-}04$ , and  $2.61\text{E-}04$ , respectively. With respect to Cu, Sirsa had the greatest ingestion-related exposure ( $7.99\text{E-}04$ ). Dermal exposure estimates were generally lower than the corresponding ingestion estimates for most metals, although Li showed relatively higher dermal exposure across the investigated districts. The superscript groupings indicate significant interdistrict differences for selected exposure estimates, whereas one-way ANOVA revealed no significant variation among districts for several metals.

A comparable assessment among children revealed distinct spatial patterns in terms of heavy metal exposure, as presented in Table 13. Ingestion-related exposure to Li was highest in Hisar ( $3.69\text{E-}06$ ) and lowest in Sirsa ( $1.39\text{E-}06$ ), whereas Al exposure was highest in Panipat ( $1.54\text{E-}01$ ), followed by Rohtak ( $1.27\text{E-}01$ ). Cr exposure was highest in Rohtak ( $1.09\text{E-}03$ ), whereas Cu was associated with the greatest ingestion-related exposure in Sirsa ( $1.86\text{E-}03$ ). Compared with most other districts, the ingestion-related exposure to Co ( $5.27\text{E-}04$ ), Ni ( $6.36\text{E-}04$ ), As ( $8.05\text{E-}04$ ), Cd ( $5.35\text{E-}04$ ), and Pb ( $6.08\text{E-}04$ ) was relatively high in hisar. Dermal exposure estimates were generally lower than ingestion-related estimates for the investigated

903 metals. One-way ANOVA further indicated significant interdistrict differences for  
904 selected exposure estimates, particularly for Li, Al, and Cr, whereas the remaining  
905 metals largely exhibited statistically comparable values among districts. Overall, the  
906 findings demonstrate age- and metal-specific spatial variability in exposure estimates,  
907 with Hisar, Rohtak, Panipat, and Sirsa showing comparatively elevated exposure to  
908 different metals and pathways.

909 **Table 12.** District-wise variation in mean adult exposure estimates of heavy metals through ingestion and dermal contact with canal water,  
910 assessed using one-way analysis of variance

| Sl. No | Adult | Mean                | Rohtak                          | Hisar                           | Sirsa                           | Jind                            | Panipat                         | Kurukshetra                     | Ambala                          |
|--------|-------|---------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
| 1.     | Li    | Exp <sub>ing</sub>  | 5.27E-04±8.45E-06 <sup>ab</sup> | 7.07E-04±2.56E-05 <sup>b</sup>  | 2.66E-04±8.79E-05 <sup>a</sup>  | 5.04E-04±8.84E-06 <sup>ab</sup> | 4.02E-04±4.21E-06 <sup>ab</sup> | 5.42E-04±1.08E-04 <sup>ab</sup> | 6.22E-04±8.72E-06 <sup>ab</sup> |
|        |       | Exp <sub>derm</sub> | 5.27E-04±8.45E-06 <sup>ab</sup> | 7.07E-04±1.70E-04 <sup>b</sup>  | 2.66E-04±8.79E-05 <sup>a</sup>  | 5.04E-04±8.84E-06 <sup>ab</sup> | 4.02E-04±4.21E-06 <sup>ab</sup> | 5.42E-04±1.08E-04 <sup>ab</sup> | 6.22E-04±8.72E-06 <sup>ab</sup> |
| 2.     | Al    | Exp <sub>ing</sub>  | 5.43E-02±1.08E-02 <sup>b</sup>  | 3.17E-03±2.66E-03 <sup>a</sup>  | 9.53E-03±2.98E-03 <sup>a</sup>  | 1.39E-02±7.66E-03 <sup>a</sup>  | 6.60E-02±1.17E-03 <sup>b</sup>  | 1.54E-02±2.98E-03 <sup>a</sup>  | 1.55E-02±3.32E-04 <sup>a</sup>  |
|        |       | Exp <sub>derm</sub> | 2.84E-04±5.64E-05 <sup>b</sup>  | 1.65E-05±1.39E-05 <sup>a</sup>  | 4.97E-05±1.55E-05 <sup>a</sup>  | 7.27E-05±4.00E-05 <sup>a</sup>  | 3.44E-04±6.13E-06 <sup>b</sup>  | 8.02E-05±1.55E-05 <sup>a</sup>  | 8.10E-05±1.73E-06 <sup>a</sup>  |
| 3.     | Cr    | Exp <sub>ing</sub>  | 4.66E-04±1.14E-04 <sup>b</sup>  | 2.34E-04±2.18E-04 <sup>ab</sup> | 5.60E-05±4.37E-06 <sup>ab</sup> | 6.37E-05±1.09E-05 <sup>ab</sup> | 1.45E-04±1.70E-06 <sup>ab</sup> | 4.76E-05±8.99E-06 <sup>a</sup>  | 5.96E-05±2.11E-06 <sup>ab</sup> |
|        |       | Exp <sub>derm</sub> | 4.83E-06±1.14E-06 <sup>b</sup>  | 2.44E-06±2.28E-06 <sup>ab</sup> | 5.85E-07±4.56E-08 <sup>ab</sup> | 6.65E-07±1.14E-07 <sup>ab</sup> | 1.52E-06±1.77E-08 <sup>ab</sup> | 4.97E-07±9.39E-08 <sup>a</sup>  | 6.22E-07±2.21E-08 <sup>ab</sup> |
| 4.     | Co    | Exp <sub>ing</sub>  | 2.42E-05±4.87E-06 <sup>a</sup>  | 2.26E-04±2.24E-04 <sup>a</sup>  | 6.14E-06±1.74E-06 <sup>a</sup>  | 7.37E-06±3.30E-06 <sup>a</sup>  | 3.28E-05±1.49E-07 <sup>a</sup>  | 6.79E-06±1.34E-06 <sup>a</sup>  | 7.75E-06±9.29E-08 <sup>a</sup>  |
|        |       | Exp <sub>derm</sub> | 0.00E+00±0.00E+00 <sup>a</sup>  | 1.18E-06±1.17E-06 <sup>a</sup>  | 3.21E-08±9.06E-09 <sup>a</sup>  | 3.85E-08±1.72E-08 <sup>a</sup>  | 1.71E-07±7.79E-10 <sup>a</sup>  | 3.54E-08±6.99E-09 <sup>a</sup>  | 4.04E-08±4.85E-10 <sup>a</sup>  |
| 5.     | Ni    | Exp <sub>ing</sub>  | 2.37E-04±5.23E-05 <sup>a</sup>  | 2.72E-04±2.58E-04 <sup>a</sup>  | 5.75E-05±5.31E-06 <sup>a</sup>  | 4.53E-05±9.22E-06 <sup>a</sup>  | 1.09E-04±7.82E-07 <sup>a</sup>  | 4.22E-0±8.26E-06 <sup>a</sup>   | 4.73E-05±8.63E-07 <sup>a</sup>  |
|        |       | Exp <sub>derm</sub> | 1.33E-06±3.33E-07 <sup>a</sup>  | 1.42E-06±1.35E-06 <sup>a</sup>  | 3.00E-07±2.77E-08 <sup>a</sup>  | 2.36E-07±4.81E-08 <sup>a</sup>  | 5.71E-07±4.08E-09 <sup>a</sup>  | 2.20E-07±4.31E-08 <sup>a</sup>  | 2.47E-07±4.51E-09 <sup>a</sup>  |
| 6.     | Cu    | Exp <sub>ing</sub>  | 8.05E-05±1.61E-05 <sup>a</sup>  | 2.37E-04±2.26E-04 <sup>a</sup>  | 7.99E-04±6.46E-04 <sup>a</sup>  | 5.18E-05±6.27E-06 <sup>a</sup>  | 1.02E-04±2.65E-06 <sup>a</sup>  | 3.28E-05±6.56E-06 <sup>a</sup>  | 1.26E-04±8.71E-05 <sup>a</sup>  |
|        |       | Exp <sub>derm</sub> | 5.00E-07±2.24E-07 <sup>a</sup>  | 1.24E-06±1.18E-06 <sup>a</sup>  | 4.17E-06±3.37E-06 <sup>a</sup>  | 2.70E-07±3.27E-08 <sup>a</sup>  | 5.33E-07±1.38E-08 <sup>a</sup>  | 1.71E-07±3.42E-08 <sup>a</sup>  | 6.60E-07±4.55E-07 <sup>a</sup>  |
| 7.     | As    | Exp <sub>ing</sub>  | 9.18E-05±5.11E-06 <sup>a</sup>  | 3.45E-04±2.66E-04 <sup>a</sup>  | 8.93E-05±1.92E-05 <sup>a</sup>  | 7.73E-05±1.54E-06 <sup>a</sup>  | 6.67E-05±1.15E-06 <sup>a</sup>  | 7.58E-05±1.49E-05 <sup>a</sup>  | 9.26E-05±1.58E-06 <sup>a</sup>  |
|        |       | Exp <sub>derm</sub> | 1.67E-07±1.67E-07 <sup>a</sup>  | 1.80E-06±1.39E-06 <sup>a</sup>  | 4.66E-07±1.00E-07 <sup>a</sup>  | 4.03E-07±8.03E-09 <sup>a</sup>  | 3.48E-07±6.00E-09 <sup>a</sup>  | 3.95E-07±7.80E-08 <sup>a</sup>  | 4.83E-07±8.25E-09 <sup>a</sup>  |
| 8.     | Cd    | Exp <sub>ing</sub>  | 1.67E-06±4.22E-07 <sup>a</sup>  | 2.29E-04±2.29E-04 <sup>a</sup>  | 1.37E-06±9.14E-08 <sup>a</sup>  | 5.33E-07±4.59E-08 <sup>a</sup>  | 1.20E-06±1.25E-07 <sup>a</sup>  | 6.71E-07±1.22E-07 <sup>a</sup>  | 5.71E-07±1.48E-08 <sup>a</sup>  |
|        |       | Exp <sub>derm</sub> | 0.00E+00±0.00E+00 <sup>a</sup>  | 1.20E-06±1.19E-06 <sup>a</sup>  | 7.13E-09±4.77E-10 <sup>a</sup>  | 2.78E-09±2.39E-10 <sup>a</sup>  | 6.26E-09±6.50E-10 <sup>a</sup>  | 3.50E-09±6.36E-10 <sup>a</sup>  | 2.98E-09±7.70E-11 <sup>a</sup>  |
| 9.     | Pb    | Exp <sub>ing</sub>  | 7.65E-05±2.56E-05 <sup>a</sup>  | 2.61E-04±2.56E-04 <sup>a</sup>  | 4.67E-05±1.79E-05 <sup>a</sup>  | 2.14E-05±4.83E-06 <sup>a</sup>  | 6.74E-05±1.69E-06 <sup>a</sup>  | 2.80E-05±6.88E-06 <sup>a</sup>  | 2.30E-05±7.25E-07 <sup>a</sup>  |
|        |       | Exp <sub>derm</sub> | 0.00E+00±0.00E+00 <sup>a</sup>  | 5.44E-07±2.66E-03 <sup>a</sup>  | 9.74E-08±3.74E-08 <sup>a</sup>  | 4.47E-08±1.01E-08 <sup>a</sup>  | 1.41E-07±3.54E-09 <sup>a</sup>  | 5.84E-08±1.44E-08 <sup>a</sup>  | 4.81E-08±1.51E-09 <sup>a</sup>  |

911 **Note:** Values are presented as mean ± SEM. Exposure estimates were determined for adults through the ingestion and dermal contact pathways  
912 of canal water. Exp<sub>ing</sub> represents exposure through ingestion, whereas Exp<sub>derm</sub> represents exposure through dermal contact. Superscript lowercase  
913 letters indicate statistical grouping among the respective district-wise values. Al: Aluminium, As: Arsenic, Cd: Cadmium, Co: Cobalt, Cr:  
914 Chromium, Cu: Copper, Exp<sub>derm</sub>: Exposure through dermal contact, Exp<sub>ing</sub>: Exposure through ingestion, Li: Lithium, Ni: Nickel, Pb: Lead, SEM:  
915 Standard error of the mean

**Table 13.** Statistical comparison of mean exposure estimates of heavy metals among children through ingestion and dermal contact with canal water across selected districts of Haryana, India, using one-way analysis of variance

| Sl. No | Child | Mean                | Rohtak                          | Hisar                           | Sirsa                           | Jind                            | Panipat                         | Kurukshetra                     | Ambala                          |
|--------|-------|---------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
| 1.     | Li    | Exp <sub>ing</sub>  | 3.00E-06±0.00E+00 <sup>ab</sup> | 3.69E-06±8.86E-07 <sup>b</sup>  | 1.39E-06±6.20E-03 <sup>a</sup>  | 2.63E-06±4.61E-08 <sup>ab</sup> | 2.10E-06±2.20E-08 <sup>ab</sup> | 2.83E-06±5.62E-07 <sup>ab</sup> | 3.25E-06±4.55E-08 <sup>ab</sup> |
|        |       | Exp <sub>derm</sub> | 1.23E-03±1.97E-05 <sup>ab</sup> | 1.65E-03±3.96E-04 <sup>b</sup>  | 6.20E-04±2.05E-04 <sup>a</sup>  | 1.18E-03±2.06E-05 <sup>ab</sup> | 9.38E-04±9.83E-06 <sup>ab</sup> | 1.26E-03±2.51E-04 <sup>ab</sup> | 1.45E-03±2.04E-05 <sup>ab</sup> |
| 2.     | Al    | Exp <sub>ing</sub>  | 1.27E-01±2.52E-02 <sup>b</sup>  | 7.39E-03±6.20E-03 <sup>a</sup>  | 2.22E-02±6.95E-03 <sup>a</sup>  | 3.25E-02±1.79E-02 <sup>a</sup>  | 1.54E-01±2.74E-03 <sup>b</sup>  | 3.58E-02±6.94E-03 <sup>a</sup>  | 3.62E-02±7.74E-04 <sup>a</sup>  |
|        |       | Exp <sub>derm</sub> | 8.37E-04±1.67E-04 <sup>b</sup>  | 4.88E-05±4.09E-05 <sup>a</sup>  | 1.47E-04±4.58E-05 <sup>a</sup>  | 2.15E-04±1.18E-04 <sup>a</sup>  | 1.02E-03±1.81E-05 <sup>b</sup>  | 2.37E-04±4.58E-05 <sup>a</sup>  | 2.39E-04±5.11E-06 <sup>a</sup>  |
| 3.     | Cr    | Exp <sub>ing</sub>  | 1.09E-03±2.67E-04 <sup>b</sup>  | 5.46E-04±5.10E-04 <sup>ab</sup> | 1.31E-04±1.02E-05 <sup>ab</sup> | 1.49E-04±2.54E-05 <sup>ab</sup> | 3.39E-04±3.96E-06 <sup>ab</sup> | 1.11E-04±2.10E-05 <sup>a</sup>  | 1.39E-04±4.93E-06 <sup>ab</sup> |
|        |       | Exp <sub>derm</sub> | 1.43E-05±3.54E-06 <sup>b</sup>  | 7.21E-06±6.73E-06 <sup>ab</sup> | 1.73E-06±1.34E-07 <sup>ab</sup> | 1.96E-06±3.36E-07 <sup>ab</sup> | 4.48E-06±5.23E-08 <sup>ab</sup> | 1.47E-06±2.77E-07 <sup>a</sup>  | 1.83E-06±6.51E-08 <sup>ab</sup> |
| 4.     | Co    | Exp <sub>ing</sub>  | 5.65E-05±1.12E-05 <sup>a</sup>  | 5.27E-04±5.22E-04 <sup>a</sup>  | 1.43E-05±4.05E-06 <sup>a</sup>  | 1.72E-05±7.71E-06 <sup>a</sup>  | 7.66E-05±3.48E-07 <sup>a</sup>  | 1.58E-05±3.12E-06 <sup>a</sup>  | 1.81E-05±2.17E-07 <sup>a</sup>  |
|        |       | Exp <sub>derm</sub> | 0.00E+00±0.00E+00 <sup>a</sup>  | 3.48E-06±3.45E-06 <sup>a</sup>  | 9.46E-08±2.67E-08 <sup>a</sup>  | 1.13E-07±5.09E-08 <sup>a</sup>  | 5.06E-07±2.30E-09 <sup>a</sup>  | 1.05E-07±2.06E-08 <sup>a</sup>  | 1.19E-07±1.43E-09 <sup>a</sup>  |
| 5.     | Ni    | Exp <sub>ing</sub>  | 5.53E-04±1.22E-04 <sup>a</sup>  | 6.36E-04±6.02E-04 <sup>a</sup>  | 1.34E-04±1.24E-05 <sup>a</sup>  | 1.06E-04±2.15E-05 <sup>a</sup>  | 2.55E-04±1.82E-06 <sup>a</sup>  | 9.84E-05±1.93E-05 <sup>a</sup>  | 1.10E-04±2.01E-06 <sup>a</sup>  |
|        |       | Exp <sub>derm</sub> | 3.50E-06±3.75E-05 <sup>a</sup>  | 4.20E-06±3.97E-06 <sup>a</sup>  | 8.85E-07±8.17E-08 <sup>a</sup>  | 6.98E-07±1.42E-07 <sup>a</sup>  | 1.69E-06±1.20E-08 <sup>a</sup>  | 6.50E-07±1.27E-07 <sup>a</sup>  | 7.28E-07±1.33E-08 <sup>a</sup>  |
| 6.     | Cu    | Exp <sub>ing</sub>  | 1.88E-04±3.75E-05 <sup>a</sup>  | 5.52E-04±5.27E-04 <sup>a</sup>  | 1.86E-03±1.51E-03 <sup>a</sup>  | 1.21E-04±1.46E-05 <sup>a</sup>  | 2.38E-04±6.18E-06 <sup>a</sup>  | 7.65E-05±1.53E-05 <sup>a</sup>  | 2.95E-04±2.03E-04 <sup>a</sup>  |
|        |       | Exp <sub>derm</sub> | 1.33E-06±3.33E-07 <sup>a</sup>  | 3.64E-06±3.48E-06 <sup>a</sup>  | 1.23E-05±9.95E-06 <sup>a</sup>  | 7.98E-07±9.65E-08 <sup>a</sup>  | 1.57E-06±4.08E-08 <sup>a</sup>  | 5.05E-07±1.01E-07 <sup>a</sup>  | 1.95E-06±1.34E-06 <sup>a</sup>  |
| 7.     | As    | Exp <sub>ing</sub>  | 2.14E-04±1.18E-05 <sup>a</sup>  | 8.05E-04±6.22E-04 <sup>a</sup>  | 2.08E-04±4.48E-05 <sup>a</sup>  | 1.80E-04±3.59E-06 <sup>a</sup>  | 1.56E-04±2.68E-06 <sup>a</sup>  | 1.77E-04±3.49E-05 <sup>a</sup>  | 2.16E-04±3.69E-06 <sup>a</sup>  |
|        |       | Exp <sub>derm</sub> | 1.17E-06±1.67E-07 <sup>a</sup>  | 5.31E-06±4.10E-06 <sup>a</sup>  | 1.37E-06±2.96E-07 <sup>a</sup>  | 1.19E-06±2.37E-08 <sup>a</sup>  | 1.03E-06±1.77E-08 <sup>a</sup>  | 1.17E-06±2.30E-07 <sup>a</sup>  | 1.43E-06±2.43E-08 <sup>a</sup>  |
| 8.     | Cd    | Exp <sub>ing</sub>  | 4.33E-06±9.55E-07 <sup>a</sup>  | 5.35E-04±5.34E-04 <sup>a</sup>  | 3.19E-06±2.13E-07 <sup>a</sup>  | 1.24E-06±1.07E-07 <sup>a</sup>  | 2.80E-06±2.91E-07 <sup>a</sup>  | 1.57E-06±2.84E-07 <sup>a</sup>  | 1.33E-06±3.44E-08 <sup>a</sup>  |
|        |       | Exp <sub>derm</sub> | 0.00E+00±0.00E+00 <sup>a</sup>  | 3.53E-06±3.52E-06 <sup>a</sup>  | 2.10E-08±1.41E-09 <sup>a</sup>  | 8.21E-09±7.06E-10 <sup>a</sup>  | 1.85E-08±1.92E-09 <sup>a</sup>  | 1.03E-08±1.88E-09 <sup>a</sup>  | 8.80E-09±2.27E-10 <sup>a</sup>  |
| 9.     | Pb    | Exp <sub>ing</sub>  | 1.78E-04±5.98E-05 <sup>a</sup>  | 6.08E-04±5.97E-04 <sup>a</sup>  | 1.09E-04±4.18E-05 <sup>a</sup>  | 4.99E-05±1.13E-05 <sup>a</sup>  | 1.57E-04±3.95E-06 <sup>a</sup>  | 6.52E-05±1.61E-05 <sup>a</sup>  | 5.38E-05±1.69E-06 <sup>a</sup>  |
|        |       | Exp <sub>derm</sub> | 1.67E-07±1.67E-07 <sup>a</sup>  | 1.61E-06±1.58E-06 <sup>a</sup>  | 2.87E-07±1.10E-07 <sup>a</sup>  | 1.32E-07±2.98E-08 <sup>a</sup>  | 4.15E-07±1.04E-08 <sup>a</sup>  | 1.72E-07±4.24E-08 <sup>a</sup>  | 1.42E-07±4.47E-09 <sup>a</sup>  |

**Note:** Values are presented as mean ± SEM. Exposure estimates were determined for children through the ingestion and dermal contact pathways of canal water. Exp<sub>ing</sub> represents exposure through ingestion, whereas Exp<sub>derm</sub> represents exposure through dermal contact. Statistical differences among districts were assessed using one-way analysis of variance (ANOVA), followed by appropriate post hoc comparisons. Different lowercase superscript letters indicate statistically significant differences among district-wise means, whereas identical letters indicate

923 no significant difference. Al: Aluminum, As: Arsenic, Cd: Cadmium, Co: Cobalt, Cr: Chromium, Cu: Copper, Exp<sub>derm</sub>: Exposure through dermal  
924 contact, Exp<sub>ing</sub>: Exposure through ingestion, Li: Lithium, Ni: Nickel, Pb: Lead, SEM: Standard error of the mean

A comparative assessment of heavy metal exposure between industrial and nonindustrial regions revealed distinct differences among adults and children across the evaluated exposure pathways (Table 14). Among adults, ingestion-related exposure was generally greater in industrial regions for most metals, with Li, Al, Cr, and Ni concentrations of 5.65E-04, 3.47E-02, 2.26E-04, and 1.67E-04, respectively, compared with 4.37E-04, 1.29E-02, 5.58E-05, and 4.83E-05, respectively, in nonindustrial regions. Similarly, dermal exposure to Al and Cr was greater in industrial regions (1.81E-04 and 2.36E-06, respectively) than in nonindustrial regions (6.75E-05 and 5.82E-07, respectively). In contrast, Cu exposure was greater in nonindustrial regions, with ingestion and dermal estimates of 2.95E-04 and 1.54E-06, respectively, than in industrial regions, which were 1.36E-04 and 7.12E-07, respectively. Among children, ingestion-related exposure was consistently greater in industrial regions for most metals; for example, the concentrations of Al and Cr were 8.11E-02 and 5.28E-04, respectively, compared with 3.02E-02 and 1.30E-04, respectively, in nonindustrial regions. Similarly, the Ni exposure through ingestion was 3.89E-04 in industrial regions compared with 1.13E-04 in nonindustrial regions. Dermal exposure followed a similar pattern, whereas Cu again showed higher exposure in the nonindustrial region, with ingestion and dermal estimates of 6.87E-04 and 4.54E-06, respectively. Significant differences between industrial and nonindustrial regions were observed for Al, Cr, and Ni across both exposure pathways in adults and children, as indicated by the statistically significant markers. Overall, the results indicate a predominantly higher exposure burden for most heavy metals in industrial regions, whereas Cu exhibited the opposite spatial pattern.

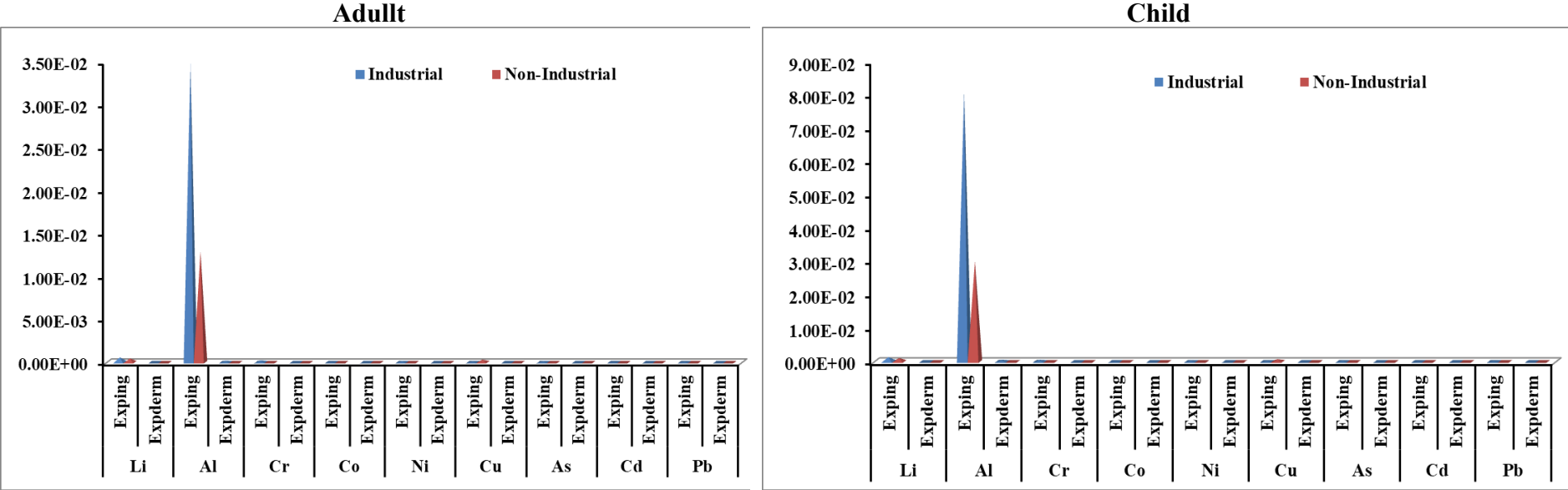
948 **Table 14.** Average daily dose of heavy metals through ingestion and dermal exposure routes among adults and children in industrial and non-  
949 industrial regions of the semi-arid region of Haryana, India

950

| Sl. No. | Heavy metals | Attributes          | Adult                                 |                                              | Child                                 |                                              |
|---------|--------------|---------------------|---------------------------------------|----------------------------------------------|---------------------------------------|----------------------------------------------|
|         |              |                     | Industrial Region<br>(Mean $\pm$ SEM) | Non-Industrial<br>Region<br>(Mean $\pm$ SEM) | Industrial Region<br>(Mean $\pm$ SEM) | Non-Industrial<br>Region<br>(Mean $\pm$ SEM) |
| 1.      | Li           | Exp <sub>ing</sub>  | 5.65E-04 $\pm$ 4.62E-05               | 4.37E-04 $\pm$ 5.27E-05                      | 1.32E-03 $\pm$ 1.08E-04               | 1.02E-03 $\pm$ 1.23E-04                      |
|         |              | Exp <sub>derm</sub> | 2.95E-06 $\pm$ 2.41E-07               | 2.28E-06 $\pm$ 2.75E-07                      | 8.70E-06 $\pm$ 7.12E-07               | 6.73E-06 $\pm$ 8.12E-07                      |
| 2.      | Al           | Exp <sub>ing</sub>  | 3.47E-02 $\pm$ 6.04E-03               | 1.29E-02 $\pm$ 2.80E-03*                     | 8.11E-02 $\pm$ 1.41E-02               | 3.02E-02 $\pm$ 6.54E-03*                     |
|         |              | Exp <sub>derm</sub> | 1.81E-04 $\pm$ 3.15E-05               | 6.75E-05 $\pm$ 1.46E-05*                     | 5.35E-04 $\pm$ 9.30E-05               | 1.99E-04 $\pm$ 4.32E-05*                     |
| 3.      | Cr           | Exp <sub>ing</sub>  | 2.26E-04 $\pm$ 6.56E-05               | 5.58E-05 $\pm$ 4.90E-06*                     | 5.28E-04 $\pm$ 1.53E-04               | 1.30E-04 $\pm$ 1.14E-05*                     |
|         |              | Exp <sub>derm</sub> | 2.36E-06 $\pm$ 6.85E-07               | 5.82E-07 $\pm$ 5.11E-08*                     | 6.97E-06 $\pm$ 2.02E-06               | 1.72E-06 $\pm$ 1.51E-07*                     |
| 4.      | Co           | Exp <sub>ing</sub>  | 7.26E-05 $\pm$ 5.54E-05               | 6.77E-06 $\pm$ 1.25E-06                      | 1.69E-04 $\pm$ 1.29E-04               | 1.58E-05 $\pm$ 2.91E-06                      |
|         |              | Exp <sub>derm</sub> | 3.79E-07 $\pm$ 2.89E-07               | 3.53E-08 $\pm$ 6.51E-09                      | 1.12E-06 $\pm$ 8.53E-07               | 1.04E-07 $\pm$ 1.92E-08                      |
| 5.      | Ni           | Exp <sub>ing</sub>  | 1.67E-04 $\pm$ 6.43E-05               | 4.83E-05 $\pm$ 4.51E-06*                     | 3.89E-04 $\pm$ 1.50E-04               | 1.13E-04 $\pm$ 1.05E-05*                     |
|         |              | Exp <sub>derm</sub> | 8.69E-07 $\pm$ 3.36E-07               | 2.52E-07 $\pm$ 2.35E-08*                     | 2.56E-06 $\pm$ 9.90E-07               | 7.44E-07 $\pm$ 6.94E-08*                     |
| 6.      | Cu           | Exp <sub>ing</sub>  | 1.36E-04 $\pm$ 5.79E-05               | 2.95E-04 $\pm$ 2.20E-04                      | 3.18E-04 $\pm$ 1.35E-04               | 6.87E-04 $\pm$ 5.13E-04                      |
|         |              | Exp <sub>derm</sub> | 7.12E-07 $\pm$ 3.02E-07               | 1.54E-06 $\pm$ 1.15E-06                      | 2.10E-06 $\pm$ 8.92E-07               | 4.54E-06 $\pm$ 3.39E-06                      |
| 7.      | As           | Exp <sub>ing</sub>  | 1.49E-04 $\pm$ 6.65E-05               | 8.08E-05 $\pm$ 7.78E-06                      | 3.48E-04 $\pm$ 1.55E-04               | 1.88E-04 $\pm$ 1.81E-05                      |
|         |              | Exp <sub>derm</sub> | 7.78E-07 $\pm$ 3.47E-07               | 4.22E-07 $\pm$ 4.06E-08                      | 2.29E-06 $\pm$ 1.02E-06               | 1.24E-06 $\pm$ 1.20E-07                      |
| 8.      | Cd           | Exp <sub>ing</sub>  | 5.82E-05 $\pm$ 5.72E-05               | 8.57E-07 $\pm$ 1.02E-07                      | 1.36E-04 $\pm$ 1.33E-04               | 2.00E-06 $\pm$ 2.37E-07                      |
|         |              | Exp <sub>derm</sub> | 3.04E-07 $\pm$ 2.98E-07               | 4.47E-09 $\pm$ 5.30E-10                      | 8.96E-07 $\pm$ 8.80E-07               | 1.32E-08 $\pm$ 1.56E-09                      |
| 9.      | Pb           | Exp <sub>ing</sub>  | 1.07E-04 $\pm$ 6.29E-05               | 3.20E-05 $\pm$ 6.71E-06                      | 2.49E-04 $\pm$ 1.47E-04               | 7.47E-05 $\pm$ 1.57E-05                      |
|         |              | Exp <sub>derm</sub> | 2.23E-07 $\pm$ 1.31E-07               | 6.68E-08 $\pm$ 1.40E-08                      | 6.58E-07 $\pm$ 3.87E-07               | 1.97E-07 $\pm$ 4.14E-08                      |

951 **Note:** Values are presented as mean  $\pm$  SEM. The average daily dose (ADD) of heavy metals was estimated for adults and children through  
952 ingestion and dermal exposure routes in industrial and non-industrial regions. Statistical differences between industrial and non-industrial

953 regions were assessed using appropriate statistical analysis, with  $p < 0.05$  considered statistically significant. An asterisk (\*) indicates a  
 954 statistically significant difference between industrial and non-industrial regions. Al: Aluminum, As: Arsenic, Cd: Cadmium, Co: Cobalt, Cr:  
 955 Chromium, Cu: Copper, ADD: Average daily dose,  $Exp_{derm}$ : Exposure through dermal contact,  $Exp_{ing}$ : Exposure through ingestion, Li: Lithium,  
 956 Ni: Nickel, Pb: Lead, SEM: Standard error of the mean  
 957



958 **Fig. 8.** Comparative carcinogenic risks of selected elements through ingestion and dermal exposure pathways in canal water samples from  
 959 industrial and non-industrial regions of Haryana, India, for adults and child

*4.4 Assessment of probabilistic human health risks due to canal water quality collected from the Industrial and Non-industrial region of Haryana*

*4.4.1 Non-carcinogenic risk assessment*

*4.4.1.1 Spatial Distribution of Non-Carcinogenic Health Risk in Adults in the Industrial and Non-industrial region of Haryana*

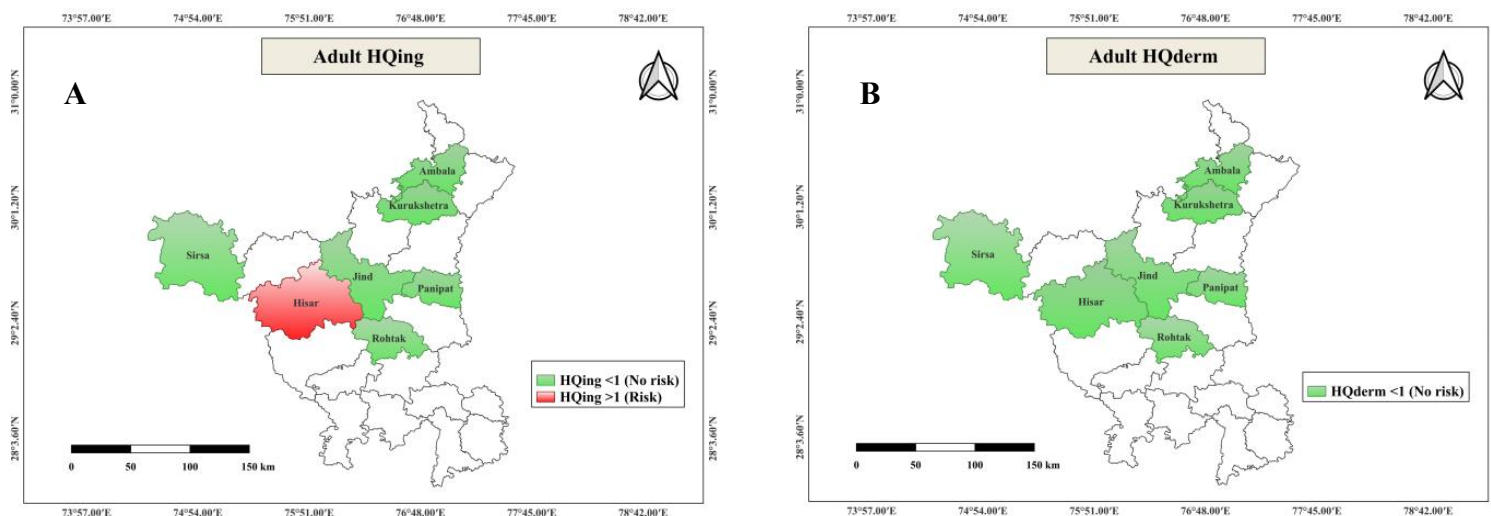
Lithium exhibited significant spatial variation ( $p < 0.05$ ). The highest  $HQ_{ing}$  and HI values ( $0.354 \pm 0.085$ ) were recorded for Hisar (Table 15), which were significantly greater than those recorded in Sirsa ( $0.133 \pm 0.044$ ). In contrast, Rohtak, Jind, Panipat, Kurukshetra, and Ambala did not differ significantly from either group. The  $HQ_{derm}$  values for Li remained negligible in all the districts. The spatial variation in aluminum content was also significant ( $p < 0.05$ ). Compared with Hisar, Sirsa, Jind, Kurukshetra, and Ambala, Rohtak (HI:  $0.338 \pm 0.067$ ) and Panipat (HI:  $0.410 \pm 0.007$ ) presented significantly higher HI values. Similar spatial trends were observed for  $HQ_{ing}$  and  $HQ_{derm}$ . The heavy metal concentrations used for health risk estimation are expressed in ppm. Chromium content significantly varied between  $HQ_{derm}$  and HI ( $p < 0.05$ ). The highest HI was observed in Rohtak ( $0.375 \pm 0.092$ ), which differed significantly from that in Kurukshetra ( $0.038 \pm 0.007$ ), whereas the HI of Hisar, Sirsa, Jind, Panipat, and Ambala (ab) did not significantly differ between the groups.  $HQ_{ing}$  values remained negligible in all districts. No significant differences ( $p > 0.05$ ) were observed among the districts for Co, Ni, Cu, As, Cd, and Pb, as all the corresponding values were similar. The highest HI values were nevertheless recorded for Co ( $0.752 \pm 0.746$ ), Ni ( $0.049 \pm 0.047$ ), As ( $1.152 \pm 0.889$ ), Cd ( $0.482 \pm 0.481$ ), and Pb ( $0.075 \pm 0.074$ ), whereas the highest HI for Cu was observed in Sirsa ( $0.020 \pm 0.016$ ) (Table 15).

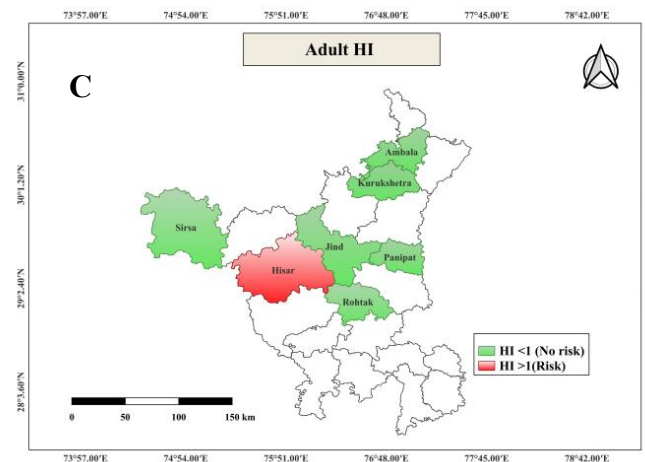
984 **Table 15.** Estimation of non-carcinogenic risk assessment of various heavy metals in Adults in different districts of Haryana

985

| Heavy metals | Attributes         | Rohtak                    | Hisar                     | Sirsa                     | Jind                      | Panipat                   | Kurukshetra               | Ambala                    |
|--------------|--------------------|---------------------------|---------------------------|---------------------------|---------------------------|---------------------------|---------------------------|---------------------------|
| Li           | HQ <sub>ing</sub>  | 0.263±0.004 <sup>ab</sup> | 0.354±0.085 <sup>b</sup>  | 0.133±0.044 <sup>a</sup>  | 0.252±0.004 <sup>ab</sup> | 0.201±0.002 <sup>ab</sup> | 0.271±0.054 <sup>ab</sup> | 0.311±0.004 <sup>ab</sup> |
|              | HQ <sub>derm</sub> | 0.000±0.000 <sup>a</sup>  | 0.000±0.000 <sup>a</sup>  | 0.000±0.000 <sup>a</sup>  | 0.000±0.000 <sup>a</sup>  | 0.000±0.000 <sup>a</sup>  | 0.000±0.000 <sup>a</sup>  | 0.000±0.000 <sup>a</sup>  |
|              | HI                 | 0.263±0.004 <sup>ab</sup> | 0.354±0.085 <sup>b</sup>  | 0.133±0.044 <sup>a</sup>  | 0.252±0.004 <sup>ab</sup> | 0.201±0.002 <sup>ab</sup> | 0.271±0.054 <sup>ab</sup> | 0.311±0.004 <sup>ab</sup> |
| Al           | HQ <sub>ing</sub>  | 0.054±0.011 <sup>b</sup>  | 0.003±0.003 <sup>a</sup>  | 0.010±0.003 <sup>a</sup>  | 0.014±0.008 <sup>a</sup>  | 0.066±0.001 <sup>b</sup>  | 0.015±0.003 <sup>a</sup>  | 0.016±0.000 <sup>a</sup>  |
|              | HQ <sub>derm</sub> | 0.284±0.056 <sup>b</sup>  | 0.017±0.014 <sup>a</sup>  | 0.050±0.016 <sup>a</sup>  | 0.073±0.040 <sup>a</sup>  | 0.344±0.006 <sup>b</sup>  | 0.080±0.016 <sup>a</sup>  | 0.081±0.002 <sup>a</sup>  |
|              | HI                 | 0.338±0.067 <sup>b</sup>  | 0.020±0.017 <sup>a</sup>  | 0.059±0.019 <sup>a</sup>  | 0.087±0.048 <sup>a</sup>  | 0.410±0.007 <sup>b</sup>  | 0.096±0.019 <sup>a</sup>  | 0.097±0.002 <sup>a</sup>  |
| Cr           | HQ <sub>ing</sub>  | 0.000±0.000 <sup>a</sup>  | 0.000±0.000 <sup>a</sup>  | 0.000±0.000 <sup>a</sup>  | 0.000±0.000 <sup>a</sup>  | 0.000±0.000 <sup>a</sup>  | 0.000±0.000 <sup>a</sup>  | 0.000±0.000 <sup>a</sup>  |
|              | HQ <sub>derm</sub> | 0.374±0.092 <sup>b</sup>  | 0.188±0.175 <sup>ab</sup> | 0.045±0.004 <sup>ab</sup> | 0.051±0.009 <sup>ab</sup> | 0.117±0.001 <sup>ab</sup> | 0.038±0.007 <sup>a</sup>  | 0.048±0.002 <sup>ab</sup> |
|              | HI                 | 0.375±0.092 <sup>b</sup>  | 0.188±0.176 <sup>ab</sup> | 0.045±0.004 <sup>ab</sup> | 0.051±0.009 <sup>ab</sup> | 0.117±0.001 <sup>ab</sup> | 0.038±0.007 <sup>a</sup>  | 0.048±0.002 <sup>ab</sup> |
| Co           | HQ <sub>ing</sub>  | 0.081±0.016 <sup>a</sup>  | 0.752±0.746 <sup>a</sup>  | 0.020±0.006 <sup>a</sup>  | 0.025±0.011 <sup>a</sup>  | 0.109±0.000 <sup>a</sup>  | 0.023±0.004 <sup>a</sup>  | 0.026±0.000 <sup>a</sup>  |
|              | HQ <sub>derm</sub> | 0.000±0.000 <sup>a</sup>  | 0.000±0.000 <sup>a</sup>  | 0.000±0.000 <sup>a</sup>  | 0.000±0.000 <sup>a</sup>  | 0.000±0.000 <sup>a</sup>  | 0.000±0.000 <sup>a</sup>  | 0.000±0.000 <sup>a</sup>  |
|              | HI                 | 0.081±0.016 <sup>a</sup>  | 0.752±0.746 <sup>a</sup>  | 0.020±0.006 <sup>a</sup>  | 0.025±0.011 <sup>a</sup>  | 0.109±0.000 <sup>a</sup>  | 0.023±0.004 <sup>a</sup>  | 0.026±0.000 <sup>a</sup>  |
| Ni           | HQ <sub>ing</sub>  | 0.012±0.003 <sup>a</sup>  | 0.014±0.013 <sup>a</sup>  | 0.003±0.000 <sup>a</sup>  | 0.002±0.000 <sup>a</sup>  | 0.005±0.000 <sup>a</sup>  | 0.002±0.000 <sup>a</sup>  | 0.002±0.000 <sup>a</sup>  |
|              | HQ <sub>derm</sub> | 0.031±0.007 <sup>a</sup>  | 0.036±0.034 <sup>a</sup>  | 0.007±0.001 <sup>a</sup>  | 0.006±0.001 <sup>a</sup>  | 0.014±0.000 <sup>a</sup>  | 0.006±0.001 <sup>a</sup>  | 0.006±0.000 <sup>a</sup>  |
|              | HI                 | 0.043±0.009 <sup>a</sup>  | 0.049±0.047 <sup>a</sup>  | 0.010±0.001 <sup>a</sup>  | 0.008±0.002 <sup>a</sup>  | 0.020±0.000 <sup>a</sup>  | 0.008±0.001 <sup>a</sup>  | 0.009±0.000 <sup>a</sup>  |
| Cu           | HQ <sub>ing</sub>  | 0.002±0.000 <sup>a</sup>  | 0.006±0.006 <sup>a</sup>  | 0.020±0.016 <sup>a</sup>  | 0.001±0.000 <sup>a</sup>  | 0.003±0.000 <sup>a</sup>  | 0.001±0.000 <sup>a</sup>  | 0.003±0.002 <sup>a</sup>  |
|              | HQ <sub>derm</sub> | 0.000±0.000 <sup>a</sup>  | 0.000±0.000 <sup>a</sup>  | 0.000±0.000 <sup>a</sup>  | 0.000±0.000 <sup>a</sup>  | 0.000±0.000 <sup>a</sup>  | 0.000±0.000 <sup>a</sup>  | 0.000±0.000 <sup>a</sup>  |
|              | HI                 | 0.002±0.000 <sup>a</sup>  | 0.006±0.006 <sup>a</sup>  | 0.020±0.016 <sup>a</sup>  | 0.001±0.000 <sup>a</sup>  | 0.003±0.000 <sup>a</sup>  | 0.001±0.000 <sup>a</sup>  | 0.003±0.002 <sup>a</sup>  |
| As           | HQ <sub>ing</sub>  | 0.306±0.017 <sup>a</sup>  | 1.150±0.888 <sup>a</sup>  | 0.298±0.064 <sup>a</sup>  | 0.258±0.005 <sup>a</sup>  | 0.222±0.004 <sup>a</sup>  | 0.253±0.050 <sup>a</sup>  | 0.309±0.005 <sup>a</sup>  |
|              | HQ <sub>derm</sub> | 0.000±0.000 <sup>a</sup>  | 0.002±0.001 <sup>a</sup>  | 0.000±0.000 <sup>a</sup>  | 0.000±0.000 <sup>a</sup>  | 0.000±0.000 <sup>a</sup>  | 0.000±0.000 <sup>a</sup>  | 0.000±0.000 <sup>a</sup>  |
|              | HI                 | 0.306±0.017 <sup>a</sup>  | 1.152±0.889 <sup>a</sup>  | 0.298±0.064 <sup>a</sup>  | 0.258±0.005 <sup>a</sup>  | 0.223±0.004 <sup>a</sup>  | 0.253±0.050 <sup>a</sup>  | 0.309±0.005 <sup>a</sup>  |
| Cd           | HQ <sub>ing</sub>  | 0.004±0.001 <sup>a</sup>  | 0.458±0.458 <sup>a</sup>  | 0.003±0.000 <sup>a</sup>  | 0.001±0.000 <sup>a</sup>  | 0.002±0.000 <sup>a</sup>  | 0.001±0.000 <sup>a</sup>  | 0.001±0.000 <sup>a</sup>  |
|              | HQ <sub>derm</sub> | 0.000±0.000 <sup>a</sup>  | 0.024±0.024 <sup>a</sup>  | 0.000±0.000 <sup>a</sup>  | 0.000±0.000 <sup>a</sup>  | 0.000±0.000 <sup>a</sup>  | 0.000±0.000 <sup>a</sup>  | 0.000±0.000 <sup>a</sup>  |
|              | HI                 | 0.004±0.001 <sup>a</sup>  | 0.482±0.481 <sup>a</sup>  | 0.003±0.000 <sup>a</sup>  | 0.001±0.000 <sup>a</sup>  | 0.003±0.000 <sup>a</sup>  | 0.001±0.000 <sup>a</sup>  | 0.001±0.000 <sup>a</sup>  |
| Pb           | HQ <sub>ing</sub>  | 0.022±0.007 <sup>a</sup>  | 0.074±0.073 <sup>a</sup>  | 0.013±0.005 <sup>a</sup>  | 0.006±0.001 <sup>a</sup>  | 0.019±0.000 <sup>a</sup>  | 0.008±0.002 <sup>a</sup>  | 0.007±0.000 <sup>a</sup>  |
|              | HQ <sub>derm</sub> | 0.000±0.000 <sup>a</sup>  | 0.001±0.001 <sup>a</sup>  | 0.000±0.000 <sup>a</sup>  | 0.000±0.000 <sup>a</sup>  | 0.000±0.000 <sup>a</sup>  | 0.000±0.000 <sup>a</sup>  | 0.000±0.000 <sup>a</sup>  |
|              | HI                 | 0.022±0.007 <sup>a</sup>  | 0.075±0.074 <sup>a</sup>  | 0.013±0.005 <sup>a</sup>  | 0.006±0.001 <sup>a</sup>  | 0.019±0.000 <sup>a</sup>  | 0.008±0.002 <sup>a</sup>  | 0.007±0.000 <sup>a</sup>  |

986 **Note:** Values are presented as Mean  $\pm$  SEM (Standard Error of the Mean). Different superscript lowercase letters (a-b) within the same row  
 987 indicate statistically significant differences among districts at  $P < 0.05$  (one-way ANOVA followed by Tukey's honestly significant difference  
 988 (HSD) post hoc test). HQ and HI are dimensionless indices. HQ values were calculated separately for the ingestion (HQ<sub>ing</sub>) and dermal (HQ<sub>derm</sub>)  
 989 exposure pathways, whereas HI represents the cumulative non-carcinogenic risk from both exposure routes. Al: Aluminum, As: Arsenic, Cd:  
 990 Cadmium, Co: Cobalt, Cr: Chromium, Cu: Copper, HI: Hazard Index, HQ: Hazard Quotient, HQ<sub>derm</sub>: Hazard Quotient through Dermal  
 991 Exposure, HQ<sub>ing</sub>: Hazard Quotient through Ingestion, HSD: Honestly Significant Difference, Li: Lithium, Mean  $\pm$  SEM: Mean  $\pm$  Standard Error  
 992 of the Mean, Ni: Nickel, Pb: Lead, SEM: Standard Error of the Mean  
 993





994  
 995 **Fig. 9 (A-C).** Spatial distribution of the non-carcinogenic health risk indices for adults through canal water exposure in the selected districts of  
 996 Haryana, India. (A) Hazard Quotient through ingestion ( $HQ_{ing}$ ), (B) Hazard Quotient through dermal exposure ( $HQ_{derm}$ ), and (C) Hazard Index  
 997 (HI). Green indicates  $HQ_{ing}$ ,  $HQ_{derm}$ , or  $HI < 1$  (no appreciable non-carcinogenic risk), whereas red indicates  $HQ_{ing}$  or  $HI > 1$  (potential non-  
 998 carcinogenic risk). The classification is based on the United States Environmental Protection Agency (USEPA) health risk assessment guidelines

999 Graphical representation of the noncarcinogenic risk assessment of various heavy  
1000 metals in adults in different districts of Haryana. The spatial distribution of adult  
1001 noncarcinogenic health risk across the investigated districts of Haryana is shown in  
1002 Fig. 9. The  $HQ_{ing}$  map revealed distinct spatial heterogeneity, with Hisar being the  
1003 only district classified in the  $HQ_{ing} > 1$  category, indicating potential noncarcinogenic  
1004 risk through the ingestion pathway. In contrast, Rohtak, Sirsa, Jind, Panipat,  
1005 Kurukshetra, and Ambala remained within the  $HQ_{ing} < 1$  category. The spatial  
1006 distribution of  $HQ_{derm}$  demonstrated a uniform pattern across the study area, with all  
1007 investigated districts below the acceptable threshold ( $HQ_{derm} < 1$ ). No district  
1008 exceeded the reference limit. A comparable spatial pattern was observed for the  
1009 overall hazard index (HI). Hisar was the only district categorized as having a  $HI > 1$ ,  
1010 while the remaining districts were consistently classified as having a  $HI < 1$ . The  
1011 geographical distribution of HI closely mirrored that of  $HQ_{ing}$ , indicating that the  
1012 overall noncarcinogenic risk pattern was primarily associated with the ingestion  
1013 pathway.

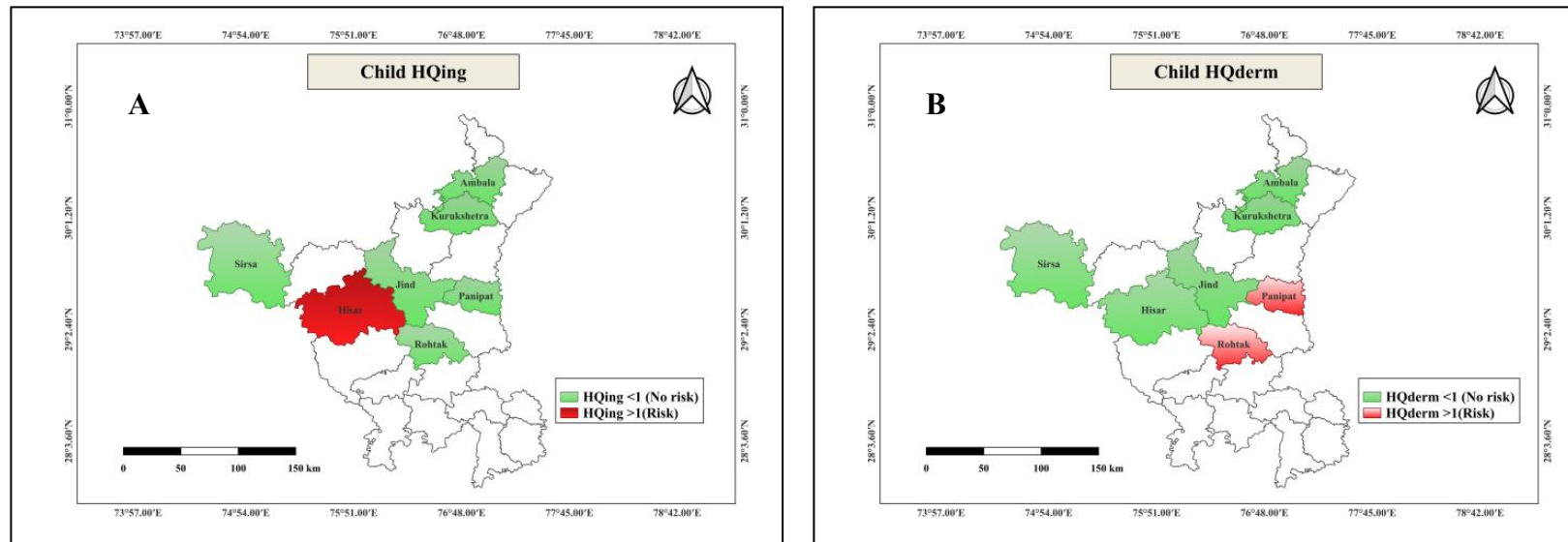
#### **4.4.1.2 Spatial Distribution of Non-Carcinogenic Health Risk of Children in Industrial and Non-industrial Regions of Haryana**

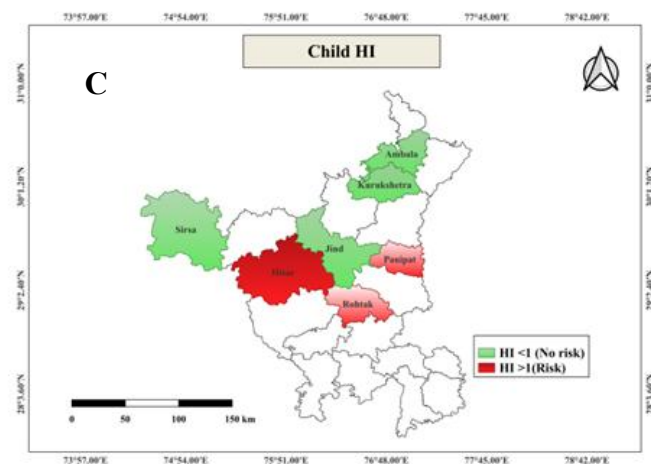
Lithium exhibited significant spatial variation ( $p < 0.05$ ). The highest  $HQ_{ing}$  and HI values were recorded in Hisar ( $0.825 \pm 0.198$ ), which were significantly greater than those observed in Sirsa ( $0.310 \pm 0.103$ ) (Table 16). In contrast, Rohtak, Jind, Panipat, Kurukshetra, and Ambala did not differ significantly from either group. The  $HQ_{derm}$  values for Li remained negligible in all the districts. The spatial variation in aluminum content was also significant ( $p < 0.05$ ). Compared with Hisar, Sirsa, Jind, Kurukshetra, and Ambala, Rohtak (HI:  $0.963 \pm 0.192$ ) and Panipat (HI:  $1.170 \pm 0.021$ ) presented significantly higher HI values. Similar statistically significant trends were observed for  $HQ_{ing}$  and  $HQ_{derm}$ . Chromium demonstrated significant spatial variation in  $HQ_{derm}$  and HI ( $p < 0.05$ ). The highest HI was observed in Rohtak ( $1.105 \pm 0.272$ ), which was significantly greater than that in Kurukshetra ( $0.113 \pm 0.021$ ), whereas the HI in Hisar, Sirsa, Jind, Panipat, and Ambala did not differ significantly from that in either group.  $HQ_{ing}$  values remained negligible throughout the study area. No significant spatial variation ( $p > 0.05$ ) was observed for Co, Ni, Cu, As, Cd, or Pb. Nevertheless, the highest HI values were recorded for Co ( $1.756 \pm 1.740$ ), Ni ( $0.137 \pm 0.129$ ), As ( $2.689 \pm 2.076$ ), Cd ( $1.140 \pm 1.138$ ), and Pb ( $0.175 \pm 0.172$ ), whereas Sirsa presented the highest HI for Cu ( $0.048 \pm 0.039$ ). Among the investigated heavy metals, the HI values exceeded the reference threshold of 1 for Al in Panipat ( $1.170 \pm 0.021$ ), Cr in Rohtak ( $1.105 \pm 0.272$ ), Co in Hisar ( $1.756 \pm 1.740$ ), As in Hisar ( $2.689 \pm 2.076$ ), and Cd in Hisar ( $1.140 \pm 1.138$ ). In contrast, the HI values for Li, Ni, Cu, and Pb remained below 1 across all the study districts (Table 16).

1037 **Table 16.** Estimation of non-carcinogenic risk assessment of various heavy metals in Child in different districts of Haryana

| Heavy metals | Attributes         | Rohtak                    | Hisar                     | Sirsa                     | Jind                      | Panipat                   | Kurukshetra               | Ambala                    |
|--------------|--------------------|---------------------------|---------------------------|---------------------------|---------------------------|---------------------------|---------------------------|---------------------------|
| Li           | HQ <sub>ing</sub>  | 0.614±0.010 <sup>ab</sup> | 0.825±0.198 <sup>b</sup>  | 0.310±0.103 <sup>a</sup>  | 0.588±0.010 <sup>ab</sup> | 0.469±0.005 <sup>ab</sup> | 0.632±0.126 <sup>ab</sup> | 0.726±0.010 <sup>ab</sup> |
|              | HQ <sub>derm</sub> | 0.000±0.000 <sup>a</sup>  | 0.000±0.000 <sup>a</sup>  | 0.000±0.000 <sup>a</sup>  | 0.000±0.000 <sup>a</sup>  | 0.000±0.000 <sup>a</sup>  | 0.000±0.000 <sup>a</sup>  | 0.000±0.000 <sup>a</sup>  |
|              | HI                 | 0.614±0.010 <sup>ab</sup> | 0.825±0.198 <sup>b</sup>  | 0.310±0.103 <sup>a</sup>  | 0.588±0.010 <sup>ab</sup> | 0.469±0.005 <sup>ab</sup> | 0.632±0.126 <sup>ab</sup> | 0.726±0.010 <sup>ab</sup> |
| Al           | HQ <sub>ing</sub>  | 0.127±0.025 <sup>b</sup>  | 0.007±0.006 <sup>a</sup>  | 0.022±0.007 <sup>a</sup>  | 0.033±0.018 <sup>a</sup>  | 0.154±0.003 <sup>b</sup>  | 0.036±0.007 <sup>a</sup>  | 0.036±0.001 <sup>a</sup>  |
|              | HQ <sub>derm</sub> | 0.836±0.167 <sup>b</sup>  | 0.049±0.041 <sup>a</sup>  | 0.147±0.046 <sup>a</sup>  | 0.215±0.118 <sup>a</sup>  | 1.016±0.018 <sup>b</sup>  | 0.237±0.046 <sup>a</sup>  | 0.239±0.005 <sup>a</sup>  |
|              | HI                 | 0.963±0.192 <sup>b</sup>  | 0.056±0.047 <sup>a</sup>  | 0.169±0.053 <sup>a</sup>  | 0.247±0.136 <sup>a</sup>  | 1.170±0.021 <sup>b</sup>  | 0.272±0.053 <sup>a</sup>  | 0.275±0.006 <sup>a</sup>  |
| Cr           | HQ <sub>ing</sub>  | 0.001±0.000 <sup>a</sup>  | 0.000±0.000 <sup>a</sup>  | 0.000±0.000 <sup>a</sup>  | 0.000±0.000 <sup>a</sup>  | 0.000±0.000 <sup>a</sup>  | 0.000±0.000 <sup>a</sup>  | 0.000±0.000 <sup>a</sup>  |
|              | HQ <sub>derm</sub> | 1.104±0.271 <sup>b</sup>  | 0.554±0.517 <sup>ab</sup> | 0.133±0.010 <sup>ab</sup> | 0.151±0.026 <sup>ab</sup> | 0.344±0.004 <sup>ab</sup> | 0.113±0.021 <sup>a</sup>  | 0.141±0.005 <sup>ab</sup> |
|              | HI                 | 1.105±0.272 <sup>b</sup>  | 0.555±0.518 <sup>ab</sup> | 0.133±0.010 <sup>ab</sup> | 0.151±0.026 <sup>ab</sup> | 0.345±0.004 <sup>ab</sup> | 0.113±0.021 <sup>a</sup>  | 0.141±0.005 <sup>ab</sup> |
| Co           | HQ <sub>ing</sub>  | 0.189±0.037 <sup>a</sup>  | 1.756±1.740 <sup>a</sup>  | 0.048±0.013 <sup>a</sup>  | 0.057±0.026 <sup>a</sup>  | 0.255±0.001 <sup>a</sup>  | 0.053±0.010 <sup>a</sup>  | 0.060±0.001 <sup>a</sup>  |
|              | HQ <sub>derm</sub> | 0.000±0.000 <sup>a</sup>  | 0.000±0.000 <sup>a</sup>  | 0.000±0.000 <sup>a</sup>  | 0.000±0.000 <sup>a</sup>  | 0.000±0.000 <sup>a</sup>  | 0.000±0.000 <sup>a</sup>  | 0.000±0.000 <sup>a</sup>  |
|              | HI                 | 0.189±0.037 <sup>a</sup>  | 1.756±1.740 <sup>a</sup>  | 0.048±0.013 <sup>a</sup>  | 0.057±0.026 <sup>a</sup>  | 0.255±0.001 <sup>a</sup>  | 0.053±0.010 <sup>a</sup>  | 0.060±0.001 <sup>a</sup>  |
| Ni           | HQ <sub>ing</sub>  | 0.028±0.006 <sup>a</sup>  | 0.032±0.030 <sup>a</sup>  | 0.007±0.001 <sup>a</sup>  | 0.005±0.001 <sup>a</sup>  | 0.013±0.000 <sup>a</sup>  | 0.005±0.001 <sup>a</sup>  | 0.006±0.000 <sup>a</sup>  |
|              | HQ <sub>derm</sub> | 0.091±0.020 <sup>a</sup>  | 0.105±0.099 <sup>a</sup>  | 0.022±0.002 <sup>a</sup>  | 0.017±0.004 <sup>a</sup>  | 0.042±0.000 <sup>a</sup>  | 0.016±0.003 <sup>a</sup>  | 0.018±0.000 <sup>a</sup>  |
|              | HI                 | 0.119±0.026 <sup>a</sup>  | 0.137±0.129 <sup>a</sup>  | 0.029±0.003 <sup>a</sup>  | 0.023±0.005 <sup>a</sup>  | 0.055±0.000 <sup>a</sup>  | 0.021±0.004 <sup>a</sup>  | 0.024±0.000 <sup>a</sup>  |
| Cu           | HQ <sub>ing</sub>  | 0.005±0.001 <sup>a</sup>  | 0.014±0.013 <sup>a</sup>  | 0.047±0.038 <sup>a</sup>  | 0.003±0.000 <sup>a</sup>  | 0.006±0.000 <sup>a</sup>  | 0.002±0.000 <sup>a</sup>  | 0.007±0.005 <sup>a</sup>  |
|              | HQ <sub>derm</sub> | 0.000±0.000 <sup>a</sup>  | 0.000±0.000 <sup>a</sup>  | 0.001±0.001 <sup>a</sup>  | 0.000±0.000 <sup>a</sup>  | 0.000±0.000 <sup>a</sup>  | 0.000±0.000 <sup>a</sup>  | 0.000±0.000 <sup>a</sup>  |
|              | HI                 | 0.005±0.001 <sup>a</sup>  | 0.014±0.013 <sup>a</sup>  | 0.048±0.039 <sup>a</sup>  | 0.003±0.000 <sup>a</sup>  | 0.006±0.000 <sup>a</sup>  | 0.002±0.000 <sup>a</sup>  | 0.008±0.005 <sup>a</sup>  |
| As           | HQ <sub>ing</sub>  | 0.713±0.039 <sup>a</sup>  | 2.684±2.072 <sup>a</sup>  | 0.694±0.149 <sup>a</sup>  | 0.601±0.012 <sup>a</sup>  | 0.519±0.009 <sup>a</sup>  | 0.589±0.116 <sup>a</sup>  | 0.720±0.012 <sup>a</sup>  |
|              | HQ <sub>derm</sub> | 0.001±0.000 <sup>a</sup>  | 0.005±0.004 <sup>a</sup>  | 0.001±0.000 <sup>a</sup>  | 0.001±0.000 <sup>a</sup>  | 0.001±0.000 <sup>a</sup>  | 0.001±0.000 <sup>a</sup>  | 0.001±0.000 <sup>a</sup>  |
|              | HI                 | 0.715±0.040 <sup>a</sup>  | 2.689±2.076 <sup>a</sup>  | 0.696±0.150 <sup>a</sup>  | 0.602±0.012 <sup>a</sup>  | 0.520±0.009 <sup>a</sup>  | 0.590±0.116 <sup>a</sup>  | 0.722±0.012 <sup>a</sup>  |
| Cd           | HQ <sub>ing</sub>  | 0.009±0.002 <sup>a</sup>  | 1.069±1.068 <sup>a</sup>  | 0.006±0.000 <sup>a</sup>  | 0.002±0.000 <sup>a</sup>  | 0.006±0.001 <sup>a</sup>  | 0.003±0.001 <sup>a</sup>  | 0.003±0.000 <sup>a</sup>  |
|              | HQ <sub>derm</sub> | 0.001±0.000 <sup>a</sup>  | 0.071±0.070 <sup>a</sup>  | 0.000±0.000 <sup>a</sup>  | 0.000±0.000 <sup>a</sup>  | 0.000±0.000 <sup>a</sup>  | 0.000±0.000 <sup>a</sup>  | 0.000±0.000 <sup>a</sup>  |
|              | HI                 | 0.009±0.002 <sup>a</sup>  | 1.140±1.138 <sup>a</sup>  | 0.007±0.000 <sup>a</sup>  | 0.003±0.000 <sup>a</sup>  | 0.006±0.001 <sup>a</sup>  | 0.003±0.001 <sup>a</sup>  | 0.003±0.000 <sup>a</sup>  |
| Pb           | HQ <sub>ing</sub>  | 0.051±0.017 <sup>a</sup>  | 0.174±0.171 <sup>a</sup>  | 0.031±0.012 <sup>a</sup>  | 0.014±0.003 <sup>a</sup>  | 0.045±0.001 <sup>a</sup>  | 0.019±0.005 <sup>a</sup>  | 0.015±0.000 <sup>a</sup>  |
|              | HQ <sub>derm</sub> | 0.000±0.000 <sup>a</sup>  | 0.002±0.002 <sup>a</sup>  | 0.000±0.000 <sup>a</sup>  | 0.000±0.000 <sup>a</sup>  | 0.000±0.000 <sup>a</sup>  | 0.000±0.000 <sup>a</sup>  | 0.000±0.000 <sup>a</sup>  |
|              | HI                 | 0.051±0.017 <sup>a</sup>  | 0.175±0.172 <sup>a</sup>  | 0.031±0.012 <sup>a</sup>  | 0.014±0.003 <sup>a</sup>  | 0.045±0.001 <sup>a</sup>  | 0.019±0.005 <sup>a</sup>  | 0.016±0.000 <sup>a</sup>  |

1038 **Note:** Values are presented as Mean  $\pm$  SEM (Standard Error of the Mean). Different superscript lowercase letters (a-b) within the same row  
1039 indicate statistically significant differences among districts at  $P < 0.05$  (one-way ANOVA followed by Tukey's honestly significant difference  
1040 (HSD) post hoc test). HQ and HI are dimensionless indices. HQ values were estimated separately for the ingestion (HQ<sub>ing</sub>) and dermal (HQ<sub>derm</sub>)  
1041 exposure pathways, whereas HI represents the cumulative non-carcinogenic health risk from both exposure routes. Abbreviations (A-Z): Al:  
1042 Aluminum, As: Arsenic, Cd: Cadmium, Co: Cobalt, Cr: Chromium, Cu: Copper, HI: Hazard Index, HQ: Hazard Quotient, HQ<sub>derm</sub>: Hazard  
1043 Quotient through Dermal Exposure, HQ<sub>ing</sub>: Hazard Quotient through Ingestion, HSD: Honestly Significant Difference, Li: Lithium, Mean  $\pm$   
1044 SEM: Mean  $\pm$  Standard Error of the Mean, Ni: Nickel, Pb: Lead, SEM: Standard Error of the Mean  
1045





1046 **Fig. 10 (A-C).** Spatial distribution of the non-carcinogenic health risk indices for children through canal water exposure in the selected districts  
 1047 of Haryana, India. (A) Hazard Quotient through ingestion ( $HQ_{ing}$ ), (B) Hazard Quotient through dermal exposure ( $HQ_{derm}$ ), and (C) Hazard  
 1048 Index (HI). Green indicates  $HQ_{ing}$ ,  $HQ_{derm}$ , or  $HI < 1$  (no appreciable non-carcinogenic risk), whereas red indicates  $HQ_{ing}$ ,  $HQ_{derm}$ , or  $HI > 1$   
 1049 (potential non-carcinogenic risk). The classification is based on the United States Environmental Protection Agency (USEPA) health risk  
 1050 assessment guidelines

1051 Graphical representation of the noncarcinogenic risk assessment of various heavy  
1052 metals in children in different districts of Haryana. The spatial distribution of  
1053 noncarcinogenic health risk among children across the investigated districts of  
1054 Haryana is shown in Fig. 10. The  $HQ_{ing}$  map identified Hisar as the only district  
1055 classified in the  $HQ_{ing} > 1$  category. In contrast, Rohtak, Sirsa, Jind, Panipat,  
1056 Kurukshetra, and Ambala remained within the  $HQ_{ing} < 1$  category. The  $HQ_{derm}$  map  
1057 showed a distinct spatial pattern, with Rohtak and Panipat categorized as  $HQ_{derm} > 1$ ,  
1058 indicating dermal hazard values above the reference threshold, while Hisar, Sirsa, Jind,  
1059 Kurukshetra, and Ambala remained within the  $HQ_{derm} < 1$  category. A similar spatial  
1060 distribution was observed for the overall hazard index (HI). Hisar, Rohtak, and  
1061 Panipat were classified in the  $HI > 1$  category, whereas Sirsa, Jind, Kurukshetra, and  
1062 Ambala were consistently categorized as  $HI < 1$ . The spatial distribution maps  
1063 therefore revealed three localized hotspots of overall noncarcinogenic risk in children,  
1064 whereas the remaining districts exhibited hazard indices below the acceptable  
1065 threshold.

A regional comparison of noncarcinogenic health risk revealed a generally greater risk burden in the industrial region than in the nonindustrial region for both adults and children. Among the metals investigated, Al, Cr, and Ni differed significantly across regions ( $p < 0.05$ ), whereas Li, Co, Cu, As, Cd, and Pb did not significantly differ. With respect to adults, the regional difference in Al was greatest, with significantly greater  $HQ_{ing}$  ( $0.035 \pm 0.006$ ),  $HQ_{derm}$  ( $0.181 \pm 0.032$ ), and HI ( $0.216 \pm 0.038$ ) in the industrial region than in the nonindustrial region ( $0.013 \pm 0.003$ ,  $0.068 \pm 0.015$ , and  $0.080 \pm 0.017$ , respectively). Similarly, the  $HQ_{derm}$  and HI in the industrial region ( $0.182 \pm 0.053$ ) were approximately fourfold greater than those in the nonindustrial region ( $0.045 \pm 0.004$ ), whereas the HI of Ni increased from  $0.009 \pm 0.001$  to  $0.030 \pm 0.012$  ( $p < 0.05$ ). Although Li, Co, As, Cd, and Pb did not differ significantly, their HI values were generally higher in the industrial region. In contrast, Cu concentrations were relatively high in the nonindustrial region. A comparable pattern was observed among children, with the HI in the industrial region ( $0.616 \pm 0.107$ ) being higher than that in the nonindustrial region ( $0.229 \pm 0.050$ ), while the HI values of Cr and Ni were  $0.536 \pm 0.156$  vs  $0.132 \pm 0.012$  and  $0.084 \pm 0.032$  versus  $0.024 \pm 0.002$ , respectively. Among the nonsignificant metals, As and Co had relatively high HI values in industrial children ( $1.161 \pm 0.518$  and  $0.565 \pm 0.431$ , respectively), whereas Cu remained high in nonindustrial regions ( $0.018 \pm 0.013$  vs  $0.008 \pm 0.003$ ). These adult- and child-specific regional comparisons are summarized in Table 17. Overall, industrial regions exhibited higher noncarcinogenic risk indices for most metals, with Al, Cr, and Ni accounting for the principal statistically significant regional differences, while hazard indices were generally higher among children than adults.

1090 **Table 17.** Comparative assessment of non-carcinogenic health risk indices in adults and children associated with exposure to canal water  
1091 containing heavy metals in industrial and non-industrial regions of Haryana

| Sl. No. | Heavy metals | Attributes         | Adult                                 |                                              | Child                                 |                                              |
|---------|--------------|--------------------|---------------------------------------|----------------------------------------------|---------------------------------------|----------------------------------------------|
|         |              |                    | Industrial Region<br>(Mean $\pm$ SEM) | Non-Industrial<br>Region<br>(Mean $\pm$ SEM) | Industrial Region<br>(Mean $\pm$ SEM) | Non-Industrial<br>Region<br>(Mean $\pm$ SEM) |
| 1.      | Li           | HQ <sub>ing</sub>  | 0.282 $\pm$ 0.023                     | 0.219 $\pm$ 0.026                            | 0.659 $\pm$ 0.054                     | 0.510 $\pm$ 0.061                            |
|         |              | HQ <sub>derm</sub> | 0.000 $\pm$ 0.000                     | 0.000 $\pm$ 0.000                            | 8.7E-06 $\pm$ 7.12E-07                | 6.73E-06 $\pm$ 8.12E-07                      |
|         |              | HI                 | 0.282 $\pm$ 0.023                     | 0.219 $\pm$ 0.026                            | 0.659 $\pm$ 0.054                     | 0.510 $\pm$ 0.061                            |
| 2.      | Al           | HQ <sub>ing</sub>  | 0.035 $\pm$ 0.006                     | 0.013 $\pm$ 0.003*                           | 0.081 $\pm$ 0.014                     | 0.030 $\pm$ 0.007*                           |
|         |              | HQ <sub>derm</sub> | 0.181 $\pm$ 0.032                     | 0.068 $\pm$ 0.015*                           | 0.535 $\pm$ 0.093                     | 0.199 $\pm$ 0.043*                           |
|         |              | HI                 | 0.216 $\pm$ 0.038                     | 0.080 $\pm$ 0.017*                           | 0.616 $\pm$ 0.107                     | 0.229 $\pm$ 0.050*                           |
| 3.      | Cr           | HQ <sub>ing</sub>  | 0.0002 $\pm$ 4.37E-05                 | 3.72E-05 $\pm$ 3.27E-06*                     | 0.0004 $\pm$ 0.0001                   | 8.67E-05 $\pm$ 7.62E-06*                     |
|         |              | HQ <sub>derm</sub> | 0.182 $\pm$ 0.053                     | 0.045 $\pm$ 0.004*                           | 0.536 $\pm$ 0.155                     | 0.132 $\pm$ 0.012*                           |
|         |              | HI                 | 0.182 $\pm$ 0.053                     | 0.045 $\pm$ 0.004*                           | 0.536 $\pm$ 0.156                     | 0.132 $\pm$ 0.012*                           |
| 4.      | Co           | HQ <sub>ing</sub>  | 0.242 $\pm$ 0.185                     | 0.023 $\pm$ 0.004                            | 0.565 $\pm$ 0.431                     | 0.053 $\pm$ 0.010                            |
|         |              | HQ <sub>derm</sub> | 0.023 $\pm$ 0.004                     | 3.53E-08 $\pm$ 6.51E-09                      | 1.12E-06 $\pm$ 8.53E-07               | 1.04E-07 $\pm$ 1.92E-08                      |
|         |              | HI                 | 0.242 $\pm$ 0.185                     | 0.023 $\pm$ 0.004                            | 0.565 $\pm$ 0.431                     | 0.053 $\pm$ 0.010                            |
| 5.      | Ni           | HQ <sub>ing</sub>  | 0.008 $\pm$ 0.003                     | 0.002 $\pm$ 0.000*                           | 0.019 $\pm$ 0.008                     | 0.006 $\pm$ 0.001*                           |
|         |              | HQ <sub>derm</sub> | 0.022 $\pm$ 0.008                     | 0.006 $\pm$ 0.001*                           | 0.064 $\pm$ 0.025                     | 0.019 $\pm$ 0.002*                           |
|         |              | HI                 | 0.030 $\pm$ 0.012                     | 0.009 $\pm$ 0.001*                           | 0.084 $\pm$ 0.032                     | 0.024 $\pm$ 0.002*                           |
| 6.      | Cu           | HQ <sub>ing</sub>  | 0.003 $\pm$ 0.001                     | 0.007 $\pm$ 0.006                            | 0.008 $\pm$ 0.003                     | 0.017 $\pm$ 0.013                            |
|         |              | HQ <sub>derm</sub> | 5.93E-05 $\pm$ 2.52E-05               | 0.000128 $\pm$ 9.57E-05                      | 0.0002 $\pm$ 7.43E-05                 | 0.000378 $\pm$ 0.0003                        |
|         |              | HI                 | 0.003 $\pm$ 0.001                     | 0.007 $\pm$ 0.006                            | 0.008 $\pm$ 0.003                     | 0.018 $\pm$ 0.013                            |
| 7.      | As           | HQ <sub>ing</sub>  | 0.497 $\pm$ 0.222                     | 0.269 $\pm$ 0.026                            | 1.159 $\pm$ 0.517                     | 0.628 $\pm$ 0.060                            |
|         |              | HQ <sub>derm</sub> | 0.001 $\pm$ 0.000                     | 0.000 $\pm$ 4.06E-05                         | 0.002 $\pm$ 0.001                     | 0.001 $\pm$ 0.000                            |
|         |              | HI                 | 0.497 $\pm$ 0.222                     | 0.270 $\pm$ 0.026                            | 1.161 $\pm$ 0.518                     | 0.629 $\pm$ 0.061                            |
| 8.      | Cd           | HQ <sub>ing</sub>  | 0.116 $\pm$ 0.114                     | 0.002 $\pm$ 0.000                            | 0.271 $\pm$ 0.267                     | 0.004 $\pm$ 0.0005                           |

|    |    |                    |               |                     |               |                   |
|----|----|--------------------|---------------|---------------------|---------------|-------------------|
|    |    | HQ <sub>derm</sub> | 0.006 ± 0.006 | 8.95E-05 ± 1.06E-05 | 0.018 ± 0.018 | 0.0003 ± 3.13E-05 |
|    |    | HI                 | 0.122 ± 0.120 | 0.0018 ± 0.0002     | 0.289 ± 0.284 | 0.0043 ± 0.0005   |
| 9. | Pb | HQ <sub>ing</sub>  | 0.071 ± 0.042 | 0.071 ± 0.042       | 0.071 ± 0.042 | 0.021 ± 0.004     |
|    |    | HQ <sub>derm</sub> | 0.001 ± 0.000 | 0.001 ± 0.000       | 0.001 ± 0.000 | 0.000 ± 4.14E-05  |
|    |    | HI                 | 0.072 ± 0.042 | 0.072 ± 0.042       | 0.072 ± 0.042 | 0.022 ± 0.005     |

1092 **Note:** Values are presented as mean ± SEM. HQ<sub>ing</sub> and HQ<sub>derm</sub> represent the hazard quotient associated with ingestion and dermal exposure  
 1093 pathways, respectively, whereas HI represents the hazard index obtained from the combined exposure pathways. An asterisk (\*) indicates a  
 1094 statistically significant difference between industrial and non-industrial regions ( $p < 0.05$ ). Values of HI > 1 indicate a potential non-  
 1095 carcinogenic health risk. Al: Aluminum; As: Arsenic; Cd: Cadmium; Co: Cobalt; Cr: Chromium; Cu: Copper; HI: Hazard Index; HQ<sub>derm</sub>: Hazard  
 1096 Quotient through Dermal Exposure; HQ<sub>ing</sub>: Hazard Quotient through Ingestion; Li: Lithium; Ni: Nickel; Pb: Lead; SEM: Standard Error of the  
 1097 Mean

#### 4.4.2 Carcinogenic risk assessment

##### 4.4.2.1 Spatial Distribution of Carcinogenic Health Risk of Adults in Industrial and Non-industrial region of Haryana

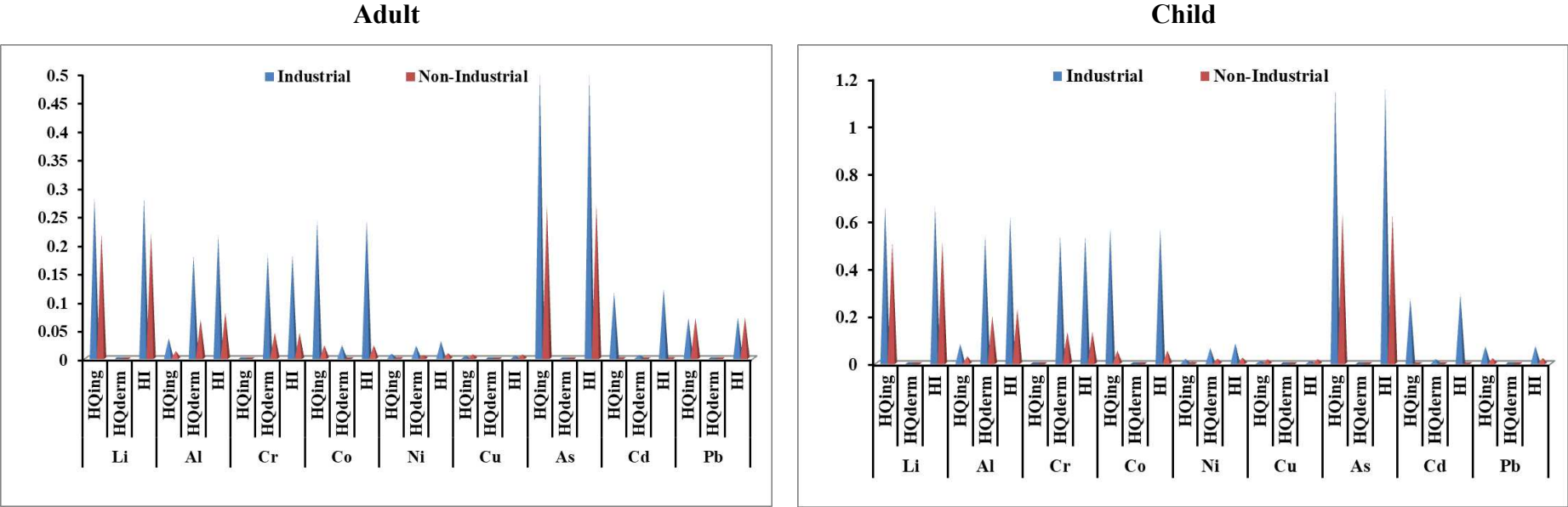
The carcinogenic risk associated with exposure to chromium, arsenic, and lead in canal water across different districts of Haryana is presented in Table 18. A significant difference ( $p < 0.05$ ) was observed only for chromium, with Rohtak exhibiting a significantly higher CR than Kurukshetra did, while the remaining districts showed no significant differences. The CR values for Cr ranged from  $7.61\text{E-}06 \pm 1.44\text{E-}06$  in Kurukshetra to  $7.46\text{E-}05 \pm 1.83\text{E-}05$  in Rohtak. In contrast, arsenic and lead did not exhibit significant spatial variation among the districts ( $p > 0.05$ ). For arsenic, the CR values ranged from  $9.98\text{E-}05 \pm 1.64\text{E-}06$  in Panipat to  $5.18\text{E-}04 \pm 4.00\text{E-}04$  in Hisar. Similarly, the CR values for lead varied from  $1.71\text{E-}07 \pm 3.87\text{E-}08$  in Jind to  $2.09\text{E-}06 \pm 2.05\text{E-}06$  in Hisar, with no statistically significant differences among the districts.

Chromium exhibited significant spatial variation ( $p < 0.05$ ), with Rohtak recording a significantly higher CR than Kurukshetra did, whereas the remaining districts showed no significant differences (Table 19). The CR values for Cr ranged from  $2.48\text{E-}07 \pm 4.69\text{E-}08$  in Kurukshetra to  $2.43\text{E-}06 \pm 5.98\text{E-}07$  in Rohtak. In contrast, no significant differences ( $p > 0.05$ ) were observed among the districts for arsenic (As) or lead (Pb). The CR values for As varied from  $1.27\text{E-}06 \pm 2.19\text{E-}08$  in Panipat to  $6.59\text{E-}06 \pm 5.09\text{E-}06$  in Hisar, whereas Pb ranged from  $6.70\text{E-}08 \pm 1.51\text{E-}08$  in Jind to  $8.16\text{E-}07 \pm 8.01\text{E-}07$  in Hisar (Table 19), with statistically comparable values across all the districts.

Significant spatial variation ( $p < 0.05$ ) was observed only for chromium, with Rohtak showing a significantly higher CI than Kurukshetra did, whereas the

1123 remaining districts showed no significant differences (Table 20). The CI values for Cr  
1124 ranged from  $7.86\text{E-}06 \pm 1.49\text{E-}06$  in Kurukshetra to  $7.7\text{E-}05 \pm 1.89\text{E-}05$  in Rohtak. In  
1125 contrast, there were no significant differences ( $p > 0.05$ ) among the districts for  
1126 arsenic or lead. The CI values for As ranged from  $1.01\text{E-}04 \pm 1.74\text{E-}06$  in Panipat to  
1127  $5.24\text{E-}04 \pm 4.05\text{E-}04$  in Hisar. Similarly, the CI values for Pb varied from  $2.38\text{E-}07 \pm$   
1128  $5.38\text{E-}08$  in Jind to  $2.9\text{E-}06 \pm 2.85\text{E-}06$  in Hisar, with statistically comparable values  
1129 across all the districts (Table 20).

1130



1131 **Fig. 11.** Comparative carcinogenic health risk through ingestion, dermal, and inhalation exposure pathways for adults and children in industrial  
1132 and non-industrial regions of Haryana, India

1133 **Table 18.** Cancer risk (CR) in adult associated with ingestion exposure to canal water containing heavy metals (Cr, As, Pb) across different  
1134 districts of Haryana  
1135

| Sl. No. | Metals | Attributes | Rohtak                             | Hisar                               | Sirsa                               | Jind                                | Panipat                             | Kurukshetra                        | Ambala                              |
|---------|--------|------------|------------------------------------|-------------------------------------|-------------------------------------|-------------------------------------|-------------------------------------|------------------------------------|-------------------------------------|
| 1.      | Cr     | Mean±SEM   | 7.46E-05±<br>1.83E-05 <sup>b</sup> | 3.74E-05±<br>3.49E-05 <sup>ab</sup> | 8.97E-06±<br>6.98E-07 <sup>ab</sup> | 1.02E-05±<br>1.74E-06 <sup>ab</sup> | 2.33E-05±<br>2.72E-07 <sup>ab</sup> | 7.61E-06±<br>1.44E-06 <sup>a</sup> | 9.53E-06±<br>3.38E-07 <sup>ab</sup> |
| 2.      | As     | Mean±SEM   | 1.38E-04±<br>7.62E-06 <sup>a</sup> | 5.18E-04±<br>4.00E-04 <sup>a</sup>  | 1.34E-<br>04±2.88E-05 <sup>a</sup>  | 1.16E-<br>04±2.39E-06 <sup>a</sup>  | 9.98E-<br>05±1.64E-06 <sup>a</sup>  | 1.14E-<br>04±2.23E-05 <sup>a</sup> | 1.39E-<br>04±2.34E-06 <sup>a</sup>  |
| 3.      | Pb     | Mean±SEM   | 6.11E-07±<br>2.05E-07 <sup>a</sup> | 2.09E-06±<br>2.05E-06 <sup>a</sup>  | 3.73E-07±<br>1.43E-07 <sup>a</sup>  | 1.71E-07±<br>3.87E-08 <sup>a</sup>  | 5.39E-07±<br>1.36E-08 <sup>a</sup>  | 2.24E-07±<br>5.51E-08 <sup>a</sup> | 1.84E-07±<br>5.8E-09 <sup>a</sup>   |

1136 **Note:** Values are presented as Mean ± SEM (Standard Error of the Mean). Different superscript lowercase letters (a-b) within the same row  
1137 indicate statistically significant differences among districts at  $P < 0.05$  (one-way ANOVA followed by Tukey's honestly significant difference  
1138 (HSD) post hoc test). Means sharing at least one common superscript letter are not significantly different ( $P > 0.05$ ). CR values represent the  
1139 carcinogenic risk associated with the ingestion exposure pathway and are dimensionless. As: Arsenic, CR: Carcinogenic Risk, Cr: Chromium,  
1140 HSD: Honestly Significant Difference, Mean ± SEM: Mean ± Standard Error of the Mean, Pb: Lead, SEM: Standard Error of the Mean

1141 **Table 19.** Cancer risk (CR) in adult associated with dermal exposure to canal water containing heavy metals (Cr, As, Pb) across different  
1142 districts of Haryana  
1143

| Sl. No. | Metals | Attributes | Rohtak                             | Hisar                               | Sirsa                               | Jind                                 | Panipat                             | Kurukshetra                        | Ambala                             |
|---------|--------|------------|------------------------------------|-------------------------------------|-------------------------------------|--------------------------------------|-------------------------------------|------------------------------------|------------------------------------|
| 1.      | Cr     | Mean±SEM   | 2.43E-06±<br>5.98E-07 <sup>b</sup> | 1.22E-06±<br>1.14E-06 <sup>ab</sup> | 2.92E-07±<br>2.28E-08 <sup>ab</sup> | 3.32E-07±<br>5.69E-08 <sup>a b</sup> | 7.59E-07±<br>8.86E-09 <sup>ab</sup> | 2.48E-07±<br>4.69E-08 <sup>a</sup> | 3.11E-07±<br>1.1E-08 <sup>ab</sup> |
| 2.      | As     | Mean±SEM   | 1.75E-06±<br>9.7E-08 <sup>a</sup>  | 6.59E-06±<br>5.09E-06 <sup>a</sup>  | 1.71E-06±<br>3.67E-07 <sup>a</sup>  | 1.48E-06±<br>2.94E-08 <sup>a</sup>   | 1.27E-06±<br>2.19E-08 <sup>a</sup>  | 1.45E-06±<br>2.86E-07 <sup>a</sup> | 1.77E-06±<br>3.02E-08 <sup>a</sup> |
| 3.      | Pb     | Mean±SEM   | 2.39E-07±<br>8.03E-08 <sup>a</sup> | 8.16E-07±<br>8.01E-07 <sup>a</sup>  | 1.46E-07±<br>5.61E-08 <sup>a</sup>  | 6.7E-08±<br>1.51E-08 <sup>a</sup>    | 2.11E-07±<br>5.31E-09 <sup>a</sup>  | 8.76E-08±<br>2.16E-08 <sup>a</sup> | 7.22E-08±<br>2.27E-09 <sup>a</sup> |

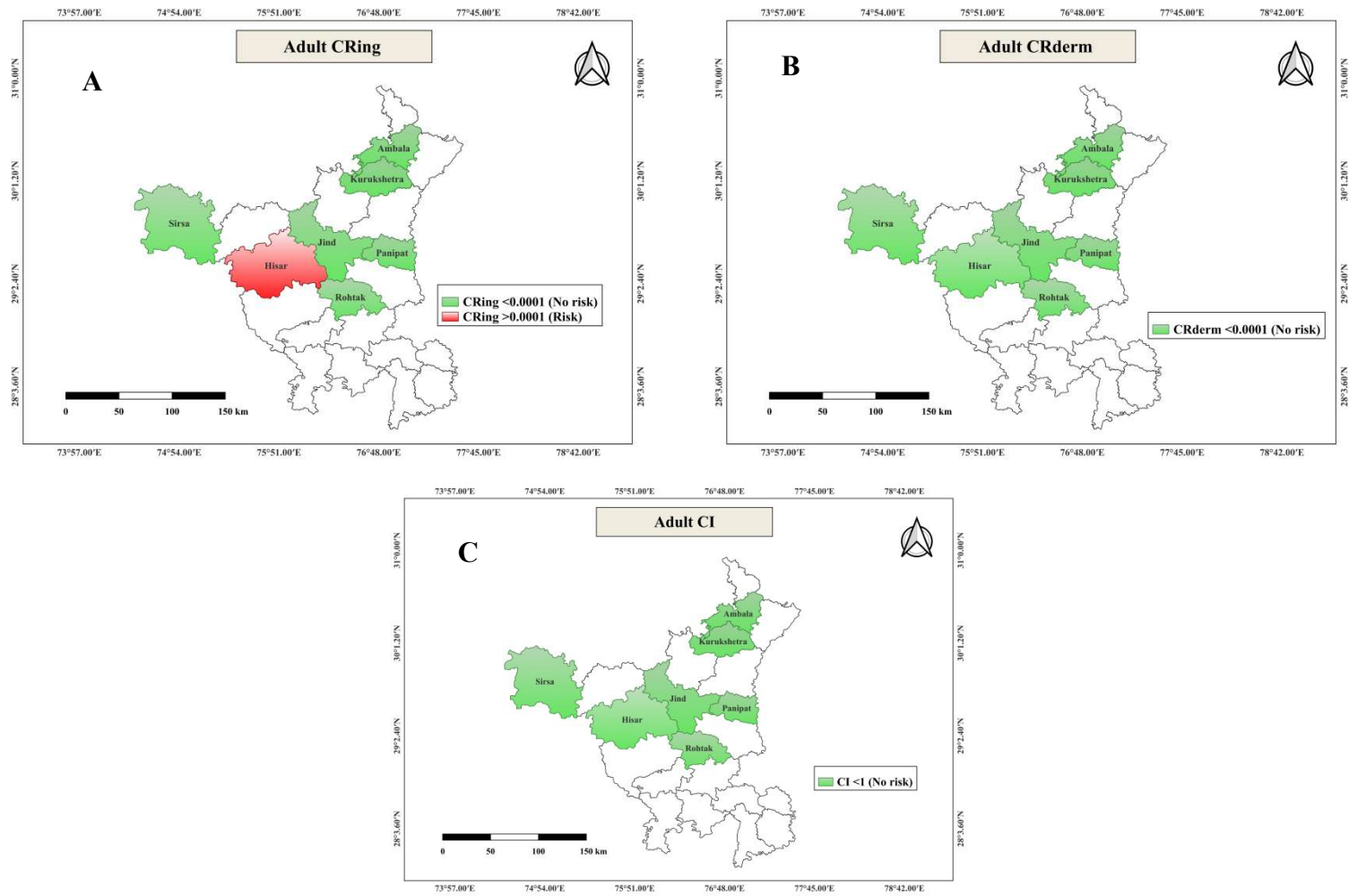
1144 **Note:** Values are presented as Mean ± SEM (Standard Error of the Mean). Different superscript lowercase letters (a-b) within the same row  
1145 indicate statistically significant differences among districts at  $P < 0.05$  (one-way ANOVA followed by Tukey's honestly significant difference

1146 (HSD) post hoc test). Means sharing at least one common superscript letter are not significantly different ( $P > 0.05$ ). CR values represent the  
 1147 carcinogenic risk associated with the dermal exposure pathway and are dimensionless. As: Arsenic, CR: Carcinogenic Risk, Cr: Chromium,  
 1148 HSD: Honestly Significant Difference, Mean  $\pm$  SEM: Mean  $\pm$  Standard Error of the Mean, Pb: Lead, SEM: Standard Error of the Mean

1149 **Table 20.** Total cancer index (CI) in adult due exposure to canal water containing heavy metals (Cr, As, Pb) across different districts of Haryana  
 1150

| Sl. No. | Metals | Attributes     | Rohtak                                       | Hisar                                        | Sirsa                                        | Jind                                         | Panipat                                      | Kurukshetra                              | Ambala                                       |
|---------|--------|----------------|----------------------------------------------|----------------------------------------------|----------------------------------------------|----------------------------------------------|----------------------------------------------|------------------------------------------|----------------------------------------------|
| 1.      | Cr     | Mean $\pm$ SEM | 7.7E-05 $\pm$<br>1.89E-05 <sup>b</sup>       | 3.87E-05 $\pm$<br>3.61E-05 <sup>ab</sup>     | 9.26E-06 $\pm$<br>7.21E-07 <sup>ab</sup>     | 1.05E-05 $\pm$<br>1.8E-06 <sup>ab</sup>      | 2.4E-05 $\pm$<br>2.81E-07 <sup>ab</sup>      | 7.86E-06 $\pm$<br>1.49E-06 <sup>a</sup>  | 9.84E-06 $\pm$<br>3.49E-07 <sup>ab</sup>     |
| 2.      | As     | Mean $\pm$ SEM | 1.39E-<br>04 $\pm$ 7.71E-<br>06 <sup>a</sup> | 5.24E-<br>04 $\pm$ 4.05E-<br>04 <sup>a</sup> | 1.36E-<br>04 $\pm$ 2.92E-<br>05 <sup>a</sup> | 1.17E-<br>04 $\pm$ 2.34E-<br>06 <sup>a</sup> | 1.01E-<br>04 $\pm$ 1.74E-<br>06 <sup>a</sup> | 1.15E-<br>04 $\pm$ 2.27E-05 <sup>a</sup> | 1.41E-<br>04 $\pm$ 2.40E-<br>06 <sup>a</sup> |
| 3.      | Pb     | Mean $\pm$ SEM | 8.5E-07 $\pm$<br>2.85E-07 <sup>a</sup>       | 2.9E-06 $\pm$<br>2.85E-06 <sup>a</sup>       | 5.19E-07 $\pm$<br>1.99E-07 <sup>a</sup>      | 2.38E-07 $\pm$<br>5.38E-08 <sup>a</sup>      | 7.51E-07 $\pm$<br>1.89E-08 <sup>a</sup>      | 3.11E-07 $\pm$<br>7.66E-08 <sup>a</sup>  | 2.56E-07 $\pm$<br>8.08E-09 <sup>a</sup>      |

1151 **Note:** Values are presented as Mean  $\pm$  SEM (Standard Error of the Mean). Different superscript lowercase letters (a-b) within the same row  
 1152 indicate statistically significant differences among districts at  $P < 0.05$  (one-way ANOVA followed by Tukey's honestly significant difference  
 1153 (HSD) post hoc test). Means sharing at least one common superscript letter are not significantly different ( $P > 0.05$ ). CI values represent the total  
 1154 cancer index associated with combined exposure to Cr, As, and Pb through canal water and are dimensionless. As: Arsenic, CI: Cancer Index, Cr:  
 1155 Chromium, HSD: Honestly Significant Difference, Mean  $\pm$  SEM: Mean  $\pm$  Standard Error of the Mean, Pb: Lead, SEM: Standard Error of the  
 1156 Mean



1158 **Fig. 12 (A-C).** Spatial distribution of adult carcinogenic risk indices in canal water across the selected districts of Haryana, India: (A) Cancer  
1159 Risk through ingestion ( $CR_{ing}$ ), (B) Cancer Risk through dermal exposure ( $CR_{derm}$ ), and (C) Cancer Index (CI). Green indicates no acceptable  
1160 carcinogenic risk, whereas red indicates potential carcinogenic risk, according to USEPA guidelines

1161 Graphical representation of the carcinogenic risk assessment of various heavy metals  
1162 in adults in different districts of Haryana. The spatial distribution of carcinogenic risk  
1163 in adults across different districts of Haryana is illustrated in Fig. 12. The  $CR_{ing}$  map  
1164 revealed that Hisar was the only district categorized as a risk zone ( $CR_{ing} \geq 0.0001$ ).  
1165 In contrast, Rohtak, Sirsa, Jind, Panipat, Kurukshetra, and Ambala remained in the  
1166 no-risk category ( $CR_{ing} < 0.0001$ ). In contrast, the  $CR_{derm}$  map indicated that all  
1167 districts were classified within the no-risk category ( $CR_{derm} < 0.0001$ ), with no district  
1168 exceeding the carcinogenic risk threshold through dermal exposure. Similarly, the  
1169 total cancer index (CI) map revealed that all the districts remained below the  
1170 threshold value ( $CI < 1$ ), indicating that the combined assessment of the selected  
1171 heavy metals revealed no overall carcinogenic risk.

#### **4.4.2.2 Spatial Distribution of Carcinogenic Health Risk of Child in Industrial and Non-industrial region of Haryana**

A significant difference ( $p < 0.05$ ) was observed only for chromium, with Rohtak exhibiting a significantly higher CR than Kurukshetra did, whereas the remaining districts showed no significant differences. The CR values for Cr ranged from  $1.78\text{E-}05 \pm 3.36\text{E-}06$  in Kurukshetra to  $0.000174 \pm 4.28\text{E-}05$  in Rohtak (Table 21). No significant spatial variation ( $p > 0.05$ ) was observed for arsenic or lead. The CR values for As ranged from  $2.33\text{E-}04 \pm 4.02\text{E-}06$  in Panipat to  $1.21\text{E-}03 \pm 9.32\text{E-}04$  in Hisar. Similarly, the Pb values varied from  $3.99\text{E-}07 \pm 9.02\text{E-}08$  in Jind to  $4.87\text{E-}06 \pm 4.77\text{E-}06$  in Hisar, with statistically comparable values among all the districts (Table 21).

Chromium showed significant spatial variation ( $p < 0.05$ ), with Rohtak having a significantly higher CR than Kurukshetra had, while no significant differences were observed among the remaining districts. The CR values for Cr ranged from  $7.33\text{E-}07 \pm 1.38\text{E-}07$  in Kurukshetra to  $7.18\text{E-}06 \pm 1.76\text{E-}06$  in Rohtak (Table 22). No significant differences ( $p > 0.05$ ) were detected among the districts for arsenic or lead. The CR values for As ranged from  $3.76\text{E-}06 \pm 6.47\text{E-}08$  in Panipat to  $1.94\text{E-}05 \pm 1.50\text{E-}05$  in Hisar, whereas Pb ranged from  $1.98\text{E-}07 \pm 4.46\text{E-}08$  in Jind to  $2.41\text{E-}06 \pm 2.36\text{E-}06$  in Hisar (Table 22).

Significant spatial variation ( $p < 0.05$ ) was observed only for chromium, with Rohtak showing a significantly higher CI than Kurukshetra did, whereas the remaining districts showed no significant differences. The CI values for Cr ranged from  $1.85\text{E-}05 \pm 3.50\text{E-}06$  in Kurukshetra to  $0.000181 \pm 4.45\text{E-}05$  in Rohtak (Table 23). No significant spatial variation ( $p > 0.05$ ) was observed for arsenic or lead. The CI values for As ranged from  $2.33\text{E-}04 \pm 4.02\text{E-}06$  in Panipat to  $1.21\text{E-}03 \pm 9.32\text{E-}04$

1197 in Hisar. Similarly, the Pb concentrations ranged from  $5.97\text{E-}07 \pm 1.35\text{E-}07$  in Jind to  
1198  $7.27\text{E-}06 \pm 7.14\text{E-}06$  in Hisar (Table 23), with no statistically significant differences  
1199 among the districts.

1200 **Table 21.** Cancer risk (CR) in child associated with ingestion exposure to canal water containing heavy metals (Cr, As, Pb) across different  
1201 districts of Haryana  
1202

| Sl.No. | Metals | Attributes        | Rohtak                                 | Hisar                                  | Sirsa                                  | Jind                                   | Panipat                                | Kurukshetra                        | Ambala                                 |
|--------|--------|-------------------|----------------------------------------|----------------------------------------|----------------------------------------|----------------------------------------|----------------------------------------|------------------------------------|----------------------------------------|
| 1.     | Cr     | Mean±SEM<br>(ppm) | 0.000174±<br>4.28E-05 <sup>b</sup>     | 8.73E-05±<br>8.15E-05 <sup>ab</sup>    | 2.09E-05±<br>1.63E-06 <sup>ab</sup>    | 2.38E-05±<br>4.07E-06 <sup>ab</sup>    | 5.43E-05±<br>6.34E-07 <sup>ab</sup>    | 1.78E-05±<br>3.36E-06 <sup>a</sup> | 2.22E-05±<br>7.89E-07 <sup>ab</sup>    |
| 2.     | As     | Mean±SEM          | 3.21E-<br>04±1.78E-<br>05 <sup>a</sup> | 1.21E-<br>03±9.32E-<br>04 <sup>a</sup> | 3.12E-<br>04±6.73E-<br>05 <sup>a</sup> | 2.71E-<br>04±5.38E-<br>06 <sup>a</sup> | 2.33E-<br>04±4.02E-<br>06 <sup>a</sup> | 2.65E-<br>04±5.23E-05 <sup>a</sup> | 3.24E-<br>04±5.53E-<br>06 <sup>a</sup> |
| 3.     | Pb     | Mean±SEM          | 1.43E-06±<br>4.78E-07 <sup>a</sup>     | 4.87E-06±<br>4.77E-06 <sup>a</sup>     | 8.71E-07±<br>3.34E-07 <sup>a</sup>     | 3.99E-07±<br>9.02E-08 <sup>a</sup>     | 1.26E-06±<br>3.16E-08 <sup>a</sup>     | 5.22E-07±<br>1.28E-07 <sup>a</sup> | 4.3E-07±<br>1.35E-08 <sup>a</sup>      |

1203 **Note:** Values are presented as Mean ± SEM (Standard Error of the Mean). Different superscript lowercase letters (a-b) within the same row  
1204 indicate statistically significant differences among districts at  $P < 0.05$ . Means sharing at least one common superscript letter are not  
1205 significantly different. CR values are dimensionless. As: Arsenic, CR: Carcinogenic Risk, Cr: Chromium, Mean ± SEM: Mean ± Standard Error  
1206 of the Mean, Pb: Lead, SEM: Standard Error of the Mean

1207 **Table 22.** Cancer risk (CR) in child associated with dermal exposure to canal water containing heavy metals (Cr, As, Pb) across different  
1208 districts of Haryana  
1209

| Sl.No. | Metals | Attributes | Rohtak                             | Hisar                              | Sirsa                               | Jind                                | Panipat                             | Kurukshetra                        | Ambala                              |
|--------|--------|------------|------------------------------------|------------------------------------|-------------------------------------|-------------------------------------|-------------------------------------|------------------------------------|-------------------------------------|
| 1.     | Cr     | Mean±SEM   | 7.18E-06±<br>1.76E-06 <sup>b</sup> | 3.6E-06±<br>3.36E-06 <sup>ab</sup> | 8.63E-07±<br>6.72E-08 <sup>ab</sup> | 9.81E-07±<br>1.68E-07 <sup>ab</sup> | 2.24E-06±<br>2.61E-08 <sup>ab</sup> | 7.33E-07±<br>1.38E-07 <sup>a</sup> | 9.17E-07±<br>3.26E-08 <sup>ab</sup> |
| 2.     | As     | Mean±SEM   | 5.17E-06±<br>2.86E-07 <sup>a</sup> | 1.94E-05±<br>1.5E-05 <sup>a</sup>  | 5.03E-06±<br>1.08E-06 <sup>a</sup>  | 4.36E-06±<br>8.67E-08 <sup>a</sup>  | 3.76E-06±<br>6.47E-08 <sup>a</sup>  | 4.27E-06±<br>8.43E-07 <sup>a</sup> | 5.22E-06±<br>8.9E-08 <sup>a</sup>   |
| 3.     | Pb     | Mean±SEM   | 7.06E-07±<br>2.37E-07 <sup>a</sup> | 2.41E-06±<br>2.36E-06 <sup>a</sup> | 4.31E-07±<br>1.65E-07 <sup>a</sup>  | 1.98E-07±<br>4.46E-08 <sup>a</sup>  | 6.23E-07±<br>1.57E-08 <sup>a</sup>  | 2.58E-07±<br>6.36E-08 <sup>a</sup> | 2.13E-07±<br>6.7E-09 <sup>a</sup>   |

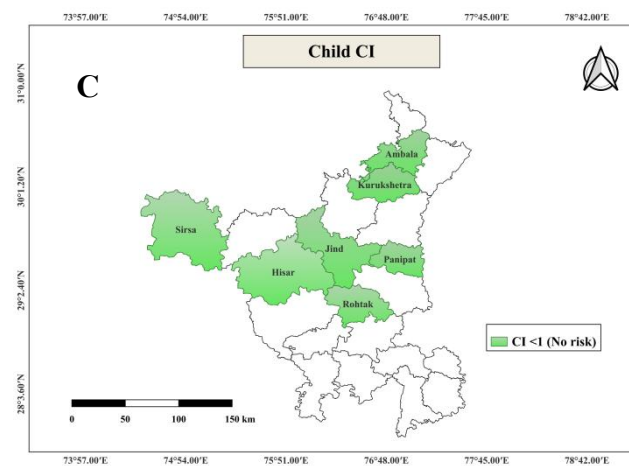
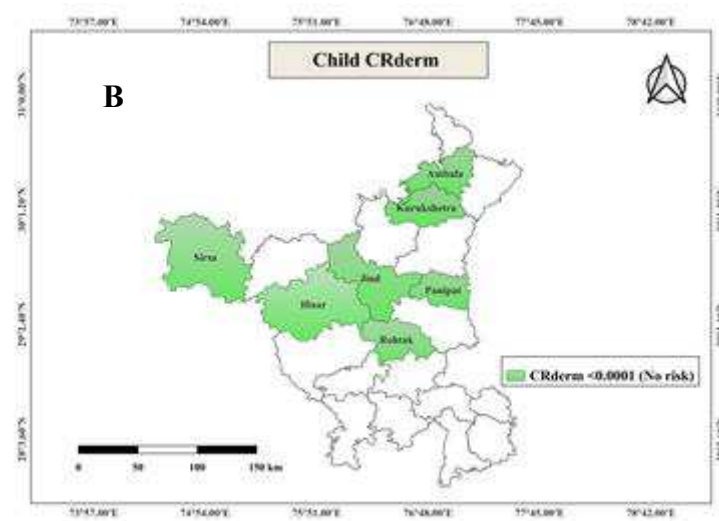
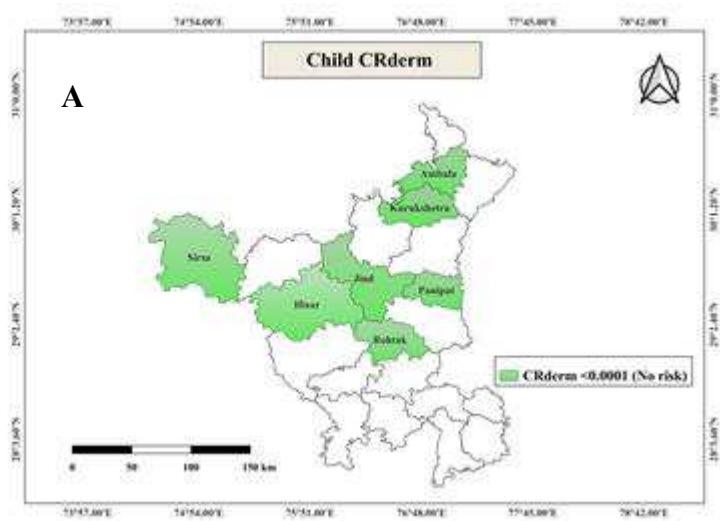
1210 **Notes:** Values are presented as Mean ± SEM (Standard Error of the Mean). Different superscript lowercase letters (a-b) within the same row  
1211 indicate statistically significant differences among districts at  $P < 0.05$ . Means sharing at least one common superscript letter are not

significantly different. CR values are dimensionless. As: Arsenic, CR: Carcinogenic Risk, Cr: Chromium, Mean  $\pm$  SEM: Mean  $\pm$  Standard Error of the Mean, Pb: Lead, SEM: Standard Error of the Mean

**Table 23.** Total cancer index (CI) in child due exposure to canal water containing heavy metals (Cr, As, Pb) across different districts of Haryana

| Sl.No. | Metals | Attributes     | Rohtak                                       | Hisar                                        | Sirsa                                        | Jind                                         | Panipat                                      | Kurukshetra                              | Ambala                                       |
|--------|--------|----------------|----------------------------------------------|----------------------------------------------|----------------------------------------------|----------------------------------------------|----------------------------------------------|------------------------------------------|----------------------------------------------|
| 1.     | Cr     | Mean $\pm$ SEM | 0.000181 $\pm$<br>4.45E-05 <sup>b</sup>      | 9.09E-05 $\pm$<br>8.49E-05 <sup>ab</sup>     | 2.18E-05 $\pm$<br>1.7E-06 <sup>ab</sup>      | 2.48E-05 $\pm$<br>4.24E-06 <sup>ab</sup>     | 5.65E-05 $\pm$<br>6.6E-07 <sup>ab</sup>      | 1.85E-05 $\pm$<br>3.5E-06 <sup>a</sup>   | 2.32E-05 $\pm$<br>8.22E-07 <sup>ab</sup>     |
| 2.     | As     | Mean $\pm$ SEM | 3.21E-<br>04 $\pm$ 1.78E-<br>05 <sup>a</sup> | 1.21E-<br>03 $\pm$ 9.32E-<br>04 <sup>a</sup> | 3.12E-<br>04 $\pm$ 6.73E-<br>05 <sup>a</sup> | 2.71E-<br>04 $\pm$ 5.38E-<br>06 <sup>a</sup> | 2.33E-<br>04 $\pm$ 4.02E-<br>06 <sup>a</sup> | 2.65E-<br>04 $\pm$ 5.23E-05 <sup>a</sup> | 3.24E-<br>04 $\pm$ 5.53E-<br>06 <sup>a</sup> |
| 3.     | Pb     | Mean $\pm$ SEM | 2.13E-06 $\pm$<br>7.15E-07 <sup>a</sup>      | 7.27E-06 $\pm$<br>7.14E-06 <sup>a</sup>      | 1.3E-06 $\pm$<br>5E-07 <sup>a</sup>          | 5.97E-07 $\pm$<br>1.35E-07 <sup>a</sup>      | 1.88E-06 $\pm$<br>4.73E-08 <sup>a</sup>      | 7.8E-07 $\pm$<br>1.92E-07 <sup>a</sup>   | 6.43E-07 $\pm$<br>2.02E-08 <sup>a</sup>      |

**Notes:** Values are presented as Mean  $\pm$  SEM (Standard Error of the Mean). Different superscript lowercase letters (a-b) within the same row indicate statistically significant differences among districts at  $P < 0.05$ . Means sharing at least one common superscript letter are not significantly different. CI values are dimensionless. As: Arsenic, CI: Cancer Index, Cr: Chromium, Mean  $\pm$  SEM: Mean  $\pm$  Standard Error of the Mean, Pb: Lead, SEM: Standard Error of the Mean



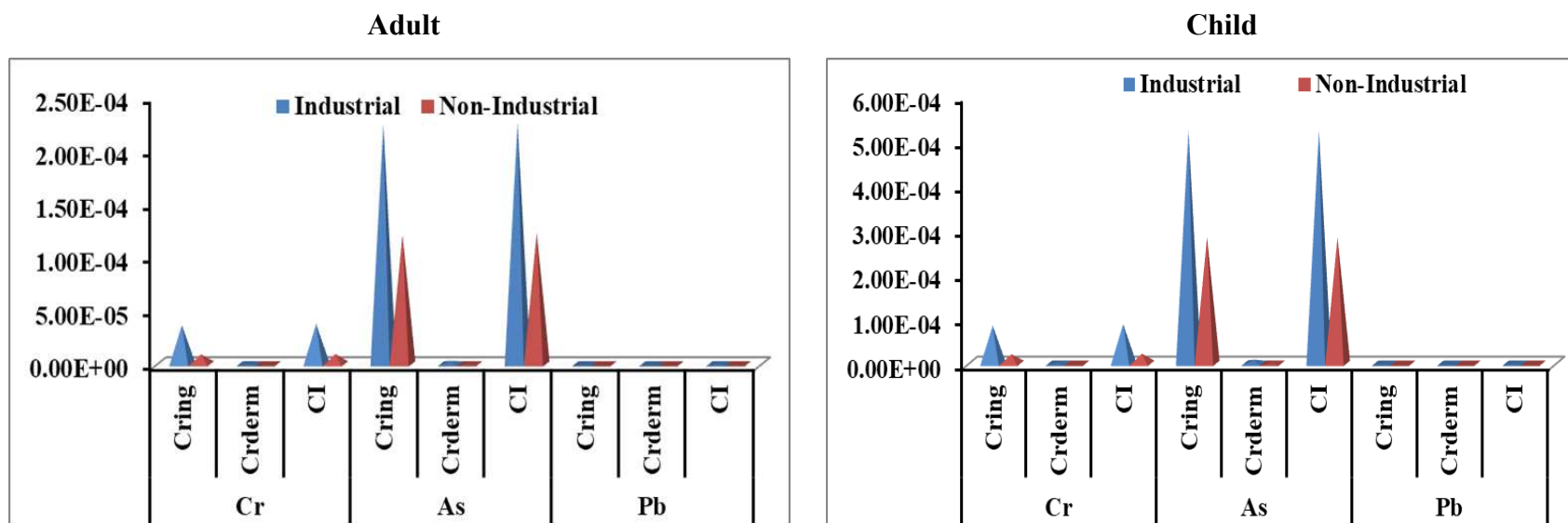
1220 **Fig. 13 (A-C).** Spatial distribution of carcinogenic health risk indices for children associated with exposure to canal water in the selected districts  
1221 of Haryana, India: (A) Cancer Risk through ingestion ( $CR_{ing}$ ), (B) Cancer Risk through dermal exposure ( $CR_{derm}$ ), and (C) Cancer Index (CI).  
1222 Green indicates no/acceptable carcinogenic risk, whereas red indicates potential carcinogenic risk, according to USEPA guidelines  
1223 Graphical representation of carcinogenic risk assessment of various heavy metals in Children in different districts of Haryana. Fig. 13 presents  
1224 the spatial distribution of carcinogenic risk in children across different districts of Haryana. The  $CR_{ing}$  map identified Rohtak, Hisar, Sirsa, and  
1225 Ambala as risk zones ( $CR_{ing} \geq 0.0001$ ), whereas Jind, Panipat, and Kurukshetra remained within the no-risk category ( $CR_{ing} < 0.0001$ ). Among  
1226 the districts, Hisar showed the highest spatial distribution of carcinogenic risk through ingestion, followed by Rohtak, while Jind, Panipat, and  
1227 Kurukshetra had comparatively lower risk levels. In contrast, the  $CR_{derm}$  map classified all districts within the no-risk category ( $CR_{derm} <$   
1228  $0.0001$ ), indicating no apparent carcinogenic risk through dermal exposure. Similarly, the total cancer index (CI) map showed that all districts  
1229 remained below the threshold value ( $CI < 1$ ), indicating no overall carcinogenic risk in children based on the combined contribution of the  
1230 assessed heavy metals.

1231 The comparative assessment revealed a generally higher carcinogenic risk in the industrial  
1232 region than in the nonindustrial region for both adults and children. Among adults, the Cr  
1233 concentration significantly differed across regions, with the ingestion-related CR increasing from  
1234  $8.92\text{E-}06 \pm 7.84\text{E-}07$  in the nonindustrial region to  $3.62\text{E-}05 \pm 1.05\text{E-}05$  in the industrial region,  
1235 whereas the dermal CR increased from  $2.91\text{E-}07 \pm 2.56\text{E-}08$  to  $1.18\text{E-}06 \pm 3.42\text{E-}07$ .  
1236 Consequently, the CI for Cr was higher in the industrial region ( $3.74\text{E-}05 \pm 1.08\text{E-}05$ ) than in the  
1237 nonindustrial region ( $9.21\text{E-}06 \pm 8.09\text{E-}07$ ). For As, the adult CI values ranged from  $2.26\text{E-}04 \pm$   
1238  $1.01\text{E-}04$  and  $1.23\text{E-}04 \pm 1.18\text{E-}05$  in industrial and nonindustrial regions, respectively, whereas  
1239 Pb had lower CI values of  $1.19\text{E-}06 \pm 7\text{E-}07$  and  $3.56\text{E-}07 \pm 7.47\text{E-}08$ , respectively. A similar  
1240 pattern was observed among children, with Cr showing a higher ingestion-related CR in the  
1241 industrial region ( $8.45\text{E-}05 \pm 2.45\text{E-}05$ ) than in the nonindustrial region ( $2.08\text{E-}05 \pm 1.83\text{E-}06$ ),  
1242 accompanied by a higher dermal CR ( $3.48\text{E-}06 \pm 1.01\text{E-}06$  vs  $8.59\text{E-}07 \pm 7.54\text{E-}08$ ). It had the  
1243 highest CI among children, with values of  $5.22\text{E-}04 \pm 2.33\text{E-}04$  and  $2.83\text{E-}04 \pm 2.72\text{E-}05$  in  
1244 industrial and nonindustrial regions, respectively. Pb had the lowest overall carcinogenic risk,  
1245 with CI values of  $2.98\text{E-}06 \pm 1.75\text{E-}06$  in industrial children and  $8.93\text{E-}07 \pm 1.87\text{E-}07$  in  
1246 nonindustrial children. Overall, the results indicated higher carcinogenic risk indices in industrial  
1247 regions and consistently greater risk estimates among children than among adults, with As  
1248 contributing the highest CI and Pb the lowest across the evaluated groups, as summarized in  
1249 Table 24.

**Table 24.** Comparative assessment of carcinogenic risk and total cancer index associated with ingestion and dermal exposure to Cr, As, and Pb in adults and children from industrial and non-industrial regions of Haryana, India

| Sl. No. | Heavy metals | Attributes | Adult                                 |                                              | Child                                 |                                              |
|---------|--------------|------------|---------------------------------------|----------------------------------------------|---------------------------------------|----------------------------------------------|
|         |              |            | Industrial Region<br>(Mean $\pm$ SEM) | Non-Industrial<br>Region<br>(Mean $\pm$ SEM) | Industrial Region<br>(Mean $\pm$ SEM) | Non-Industrial<br>Region<br>(Mean $\pm$ SEM) |
| 1.      | Cr           | CRing      | 3.62E-05 $\pm$ 1.05E-05               | 8.92E-06 $\pm$ 7.84E-07*                     | 8.45E-05 $\pm$ 2.45E-05               | 2.08E-05 $\pm$ 1.83E-06*                     |
|         |              | CRderm     | 1.18E-06 $\pm$ 3.42E-07               | 2.91E-07 $\pm$ 2.56E-08*                     | 3.48E-06 $\pm$ 1.01E-06               | 8.59E-07 $\pm$ 7.54E-08*                     |
|         |              | CI         | 3.74E-05 $\pm$ 1.08E-05               | 9.21E-06 $\pm$ 8.09E-07*                     | 8.8E-05 $\pm$ 2.55E-05                | 2.17E-05 $\pm$ 1.9E-06                       |
| 2.      | As           | CRing      | 2.24E-04 $\pm$ 9.97E-05               | 1.21E-04 $\pm$ 1.17E-05                      | 5.22E-04 $\pm$ 2.33E-04               | 2.83E-04 $\pm$ 2.72E-05                      |
|         |              | CRderm     | 2.85E-06 $\pm$ 1.27E-06               | 1.54E-06 $\pm$ 1.49E-07                      | 8.4E-06 $\pm$ 3.75E-06                | 4.55E-06 $\pm$ 4.38E-07                      |
|         |              | CI         | 2.26E-04 $\pm$ 1.01E-04               | 1.23E-04 $\pm$ 1.18E-05                      | 5.22E-04 $\pm$ 2.33E-04               | 2.83E-04 $\pm$ 2.72E-05                      |
| 3.      | Pb           | CRing      | 8.55E-07 $\pm$ 5.03E-07               | 2.56E-07 $\pm$ 5.37E-08                      | 1.99E-06 $\pm$ 1.17E-06               | 5.97E-07 $\pm$ 1.25E-07                      |
|         |              | CRderm     | 3.35E-07 $\pm$ 1.97E-07               | 1E-07 $\pm$ 2.1E-08                          | 9.87E-07 $\pm$ 5.81E-07               | 2.96E-07 $\pm$ 6.2E-08                       |
|         |              | CI         | 1.19E-06 $\pm$ 7E-07                  | 3.56E-07 $\pm$ 7.47E-08                      | 2.98E-06 $\pm$ 1.75E-06               | 8.93E-07 $\pm$ 1.87E-07                      |

**Note:** Values are presented as mean  $\pm$  SEM. Carcinogenic risk was estimated for ingestion and dermal exposure pathways, while the total cancer index (CI) represents the combined carcinogenic risk associated with the evaluated exposure pathways. An asterisk (\*) indicates a statistically significant difference between industrial and non-industrial regions ( $p < 0.05$ ). CR values and CI are dimensionless. As: Arsenic; CI: Cancer Index; Cr: Chromium; CRderm: Carcinogenic Risk through Dermal Exposure; CRing: Carcinogenic Risk through Ingestion; Pb: Lead; SEM: Standard Error of the Mean



1264 **Fig. 14.** Comparative carcinogenic risk through ingestion, dermal absorption, and inhalation exposure pathways for Chromium,  
 1265 Arsenic, and Lead in industrial and non-industrial regions of Haryana, India, showing the estimated carcinogenic risks for adults and  
 1266 children

## 5 Discussion

The present study provides an integrated assessment of heavy metal contamination in canal water across industrial and nonindustrial districts of Haryana, combining pollution indices, multivariate statistical analyses, and human health risk assessment. The observed spatial variability indicates that differences in anthropogenic inputs and local environmental conditions are likely to influence metal distributions [81]. The findings also highlight potential contamination and health-risk concerns, emphasizing the need for systematic monitoring and targeted management strategies to protect canal water quality and public health [48].

The spatial distribution of heavy metals showed considerable heterogeneity across Haryana's canal-water network, although statistically significant districtwise variation was observed only for Li and Al. The pronounced spatial differentiation of Al, particularly its elevated concentration in Panipat ( $2.309 \pm 0.041$  ppm), suggests that its occurrence may be more responsive to localized inputs and site-specific environmental conditions [82]. In contrast, the highest Li concentration was observed in Hisar ( $0.025 \pm 0.006$  ppm), indicating a spatial pattern distinct from that of Al. Similar spatial heterogeneity of heavy metals in surface-water systems has been reported in other regions, where variations in metal concentrations were associated with differences in land use, anthropogenic activities, hydrological conditions [83], and local geochemical characteristics [81]. Previous investigations have also shown that individual metals can exhibit distinct spatial patterns within the same aquatic system because differences in source characteristics, water chemistry, geological interactions, and hydrological connectivity control their mobility and distribution [84]. The absence of statistically significant districtwise differences for Cr, Co, Ni, Cu, As, Cd, and Pb, despite the localized maxima for Cr in Rohtak; Cu in Sirsa; and Co, Ni, As, Cd, and Pb in Hisar, suggests that these metals may have been

1290 influenced by relatively diffuse inputs or by hydrological mixing within the canal network rather  
1291 than by a single dominant localized source. Comparable patterns of limited spatial differentiation  
1292 for heavy metals have been reported in surface-water systems where dilution, hydrological  
1293 mixing, and diffuse anthropogenic inputs contributed to relatively homogeneous metal  
1294 distributions across sampling locations [85]. The contrasting spatial maxima observed among  
1295 individual metals may further indicate differences in their sources, environmental mobility, and  
1296 persistence within the canal system. Studies from Indian river and canal systems have similarly  
1297 reported metal-specific spatial enrichment, with different metals showing localized maxima in  
1298 areas influenced by industrial activities, urban discharge, agricultural runoff, or other site-  
1299 specific sources [46].

1300       The relatively elevated concentrations of Co, Ni, As, Cd, and Pb in Hisar, along with higher  
1301 Cr concentrations in Rohtak and Cu concentrations in Sirsa, may therefore reflect differences in  
1302 the intensity and type of anthropogenic inputs among districts. Previous studies have identified  
1303 industrial effluents, municipal wastewater, agricultural runoff, atmospheric deposition, and other  
1304 anthropogenic activities as important contributors to heavy metal inputs into freshwater systems  
1305 [86]. However, concentration patterns alone cannot assign sources, as similar metal distributions  
1306 may also arise from natural weathering and background geochemical processes. Geological  
1307 weathering and hydrogeochemical conditions have been widely documented as contributors to  
1308 heavy metal occurrence in freshwater systems, particularly where water interacts with metal-  
1309 bearing geological materials [87]. Accordingly, the district-specific patterns observed here  
1310 should be interpreted as reflecting a combination of potentially variable natural and  
1311 anthropogenic influences rather than a single source.

A comparison with earlier investigations from Haryana provides an important regional perspective. Previous studies of the Yamuna and associated canal systems in Haryana have reported substantial heavy metal contamination and, in some locations, concentrations exceeding permissible limits, particularly in areas receiving industrial and domestic wastewater inputs [11]. In contrast, all the heavy metal concentrations measured in the present canal-water samples remained below their respective standard permissible values. These differences may reflect variations in sampling locations, canal connectivity, hydrological conditions, contaminant loading, sampling periods, or changes in wastewater management practices. Temporal and spatial differences in heavy metal concentrations have likewise been reported in freshwater systems, indicating that contamination levels may vary with hydrological conditions, seasonal inputs, and changes in anthropogenic loading [88]. Thus, although the present concentrations did not exceed the guidelines, localized enrichment of specific metals remains environmentally relevant [89].

The observed pattern also suggests that the absence of statistically significant regional differences for most metals should not necessarily be interpreted as an absence of anthropogenic influence. Localized maxima may indicate episodic or diffuse inputs that are not consistent enough across districts to produce statistically significant differences [44]. Similar observations have been reported in aquatic systems where measurable metal enrichment occurred without significant spatial differences, reflecting the combined effects of dilution, mixing, variable source inputs, and natural background concentrations [90]. This distinction is particularly important for canal systems, where continuous water movement and mixing can redistribute contaminants over considerable distances and thereby reduce sharp concentration gradients between sampling locations. Hydrological transport and mixing have been recognized as

important processes that control the spatial redistribution of dissolved and particulate-associated metals in flowing freshwater systems [91].

Overall, the results indicate that heavy metal occurrence in Haryana canal water is spatially heterogeneous but remains within the applicable standard values during the sampling period. The significant variability observed for Li and Al, together with localized enrichment of Cr, Cu, Co, Ni, As, Cd, and Pb in specific districts, indicates that metal-specific monitoring is warranted rather than relying solely on regional mean concentrations [92].

The results of the radar plot analysis revealed the spatial heterogeneity of the heavy metals across the canal network, revealing that the individual metal distributions were site specific rather than uniform. Li exhibited relatively high levels in Hisar, followed by those in Rohtak and Ambala, whereas its lowest concentration occurred in Sirsa [48]. This spatial pattern may reflect differences in local geological characteristics, mineral weathering, and water–rock interactions that influence Li mobility in aquatic systems. Comparable spatial variability of trace metals has been reported in canal-water systems, where differences in metal concentrations among locations have been associated with variations in local hydrogeochemical conditions and anthropogenic influences [93]. The Al profiles of Panipat and Rohtak were particularly pronounced, with those of Panipat reaching  $2.309 \pm 0.041$  ppm, suggesting localized enrichment that may reflect a combination of anthropogenic inputs and particulate-associated transport. A recent investigation of agricultural canals in Charkhi Dadri, Haryana, similarly revealed significant spatial and temporal variability in canal-water chemistry, with Al and Cu emerging as important contributors to overall variation and contamination hotspots identified through multivariate analysis [4].

In contrast, the Cr, Co, and Cu concentrations were relatively less pronounced across most districts, although localized maxima were evident for Cr in Rohtak and Cu in Sirsa. Ni, As, Cd, and Pb displayed more prominent profiles, particularly in Hisar, indicating localized enrichment of these metals. This metal-specific spatial behavior is consistent with observations from the western Yamuna Canal in Haryana, where Ni, Cu, Cr, and Cd exhibited distinct concentration patterns, with Ni showing the highest overall abundance, followed by Cu, Cr, and Cd [94]. The same study also reported a decrease in metal concentrations along the western Yamuna Canal with increasing distance from industrial areas, suggesting that localized anthropogenic inputs can contribute to spatial differences in canal-water metal concentrations [95]. The relatively higher profiles of Ni, As, Cd, and Pb in Hisar may therefore reflect localized inputs and transport processes; however, the radar profiles alone cannot establish their specific sources. Earlier investigations of Yamuna-origin canals in Haryana also demonstrated substantial differences in heavy metal concentrations among canal systems, emphasizing the importance of site-specific pollution conditions in controlling metal occurrence [17]. Overall, the radar plots reinforce that the heavy metal distribution in the Haryana canal network is governed by metal-specific spatial behavior, with the observed patterns likely reflecting the combined influence of local geochemical conditions, hydrological transport, and localized anthropogenic inputs [82].

The suitability assessment revealed a clear distinction between widespread and localized trace element exceedance across the canal network. Li and Cd were the most widespread concerns, with concentrations exceeding the respective permissible limits across all investigated districts, whereas Cr, Co, Cu, As, and Pb remained within the applicable guideline values. Previous investigations of Haryana canal systems have also reported exceedances of permissible limits for several heavy metals [96]. Similarly, site- and metal-specific exceedance of

permissible limits have been reported for the upper Yamuna River Basin, with Al and As exceeding the acceptable limits of the BIS at several locations, while most sampling locations have low to moderate pollution levels, indicating spatially heterogeneous metal contamination [97]. The present pattern therefore indicates a more metal-specific contamination profile, with widespread guideline exceedance restricted to Li and Cd. Al and Ni showed more localized exceedances, with unsuitable classifications confined to selected districts. A recent assessment of agricultural canals in Charkhi Dadri, Haryana, similarly revealed spatially heterogeneous canal water quality and localized contamination hotspots, with Al and Cu contributing substantially to the observed variability [98]. Spatial differences in heavy metal concentrations have also been reported in the western Yamuna Canal, where metal levels varied by sampling location and proximity to industrial areas, supporting the role of localized inputs in controlling canal water quality (REF). The localized occurrence of unsuitable Al and Ni may therefore reflect differences in local inputs, transport pathways, and hydrogeochemical conditions rather than uniform contamination throughout the canal system. Conversely, a recent assessment of the Haryana stretch of the Agra Canal reported heavy metal concentrations within FAO limits, demonstrating that canal systems within the broader region can exhibit contrasting suitability profiles under different local environmental conditions [17]. Overall, the findings indicate widespread concerns for Li and Cd and localized concerns for Al and Ni. Moreover, Cr, Co, Cu, As, and Pb showed relatively favourable suitability during the study period.

A comparison between industrial and nonindustrial regions revealed a generally greater heavy metal burden in the industrial region, with the most pronounced differences observed for Al, Cr, and Ni. Aluminum showed the strongest regional contrast, increasing from  $0.453 \pm 0.098$  ppm in the nonindustrial region to  $1.216 \pm 0.211$  ppm in the industrial region. Moreover, the

concentrations of Cr and Ni were also significantly elevated in the industrial region. Similar associations between industrialization and elevated metal concentrations have been reported in the Sirsa River, where Ni concentrations were consistently above permissible limits along the river stretch and were attributed to industrial activities, untreated sewage, mining-related inputs, and other anthropogenic sources [89]. Similarly, investigations of the Kabini River in Karnataka revealed higher metal concentrations near industrial effluent inputs, with Cr and Ni among the metals showing notable enrichment in industrially influenced locations [99]. These observations support the interpretation that localized industrial inputs may contribute to the elevated Al, Cr, and Ni concentrations observed in the industrial districts of the present study [4].

Although Co, As, Cd, and Pb concentrations were also relatively high in the industrial region, the differences were not statistically significant, suggesting that multiple sources may influence their distribution rather than industrial activity alone. Recent investigations of Indian river systems have similarly demonstrated that heavy metal distributions may reflect a combination of industrial discharge, municipal inputs, agricultural runoff, and natural geochemical processes rather than a single dominant source [100]. In contrast, Cu had a higher mean concentration in nonindustrial regions, highlighting the metal-specific nature of spatial patterns and indicating that nonindustrial sources may also contribute to certain metals [101]. Overall, the significantly elevated Al, Cr, and Ni concentrations in the industrial region, together with the generally higher mean concentrations of most other metals, indicate a greater regional metal burden in industrial areas, whereas the contrasting Cu pattern emphasizes the importance of metal-specific sources and transport processes [17].

### ***5.1 Uncovering the possible sources of heavy metals in Haryana canal water***

The factor analysis revealed a strong multivariate structure in terms of the heavy metal distribution, with three factors collectively explaining 94.30% of the total variance. VF1 was the dominant factor and was strongly correlated with As, Co, Cd, Pb, Ni, Li, and Cr, suggesting that these metals may share common or closely related sources and transport pathways. Similar multivariate analyses of surface water in Haryana have revealed that soil leaching/erosion, agricultural runoff, and anthropogenic inputs are important contributors to water quality variation [102]. The association of multiple potentially toxic elements within VF1 therefore suggests a mixed influence of anthropogenic activities and natural geochemical processes rather than a single dominant source [98].

VF2 was primarily associated with Al, with a secondary contribution from Cr, indicating a comparatively distinct control on the distribution of Al. A recent investigation of agricultural canals in Haryana also revealed that Al is an important contributor to multivariate water quality variation, supporting the potential role of geochemical weathering and particulate-associated transport [39]. VF3 was dominated by Cu, indicating that its distribution may be governed by a relatively independent source or controlling process. The separation of Cu into an independent factor has similarly been reported in canal-water investigations, suggesting that Cu may have source characteristics distinct from those of other trace elements [82]. Overall, the factor structure indicates that heavy metal occurrence in the Haryana canal network is controlled by multiple interacting natural and anthropogenic influences, with the dominant factor representing a mixed-metal signature and the remaining factors reflecting more specific controls on Al/Cr and Cu [4].

## ***5.2 Possible health risks associated with canal water exposure in the Haryana semiarid region***

1447 The observed heavy metal contamination in canal water warrants consideration of its potential  
1448 implications for human health, particularly where canal water may contribute to domestic  
1449 exposure. Health risk assessment therefore provides an integrated evaluation of potential  
1450 noncarcinogenic and carcinogenic risks associated with heavy metal exposure through ingestion  
1451 and dermal contact [103]. These risks were interpreted using established toxicological reference  
1452 values, allowing evaluation of the relative contributions of individual metals and exposure  
1453 pathways across the investigated districts. This assessment provides a critical link between the  
1454 observed contamination patterns and their potential implications for human health in the Haryana  
1455 semiarid region [104].

#### 1456 ***5.2.1 Degree of contamination (DOC)***

1457 The DOC assessment indicated pronounced spatial heterogeneity in the overall heavy metal  
1458 contamination of canal water, with Rohtak showing the greatest cumulative contamination. In  
1459 contrast, Hisar and Sirsa exhibited relatively low levels. The predominance of high DOCs across  
1460 the study area suggests that contamination is not restricted to isolated sampling locations but  
1461 represents broader regional water quality concerns, with differences among districts likely  
1462 reflecting variations in metal loading, land use pressure, and local contaminant inputs [98]. A  
1463 recent assessment of the Hindon River similarly reported spatial and seasonal differences in the  
1464 degree of contamination, with higher Cdeg values associated with periods of greater heavy metal  
1465 loading and anthropogenic influence [105].

1466 The particularly high DOC observed in Rohtak may indicate the cumulative influence of  
1467 multiple contaminants rather than the dominance of a single metal. This interpretation aligns  
1468 with broader evidence that heavy metal contamination in Indian surface waters can arise from  
1469 interactions among industrial, sewage, agricultural, and geogenic sources [46]. A systematic

assessment of Himalayan water quality also revealed substantial spatial and temporal variations in the DOC. Heavy metal contamination is attributed to combined anthropogenic and natural processes, including industrial effluent, agricultural runoff, sewage disposal, mining, and rock weathering [106]. Thus, the DOC pattern observed across the Haryana canal network suggests that cumulative metal contamination is spatially heterogeneous and may reflect the combined influence of regional anthropogenic pressures and natural geochemical processes. The elevated DOC in several districts further emphasizes the need for continued monitoring of canal water quality, particularly where canal water may contribute to human or environmental exposure [107].

### ***5.2.2 Pollution load index (PLI)***

The PLI assessment indicated a consistently low cumulative heavy metal pollution load across the investigated districts, as all the PLI values remained below unity. Although Hisar recorded the highest PLI, the overall values remained within the low-pollution category, indicating that the combined metal burden was relatively limited at the regional scale. A recent systematic assessment of Himalayan water quality similarly employed the PLI and the DOC to characterize cumulative heavy metal contamination and reported substantial spatial and temporal variations in these indices [108]. The low PLI observed across the Haryana canal network, despite the localized enrichment of individual metals, suggests that elevated concentrations of specific elements did not translate to a high overall pollution load. However, the relatively high PLI at Hisar indicates a greater cumulative metal contribution at this location and warrants continued monitoring to identify potential changes in metal loading over time [2].

### ***5.3 Districtwise statistical assessment of heavy metal exposure through ingestion and dermal contact among adults and children***

1493 The districtwise exposure assessment revealed clear metal- and pathway-specific spatial  
1494 heterogeneity, with ingestion generally representing the major exposure route compared with  
1495 dermal contact. Among adults, higher ingestion exposure to Li, Co, Ni, As, Cd, and Pb was  
1496 observed in Hisar, whereas Al and Cr showed greater exposure in Panipat/Rohtak and Cu in  
1497 Sirsa. A similar predominance of the ingestion pathway over dermal exposure has been reported  
1498 for Indian river systems, where ingestion contributed substantially more to overall heavy metal  
1499 exposure than dermal contact did, particularly for Cr and Pb [102]. This pattern is also consistent  
1500 with the recent Hindon River assessment, which reported substantially higher exposure estimates  
1501 through ingestion than through dermal contact [109]. The observed district-specific differences  
1502 therefore indicate that exposure was not governed by a uniform metal source but varied  
1503 according to the spatial distribution of individual metals within the canal network [109].

1504 The exposure patterns among children showed broadly comparable spatial heterogeneity,  
1505 with Hisar, Panipat, Rohtak, and Sirsa emerging as important locations for different metals.  
1506 Previous assessments of Indian surface waters have similarly reported greater susceptibility of  
1507 children to heavy metal exposure and emphasized ingestion as the dominant exposure pathway.  
1508 However, the exposure magnitude varies substantially among metals and locations [110]. The  
1509 relatively high exposure estimates for several metals in children are therefore particularly  
1510 concerning because repeated exposure through contaminated water may increase cumulative risk  
1511 over time. However, the present findings also revealed that this pattern was not uniform across  
1512 all the metals; for example, Li showed different spatial rankings across age groups. Such age-  
1513 and metal-specific variation may reflect differences in exposure parameters, metal concentrations,  
1514 and pathway-specific uptake rather than a single controlling factor [2].

The significant interdistrict differences identified by ANOVA for selected metals, particularly Li, Al, and Cr, further support the presence of localized exposure patterns, whereas the absence of significant differences for several other metals suggests a relatively homogeneous exposure distribution across districts. Comparable spatial variability in heavy metal exposure has been reported in Indian river systems, where differences in metal concentrations, hydrological conditions, and localized anthropogenic inputs produced marked differences in health risk estimates among sampling locations [107]. Overall, the findings indicate that human exposure to heavy metals through Haryana canal water is spatially heterogeneous and strongly dependent on metal identity, age group, and exposure pathway, with ingestion representing the principal route of exposure and selected districts warranting greater attention in subsequent noncarcinogenic and carcinogenic risk evaluations [104].

The comparative exposure assessment indicates that regional industrialization clearly influences heavy metal exposure, particularly for Al, Cr, and Ni. Adults from industrial regions generally exhibit greater ingestion and dermal exposure than those from nonindustrial regions do, with the most pronounced differences observed for Al, Cr, and Ni [48]. This pattern is consistent with the greater metal burden previously observed in industrially influenced aquatic systems, where industrial effluents and associated anthropogenic inputs can increase metal availability in surface water. A recent assessment of the industrially influenced Hindon River similarly reported greater human exposure [109] through contaminated surface water and identified untreated industrial effluent as an important contributor to heavy metal contamination [109].

The significantly higher exposure to Al, Cr, and Ni in the industrial region suggests that industrial and associated anthropogenic activities may contribute to their enhanced occurrence and subsequent human exposure. Studies of surface water influenced by industrial activities in

India have similarly reported elevated concentrations of metals and associated health risk indicators, supporting the role of industrial inputs in increasing metal exposure. However, the magnitude of enrichment varies by metal and location [111]. The consistency of this pattern across both adults and children in the present study further indicates that regional differences in metal loading can translate into differences in potential human exposure. Notably, the contrast in exposure was more pronounced for Al, Cr, and Ni than for the other investigated metals, suggesting that their regional distribution may be more closely associated with industrially influenced inputs [48].

The higher exposure estimates observed in children are particularly concerning because body weight-based exposure assessment can increase susceptibility in younger people. Previous assessments of Indian surface waters have likewise reported higher exposure and health risk indices in children than in adults, with ingestion generally representing the dominant exposure pathway [110,112]. In the present study, this age-related pattern was evident for several metals, particularly Al, Cr, and Ni, indicating that the industrial–nonindustrial contrast may have greater implications for children [104].

In contrast, both adults and children were more likely to be exposed to Cu in nonindustrial regions. This contrasting pattern indicates that industrialization did not uniformly govern the distribution of all metals and those additional localized sources and transport processes may influence Cu. A comparative study of industrial and nonindustrial areas in Kutch, Gujarat, similarly revealed metal-specific spatial patterns, with some metals more concentrated in industrial areas. In contrast, others were elevated in nonindustrial areas, indicating that the distribution of heavy metals cannot always be attributed to industrial activity alone [113]. Overall, the significantly higher exposure to Al, Cr, and Ni in the industrial region indicates a

strong regional influence on human exposure. In contrast, the contrasting Cu patterns emphasize the metal-specific nature of contaminant sources and spatial transport processes [114].

#### ***5.4 Assessment of probabilistic human health risks due to canal water quality collected from the industrial and nonindustrial regions of Haryana***

##### ***5.4.1 Assessment of noncarcinogenic risk***

##### ***5.4.1.1 Spatial Distribution of Noncarcinogenic Health Risk among Adults in the Industrial and Nonindustrial Regions of Haryana***

The districtwise assessment revealed marked metal-specific variation in noncarcinogenic health risk among adults, with ingestion generally representing a more important exposure pathway than dermal contact. Li showed a significant spatial gradient, with the highest HI in Hisar, whereas Al and Cr displayed the greatest risks in Rohtak and Panipat, respectively. Comparable spatial heterogeneity in terms of heavy-metal health risk has been reported for Indian surface-water systems, where differences in metal loading and local anthropogenic pressures produced substantial variation in HQ and HI among sampling locations [109]. The relatively high Li HI in Hisar is consistent with the elevated Li exposure previously observed at this location. In contrast, the higher Al and Cr indices in Rohtak and Panipat indicate that localized enrichment of individual metals can translate into corresponding differences in health risk estimates [86].

Among the investigated metals, As represented the most prominent noncarcinogenic concern in adults, with the highest HI recorded in Hisar ( $1.152 \pm 0.889$ ), exceeding the commonly applied threshold of unity. These findings suggest that As contributes significantly to the cumulative noncarcinogenic risk at this location. A comparable pattern has been reported in Indian river systems, where hazard indices exceeded unity at specific locations or seasons, indicating potential noncarcinogenic risk associated with combined metal exposure [112].

1584 However, the absence of significant interdistrict differences for As in the present study indicates  
1585 that its relatively high HI in Hisar should be interpreted as a location-specific elevation rather  
1586 than a statistically established district-wide difference. The relatively high HI values of Co, Ni,  
1587 Cd, and Pb in Hisar further suggest that this district may represent an important exposure hotspot.  
1588 However, their spatial differences were not statistically significant.

1589 Dermal exposure contributed relatively little to the overall noncarcinogenic risk for most  
1590 metals, whereas ingestion was the principal contributor to the HI. This pathway-specific pattern  
1591 is in agreement with studies of Indian surface waters, including the Hindon River, where  
1592 ingestion produced substantially greater hazard indices than dermal exposure did, while dermal  
1593 HI values remained below unity for both adults and children [109]. The relatively greater  
1594 contribution of ingestion in the present study is therefore important because canal water may be  
1595 used for domestic purposes, as repeated oral exposure can represent a more relevant route of  
1596 metal intake than dermal contact. Overall, the spatial distribution of adult noncarcinogenic risk  
1597 was metal specific rather than uniformly distributed across districts. Hisar emerged as an  
1598 important location because of the relatively high HI values for As and several other metals. In  
1599 contrast, the risk associated with Al and Cr was greater for Rohtak and Panipat. Such spatial  
1600 heterogeneity is consistent with previous Indian surface-water assessments, where local  
1601 differences in metal loading and anthropogenic influence produced distinct patterns of health risk  
1602 among sampling locations [46,115]. These findings support district-specific monitoring and  
1603 source-oriented management, particularly for metals that contribute disproportionately to the  
1604 overall health-risk profile.

1605 The spatial distribution of adult noncarcinogenic risk indicates a predominantly localized  
1606 risk pattern, with Hisar emerging as the only district where ingestion-related HQ and overall HI

exceeded the unity threshold. This spatially restricted exceedance suggests that the potential noncarcinogenic risk was driven by the combined contribution of metals at specific locations rather than by a uniform regional contamination pattern. A comparable spatially heterogeneous risk pattern has been reported in the urban wetlands of Gurugram, Haryana, where  $HI > 1$  was observed in selected wetlands. Moreover, other locations remained below the threshold, demonstrating that human health risk can vary substantially even within the same regional water system [69].

The close similarity between the  $HI$  and  $HQ_{ing}$  distributions, together with the consistently low  $HQ_{derm}$  values, indicates that ingestion was the principal pathway governing the spatial pattern of adult noncarcinogenic risk. These findings are consistent with broader evidence from Indian surface waters, where ingestion generally contributes more strongly to heavy metal exposure and health risk than dermal contact does. For example, an assessment of the Upper Ganga River reported substantially greater ingestion-related hazard indices than dermal exposure and identified location-specific  $HI$  values exceeding unity, despite the  $HQ$  values for individual metals generally remaining below one [102]. Similarly, a health risk assessment of surface water and groundwater in an industrial region of Maharashtra revealed that the ingestion of contaminated water is the major pathway contributing to human health risk, with arsenic being the principal contributor to ingestion-related  $HI$  [116]. The isolated  $HI > 1$  classification in Hisar is therefore important because it indicates a potential noncarcinogenic concern at the district level, even though the remaining districts remained below the threshold. Such localized risk may arise from spatial differences in metal concentrations, contaminant transport, and local anthropogenic inputs. Recent assessments of Indian surface waters have likewise demonstrated that health risk indices can vary markedly among sampling locations because of differences in

metal loading and source characteristics rather than following a uniform regional pattern [107]. Overall, the spatial risk map suggests that adult noncarcinogenic risk in the Haryana canal network is primarily ingestion-driven and spatially localized, with Hisar warranting particular attention for source identification and continued monitoring.

#### ***5.4.1.2 Spatial distribution of noncarcinogenic health risk in children***

The spatial distribution of noncarcinogenic risk among children revealed a broader and more pronounced risk pattern than that observed for adults, with the HI exceeding unity for Al in Panipat; for Cr in Rohtak; and for Co, As, and Cd in Hisar. The occurrence of multiple district-specific exceedances indicates that the potential noncarcinogenic risk in children was not confined to a single contaminant or location but varied with the spatial distribution of individual metals. A review of heavy metal contamination in Indian River waters similarly reported noncarcinogenic risks for multiple metals in children. Children were generally more susceptible to both noncarcinogenic and carcinogenic effects than adults were [110].

The particularly elevated HI for As in Hisar, together with the exceedance observed for Co and Cd at the same location, identifies Hisar as an important potential exposure hotspot. However, HIs  $> 1$  for Al in Panipat and Cr in Rohtak indicate that noncarcinogenic risk is also associated with the localized enrichment of individual metals outside Hisar. A recent assessment of the Betwa-Yamuna confluence in northern India similarly reported higher arsenic-related hazard estimates in children than in adults, with the child HI exceeding unity across seasons, highlighting the importance of spatial and temporal differences in metal exposure [117].

The absence of HI exceedance for Li, Ni, Cu, and Pb across districts indicates relatively low noncarcinogenic contributions from these metals, whereas exceedances for Al, Cr, Co, As, and Cd suggest that risk was strongly metal specific and spatially heterogeneous. Similarly, the

Himalayan assessment revealed that although several metals remained below the risk threshold, individual contaminants could dominate noncarcinogenic risk at specific locations, particularly As in India. Moreover, dermal exposure generally contributes less than ingestion does [108]. Thus, the greater number of HI exceedances among children emphasizes their higher susceptibility and supports the need for age-specific risk assessment when evaluating the potential health implications of canal-water exposure [107].

The spatial distribution of noncarcinogenic risk in children showed a localized, pathway-specific pattern. Hisar was the only district with  $HQ_{ing} > 1$ , whereas Rohtak and Panipat had  $HQ_{derm} > 1$ , indicating that the dominant exposure pathway varied by district. A comparable pathway-specific pattern was reported for the Godavari River, India, where ingestion-related HQs were higher than dermal HQs were, and both exposure estimates were consistently greater in children than in adults [100]. The overall HI distribution revealed that Hisar, Rohtak, and Panipat were localized noncarcinogenic risk hotspots, whereas the remaining districts remained below the unity threshold. A comparable spatial pattern emerged for Himalayan surface waters, where children generally presented greater noncarcinogenic risks than adults did, with localized exceedances of  $HI > 1$  for several heavy metals [108]. Similarly, spatially variable heavy metal exposure in the Godavari River resulted in greater cumulative health risks for children than for adults, highlighting the influence of localized metal sources on human health risk. Overall, the findings indicate that child health risk is spatially heterogeneous and influenced by both metal distribution and exposure pathways [100].

A regional comparison revealed a consistently greater noncarcinogenic risk burden in the industrial region, particularly for Al, Cr, and Ni, with statistically significant differences for these metals in both adults and children. A direct assessment of the western Yamuna Canal and

industrially influenced waters of Yamunanagar, Haryana, similarly reported elevated heavy metal contamination in areas adjacent to industries and revealed that metal concentrations in the canal decreased with increasing distance from industrial areas, supporting the influence of localized industrial inputs on canal water quality [106]. This correspondence is particularly relevant to the present findings because the higher regional HQ and HI for Al, Cr, and Ni indicate that differences in metal loading between industrial and nonindustrial areas can translate into measurable differences in potential human health risk [97].

The higher hazard indices observed among children further indicate greater age-specific vulnerability, with the industrial–nonindustrial contrast remaining evident for Al, Cr, and Ni. A semiarid groundwater assessment from eastern India similarly reported substantial noncarcinogenic health risks associated with heavy metals and revealed that younger populations were more vulnerable, with ingestion as the principal exposure pathway [118]. The results of the Himalayan surface-water assessment reported in the present study likewise revealed greater noncarcinogenic risk among children than among adults, with ingestion identified as the predominant pathway [108]. Although Li, Co, As, Cd, and Pb did not show statistically significant regional differences, their generally higher HI in the industrial region suggests a broader, albeit statistically weaker, regional pattern. In contrast, the higher Cu risk in the nonindustrial region reinforces the metal-specific nature of regional exposure. This finding indicates that industrialization alone does not explain the distribution of all contaminants [119].

#### ***5.4.2 Carcinogenic risk assessment***

##### ***5.4.2.1 Spatial Distribution of Carcinogenic Health Risk among Adults in the Industrial and Nonindustrial Regions of Haryana***

The district-wide carcinogenic risk assessment revealed a metal-specific spatial pattern, with Cr showing the only statistically significant interdistrict variation and Rohtak exhibiting greater risk than Kurukshetra did. In contrast, As and Pb did not significantly differ spatially, although compared with Pb, As consistently contributed to a substantially greater carcinogenic burden, particularly at Hisar. This pattern is consistent with a recent systematic review of arsenic and chromium risks in Indian surface water and groundwater, which identified ingestion-related carcinogenic risk as a major concern for both metals and reported particularly frequent exceedance of the  $10^{-4}$  benchmark for As and Cr in Indian studies [106]. The relatively higher As risk observed in the present study is particularly noteworthy because most district-level As estimates approached or exceeded the  $10^{-4}$  benchmark, whereas Pb remained within a lower-risk range. Himalayan surface water assessments in the literature have similarly identified As and Cr as major contributors to ingestion-related carcinogenic risk in India, with ingestion as the dominant pathway and children generally showing greater susceptibility [108]. Recent assessments of the Betwa-Yamuna system also revealed that As was the dominant carcinogenic contributor, whereas Pb resulted in substantially lower CR values [117]. Overall, the present findings indicate that As represents a more prominent carcinogenic concern. In contrast, Cr shows greater spatial differentiation, highlighting the importance of metal-specific and location-specific monitoring of canal water quality.

The dermal carcinogenic risk assessment revealed a relatively low and highly localized risk profile, with Cr exhibiting significant spatial variation and Rohtak showing the highest risk relative to Kurukshetra. In contrast, As and Pb did not significantly differ across districts, although compared with Pb, As consistently contributed more to dermal carcinogenic risk [120]. A recent systematic review of arsenic- and chromium-contaminated groundwater and surface

water in India revealed that dermal carcinogenic risk was generally lower than ingestion-related risk. However, unacceptable dermal risk was still reported for Cr in a proportion of the assessed studies, particularly among adults. The relatively high Cr-related dermal risk in Rohtak may therefore reflect localized differences in Cr occurrence and dermal exposure potential. In contrast, the absence of significant spatial variation for As and Pb suggests a relatively consistent dermal risk distribution across districts. This finding is broadly consistent with the Indian systematic review, which revealed limited evidence of significant dermal carcinogenic risk for Cr compared with ingestion. Moreover, Cr tended to increase the risk of dermal disease in some studies [106]. Evidence from the Kolleru Lake wetland in Andhra Pradesh also demonstrated that Cr exposure through water can contribute to measurable carcinogenic risk through both exposure pathways [13], highlighting the relevance of pathway-specific assessments for Cr in Indian surface-water systems [121]. Overall, the present results indicate that dermal exposure contributes less to carcinogenic risk than ingestion does, but the localized Cr pattern and relatively higher As estimates warrant continued attention where canal water may involve repeated or prolonged human contact [85].

The total cancer index (CI) demonstrated a metal-specific spatial pattern, with Cr showing significant interdistrict variation and Rohtak exhibiting the highest cumulative carcinogenic contribution, whereas As and Pb showed no statistically significant spatial differences. Despite the absence of significant variation for As, its CI remained considerably greater than that of Cr and Pb, particularly in Hisar, indicating that As contributed substantially to the overall cumulative carcinogenic burden. This pattern is consistent with a recent systematic review of arsenic- and chromium-contaminated Indian groundwater and surface water, which reported that the carcinogenic risk was substantially greater for As than for Cr and that ingestion

was the dominant pathway for carcinogenic exposure [106]. Similarly, a recent study on surface water in the Himalayas reported that the CI remained below unity despite elevated individual CR values, with India showing relatively high carcinogenic contributions from Cr, As, Pb, and other metals; ingestion was the dominant exposure pathway [108]. A review of heavy metal contamination in Indian river water also revealed elevated cancer indices for Cr, Pb, Ni, Cd and As, with the carcinogenic risk generally greater through ingestion than through the cutaneous pathway [110]. Thus, the relatively high As contribution and localized Cr variation in the Haryana canal network indicate that cumulative carcinogenic risk is driven primarily by metal-specific contributions and spatial exposure patterns rather than by a uniform regional effect [86].

The spatial distribution of carcinogenic risk in adults showed a localized ingestion-related pattern, with Hisar the only district exceeding the  $10^{-4}$  risk threshold. In contrast, all the other districts remained below the benchmark. Similar spatial heterogeneity has been reported in Indian surface-water systems, where elevated carcinogenic risk was restricted to specific locations and was primarily associated with ingestion exposure [120]. The uniformly low dermal CR values and CI values below unity indicate that dermal exposure contributed minimally to the overall carcinogenic risk. In contrast, the cumulative carcinogenic burden remained below the threshold across the study area. Similar findings have been reported for Himalayan surface waters, where the CI remained below unity despite elevated individual CR values, with ingestion identified as the dominant pathway [108]. Overall, the present pattern indicates that adult carcinogenic risk was localized and predominantly ingestion-driven, with Hisar as the principal district requiring continued monitoring.

#### ***5.4.2.2 Spatial Distribution of Carcinogenic Health Risk of Children in Industrial and Nonindustrial Regions of Haryana.***

1767 The ingestion-related carcinogenic risk showed a metal-specific spatial pattern, with Cr  
1768 exhibiting significant interdistrict variation and the highest CR in Rohtak, whereas As showed  
1769 considerably higher CR values but no statistically significant spatial variation. This pattern is  
1770 consistent with recent evidence from Indian surface and groundwater studies, where compared  
1771 with chromium, arsenic generally resulted in greater ingestion-related carcinogenic risk, whereas  
1772 chromium resulted in a lower but still important carcinogenic risk [106]. The elevated Cr risk in  
1773 Rohtak therefore suggests a localized exposure pattern, whereas the consistently higher As  
1774 values across districts indicate more widespread carcinogenic concern. Comparable findings  
1775 have also been reported for the Betwa–Yamuna River system in northern India, where As was  
1776 identified as the dominant contributor to carcinogenic risk and where the proportion of adult  
1777 exposures exceeded the 10–4 benchmark, demonstrating the importance of arsenic exposure in  
1778 Indian surface waters [117]. Similarly, the Garhwal Himalayan assessment revealed the adult  
1779 ingestion risk sequence as  $As > Cr > Pb > Cd$ , closely corresponding to the relative pattern  
1780 observed here ( $As > Cr > Pb$ ) [122]. Overall, the results indicate that As represents the dominant  
1781 carcinogenic concern, Cr contributes more spatially differentiated risk, and Pb represents a  
1782 relatively minor contributor to ingestion-related carcinogenic risk in the Haryana canal network  
1783 [120].

1784 The dermal carcinogenic risk showed a metal- and location-specific pattern, with Cr  
1785 exhibiting significant spatial variation and Rohtak showing greater risk than Kurukshetra did,  
1786 whereas As and Pb remained statistically comparable among the districts. A recent systematic  
1787 review of arsenic- and chromium-contaminated Indian groundwater and surface water revealed  
1788 that dermal carcinogenic risk was generally lower than ingestion-related risk. However, a  
1789 proportion of Indian studies reported unacceptable dermal risk for Cr, particularly among adults

[106]. This finding supports the present observation that Cr, despite its relatively lower absolute dermal risk, showed clearer spatial differentiation than As and Pb did. Despite the absence of significant spatial variation, the higher As dermal CR in Hisar indicated that As remained the major dermal contributor among the three metals, whereas Pb contributed comparatively little. A recent assessment of Indian surface and groundwater in mining-affected areas similarly reported negligible dermal carcinogenic risk compared with ingestion, with dermal CR values remaining below 10<sup>-6</sup> for As in both adults and children [123]. Overall, the findings indicate that dermal exposure represents a secondary carcinogenic pathway. Moreover, the localized Cr pattern highlights the importance of district-specific monitoring of metal exposure in the Haryana canal network.

The total cancer index showed a metal-specific spatial pattern, with Cr exhibiting significant interdistrict variation and Rohtak showing the highest CI, whereas As and Pb did not differ significantly among the districts. Despite the lower spatial variability of As, its CI was substantially greater than that of Cr and Pb, indicating that As contributed most strongly to the cumulative carcinogenic burden. A study of the Punnakayal estuary in southern India similarly reported substantially higher total carcinogenic risks for As and Cr than for Pb, with Pb remaining within the acceptable risk range for both adults and children [124]. The higher Cr CI in Rohtak suggests a localized contribution of Cr to cumulative carcinogenic risk, whereas the relatively high As CI across districts indicates broader carcinogenic concern. A recent assessment of Himalayan surface waters revealed As > Cr > Pb for adult ingestion-related carcinogenic risk, whereas another Indian river-water study identified Cr as an important contributor to total cancer risk alongside As [122,125]. Overall, the present CI pattern indicates that As represents the major contributor to cumulative carcinogenic risk, Cr shows greater spatial

differentiation, and Pb contributes relatively little, emphasizing the importance of metal-specific monitoring and source control in the Haryana canal network.

The spatial distribution of carcinogenic risk among children revealed a more extensive ingestion-related risk pattern, with Rohtak, Hisar, Sirsa, and Ambala exceeding the  $10^{-4}$  benchmark, whereas Jind, Panipat, and Kurukshetra remained below this threshold. Comparable evidence from Indian surface-water systems shows that children can experience greater carcinogenic exposure through ingestion than adults can, particularly for As and Cr, because their exposure relative to body weight is greater. In contrast, all districts remained below the dermal CR threshold, and the combined CI also remained below unity, indicating that there was no overall cumulative carcinogenic risk despite the localized ingestion-related exceedances. A study of the Betwa-Yamuna River system similarly identified As as the dominant carcinogenic contributor and revealed that carcinogenic risk can exceed the acceptable threshold for individual exposure scenarios even when the overall risk profile varies spatially [108]. Overall, the present findings indicate that child carcinogenic risk is spatially heterogeneous and predominantly ingestion-driven, with Hisar and Rohtak warranting particular attention for continued monitoring and source-oriented risk management.

A regional comparison revealed a generally greater carcinogenic risk burden in the industrial region for both adults and children, with the most pronounced and statistically significant difference observed for Cr. This pattern is consistent with broader evidence from Indian water systems, where industrially influenced regions have frequently shown greater carcinogenic risk associated with Cr and As exposure than less impacted areas have. However, the magnitude of risk varies considerably across locations [123]. The approximately fourfold higher Cr-related CI in industrial adults and the similarly elevated risk in children suggest that

regional industrial influence may contribute to increased Cr exposure and subsequent carcinogenic risk. Despite the absence of statistical significance, the higher As CI in the industrial region indicates a similar directional pattern, whereas the much lower Pb values suggest a relatively minor contribution of Pb to the regional cancer burden. This metal-specific response aligns with Indian surface-water assessments showing that As and Cr can dominate carcinogenic risk, while individual metals may show substantially different spatial patterns [110]. The consistently higher risk estimates among children further indicate greater vulnerability in the younger population, while the contrasting magnitudes among metals emphasize that industrialization does not affect all contaminants uniformly. Overall, the findings identify the industrial region as a relatively high-risk zone, particularly for Cr, and support targeted monitoring of Cr and As in industrially influenced canal-water systems [120].

## **5.5 Human Health Implications of Heavy Metal Exposure**

The present findings have important public health implications because heavy metal contamination of canal water can create a persistent exposure pathway for populations using these water resources for domestic and other human activities. Although most districts presented noncarcinogenic and cumulative carcinogenic indices below the respective risk thresholds, the identification of localized risk hotspots, particularly for As, Cr and selected other metals, indicates that regional averages may mask location-specific concerns [106]. Investigations of Indian surface water have similarly shown that heavy metal contamination and associated health risks can vary substantially by location, with industrial, municipal, and agricultural inputs contributing to spatial differences in water quality [110,126]. The present findings therefore support continued, spatially resolved monitoring rather than relying solely on regional mean concentrations.

The relatively high exposure and risk estimates observed among children further emphasize their vulnerability to multimetal exposure. Recent assessments of Indian water systems have consistently reported higher health risk estimates among children than among adults, largely because of their higher water intake-to-body weight ratio and greater physiological susceptibility [100,108]. This is particularly relevant to As and Pb, for which long-term exposure can produce serious neurological, developmental, renal and carcinogenic effects. The World Health Organization recognizes inorganic As as a confirmed human carcinogen. This highlights the adverse developmental effects associated with exposure during early life, while children are particularly susceptible to the neurological effects of Pb. Accordingly, future water safety assessments in the study region should incorporate child-focused surveillance [107].

The predominance of ingestion-related risk over dermal exposure in the present assessment further indicates that oral exposure represents the principal pathway of concern. This finding is in agreement with Indian river water studies in which ingestion contributed substantially more to carcinogenic and noncarcinogenic risk than cutaneous exposure did. The relatively high risk observed in industrial districts, particularly for Al, Cr, and Ni, also indicates the importance of controlling industrial discharge and other anthropogenic inputs [46]. Evidence from the Yamuna system shows that industrial effluents, sewage and agricultural runoff can collectively contribute to heavy metal loading, with industrialized stretches receiving substantial pollutant inputs. Therefore, risk reduction should combine industrial effluent treatment, improved wastewater management, source-specific surveillance and regular monitoring of canal-water quality. In semiarid Haryana, these measures are particularly important because sustained dependence on canal-based water resources can increase the consequences of persistent contamination [127].

## **5.6 Contribution to Sustainable Development Goals (SDGs)**

The present study contributes directly to SDG 3 (good health and well-being) by identifying heavy metal exposure pathways, spatial risk hotspots and population groups that are potentially more vulnerable to adverse health effects. The observed child-specific risk profile and the identification of As and Cr as key contributors provide evidence to support preventive environmental health surveillance and targeted risk-reduction strategies [128]. This aligns particularly with SDG Target 3.9, which calls for reducing illness and deaths attributable to hazardous chemicals and air, water and soil pollution. These findings therefore provide a scientific basis for integrating water-quality surveillance with population-level health-risk assessments in vulnerable communities [129]. This study also directly supports SDG 6 (Clean Water and Sanitation), particularly Target 6.3, which emphasizes improving water quality by reducing pollution, minimizing the release of hazardous chemicals and increasing the safe treatment and reuse of wastewater. Identifying industrially influenced risk patterns, localized contamination hotspots, and dominant exposure pathways provides region-specific evidence for strengthening canal-water monitoring and pollution-control programs [130]. Recent Indian studies similarly emphasize integrated monitoring and source-oriented management as essential for reducing heavy metal risks in surface water systems. Overall, the integration of spatial metal assessment, source evaluation, and human health risk characterization provides a practical framework for evidence-based water governance in the semiarid Haryana region and supports progress toward healthier communities and more sustainable water resource management [103].

## **6 Conclusion**

This study demonstrated that heavy metal contamination in semiarid regions of the Indian canal network is spatially heterogeneous and shaped by both metal-specific behavior and contrasting anthropogenic pressures. Li and Al showed significant spatial variability, whereas Li and Cd

represented the most widespread guideline concerns, and Al and Ni exhibited localized exceedances. The industrial region carried a greater overall metal burden, most clearly reflected by the significantly higher concentrations of Al, Cr, and Ni, whereas the contrasting Cu pattern in nonindustrial areas indicates that industrial activity alone does not govern metal distribution. Multivariate analysis further supported a mixed-source structure: As, Co, Cd, Pb, Ni, Li, and Cr were strongly associated with the dominant factor, whereas Al, Cr and Cu were more distinctly controlled, collectively accounting for 94.30% of the variance. The high DOC values across most districts, despite uniformly low PLI values, indicate that cumulative contamination and overall pollution loading capture different dimensions of canal-water quality.

From a human-health perspective, ingestion was the principal exposure pathway, and compared with adults, children consistently exhibited greater exposure and noncarcinogenic risk. Hisar, Rohtak, and Panipat emerged as localized child-risk hotspots, with Al, Cr, Co, As, and Cd contributing to HI exceedances at specific locations. Carcinogenic risk was predominantly associated with ingestion, with As contributing the greatest cumulative burden, Cr showing the clearest spatial differentiation, and Pb contributing relatively little. Although the combined cancer index remained below unity, localized ingestion-related risks among children and the higher carcinogenic burden in industrial districts warrant continued surveillance. Collectively, these findings establish a spatially resolved baseline for metal monitoring and health risk management of canal water and support targeted pollution control, particularly around industrially influenced reaches, while contributing directly to the objectives of SDG 3 and SDG 6.

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#### 1934 **CRedit authorship contribution statement**

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1938 Resources, Validation, Visualization, Writing - Original Draft, K. K. S.: Formal Analysis,  
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1950 Data will be available from the corresponding author upon good scientific reason and request.

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1952 **Ethical Approval**

1953 Not applicable, as this study did not involve human participants or animals.

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1956 **Consent to Participate**

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