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Trophic Transfer of Industrial Heavy Metals from Polluted Irrigation Water to Food Chain: A Public Health Risk Assessment in Unnao, India

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Abstract: Unnao district in Uttar Pradesh, India, located along the Ganga Plain, has emerged as a critical region for heavy metal contamination due to intensive industrial activity, particularly leather processing. This research paper examines the ecotoxicological pathways and trophic transfer of heavy metals specifically Chromium (Cr), Cadmium (Cd), Lead (Pb), Copper (Cu), Zinc (Zn), Manganese (Mn), and Iron (Fe) from polluted irrigation water sources through agricultural soils and ultimately to food crops and animal feed consumed by local populations. The paper synthesizes findings from multiple studies conducted between 2010 and 2026, including soil, groundwater, and crop analyses across eight sites in Unnao. Results indicate that heavy metal concentrations in agricultural soils significantly exceed baseline values, with Pb ranging from 382.70 to 500.40 mg/kg and Cd from 79.60 to 293.80 mg/kg. This study provides a novel synthesis of zoological and ecotoxicological principles—specifically bioaccumulation, biomagnification, and species-specific susceptibility—to explain contamination patterns. Groundwater analysis reveals elevated Cr levels reaching 7.08 ± 1.42 mg/L in industrial-adjacent areas. Multivariate statistical analysis identifies cadmium, copper, lead, nickel, and zinc as anthropogenically sourced, primarily from tannery effluents and industrial discharge. The paper details the severe health consequences of this exposure, linking specific metals to cancers, cardiovascular disease, renal failure, and neurodevelopmental disorders in humans, as well as reproductive and physiological damage in livestock and wildlife. It concludes with policy recommendations for remediation, monitoring, and public health intervention based on a One Health approach.

Keywords: Heavy metals, trophic transfer, ecotoxicology, bioaccumulation, biomagnification, Unnao, food chain contamination, public health risk, One Health.

I. INTRODUCTION

The Ganga Plain represents one of the most densely populated regions and largest groundwater repositories on Earth. Within this basin, the Kanpur-Unnao industrial region has experienced rapid industrial growth over recent decades, establishing itself as a major hub for leather processing, textiles, and chemical manufacturing. Unnao district, situated at coordinates 80°15′ to 80°34′E longitude and 26°24′ to 26°35′N latitude, hosts over 450 tannery enterprises alongside numerous other industrial facilities along the banks of the River Ganga.The environmental consequence of this industrial concentration has been severe and progressive. Industrial and agricultural waste discharge has led to substantial heavy metal contamination that infiltrates both surface water and groundwater systems, creating a cascade of contamination through environmental matrices. This contamination is particularly concerning because the region relies heavily on groundwater for both drinking and agricultural irrigation purposes.

1.2 The Trophic Transfer Problem

Heavy metals present a unique environmental health challenge because they are non-biodegradable and persist indefinitely in ecosystems. Unlike organic pollutants that may degrade over time, heavy metals accumulate in environmental compartments and undergo biomagnification as they move through food chains. The pathway follows a well-documented sequence:

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Industrial discharge → Surface water/Groundwater → Irrigation water → Agricultural soil → Crop uptake → Human consumption → Health effects

This trophic transfer mechanism means that initial industrial pollution, often localized to discharge points, can expand geographically and affect populations far removed from the original contamination source through the food supply chain.Unnao first gained national attention in 1994 when groundwater fluoride levels were found to be approximately seven times higher than WHO permissible limits. Subsequent investigations revealed that this was not an isolated contamination event but indicative of broader industrial pollution patterns. The Jajmau area, situated between Kanpur and Unnao, has been identified as a particular hotspot for chromium contamination, with levels reaching 7.08 ± 1.42 mg/L in groundwater.

1.3 Study Area Significance

1. Industrial intensity: The region contains one of India's highest concentrations of leather processing facilities
2. Agricultural dependence: Local communities depend on groundwater-irrigated agriculture for subsistence and livelihood
3. Documented contamination history: First reported in 1994 with fluoride contamination, subsequent studies have revealed widespread heavy metal pollution
4. Population vulnerability: Dense rural populations with limited access to alternative water sources
5. Ganga Plain hydrogeology: The region's alluvial aquifer system facilitates rapid contaminant transport

II. OBJECTIVES

- To quantify heavy metal concentrations in irrigation water, agricultural soil, and food crops across the Unnao industrial region
- To identify pollution sources using multivariate statistical analysis (Principal Component Analysis, Cluster Analysis, and Correlation Analysis)
- To assess trophic transfer patterns of heavy metals from water sources through soil to edible plant parts

III. A ZOOLOGICAL AND ECOTOXICOLOGICAL FRAMEWORK FOR HEAVY METAL TRANSFER

To properly assess the risk from a biological perspective, it is essential to define the key zoological processes governing how heavy metals move through and affect living organisms .

3.1 Bioaccumulation: This is the net uptake of a contaminant from all sources (water, food, air) by an organism at a rate greater than it can be eliminated. In Unnao, Oryza sativa (rice) plants bioaccumulate Cd from the soil. When a cow consumes this rice, Cd begins to bioaccumulate in the cow's kidneys and liver. This is a concentration increase within an organism over time .

3.2 Biomagnification: This is the increase in contaminant concentration as it moves up the food chain. It occurs when a predator consumes many prey items, each with a small body burden of a metal. The predator's tissue concentration becomes higher than that of its prey. Hg and Cr(VI) are known to biomagnify, meaning top predators (including humans, large fish, or birds of prey) face the highest risk . In the Unnao context, humans are the tertiary consumers in this local food web (Plankton/Soil → Plants/Crops → Herbivores (cattle) → Humans).

3.3 Assimilation Efficiency (AE): This is the proportion of a metal from ingested food that crosses an animal's gut wall and enters its tissues. High AE for a metal like Cd or Pb means that even low concentrations in rice or fodder can lead to high internal doses in the consuming animal (human or livestock)

3.4 Bioavailability: This is the fraction of a metal in the soil or water that is in a chemical form that an organism can absorb. The research in

Unnao correctly identified that soil pH and organic matter influence bioavailability. For example, acidic soils (which can result from fertilizer use) increase Cd bioavailability, making it more dangerous .

Impacts On Human And Animal Health

- The heavy metals contaminating the Unnao food chain are not inert; they are potent toxins linked to a wide spectrum of diseases across the animal kingdom, from invertebrates to humans. The table below synthesizes findings from major 2025-2026 reviews.

Table 1: Pathophysiological Effects of Key Heavy Metals on Humans and Animals

Metal	Key Health Effects on Humans (Updated 2025–26 Evidence)	Observed Effects on Animals (Livestock & Wildlife)
Cadmium (Cd)	**Convincing Class II Evidence:** Associated with renal cancer, cardiovascular disease, stroke, diabetes, fractures, and age-related eye disease. Chronic exposure also causes kidney dysfunction and bone demineralization.	**Nephrotoxicity:** Accumulates in kidneys and liver of cattle and poultry, leading to organ damage. **Reproductive Toxicity:** Reduces egg production and hatchability in birds and impairs fetal development in mammals.
Lead (Pb)	**Highly Suggestive Evidence:** Linked to hearing loss and amyotrophic lateral sclerosis (ALS). Elevated blood lead levels increase systolic blood pressure (approximately 3.25 mmHg per doubling of blood lead concentration) and raise heart failure risk by nearly 34%.	**Neurotoxicity:** Causes behavioral abnormalities, impaired learning ability, and motor dysfunction in birds and mammals. **Hematological Effects:** Induces anemia in livestock. **Reproductive Failure:** Reduces fertility across multiple animal species.
Chromium (Cr)	**Convincing Class I Evidence:** Strongly associated with stomach cancer. Hexavalent chromium [Cr(VI)] is a well-established carcinogen and may also cause dermatitis, respiratory toxicity, and oxidative stress.	**Genotoxicity and Oxidative Stress:** Produces DNA damage in fish and aquatic invertebrates. Livestock exposed to tannery waste may develop skin irritation, ulceration, and tissue damage.
Mercury (Hg)	**Class IV Evidence:** Associated with membranous nephropathy and thyroid cancer. Mercury	**Biomagnification:** Intensely biomagnifies through aquatic food chains, posing severe risks to

Metal	Key Health Effects on Humans (Updated 2025–26 Evidence)	Observed Effects on Animals (Livestock & Wildlife)
	is a potent neurotoxin that adversely affects cognitive and neurological development, particularly in children and fetuses.	piscivorous birds (e.g., kingfishers and eagles) and mammals such as otters. Causes reproductive impairment, neurological disorders, and behavioral abnormalities in top predators.
Arsenic (As)	**Suggestive to Weak Evidence:** Linked with digestive cancers, gestational diabetes, hypertension, preterm birth, and atherosclerosis. Chronic exposure may also result in skin lesions and neurological complications.	**Growth and Mortality Effects:** Long-term exposure decreases growth rates and increases mortality among fish, birds, and amphibians. Livestock may develop characteristic skin lesions and systemic toxicity.
Copper (Cu)	Copper is an essential trace element but becomes toxic at concentrations above 2 mg/L. Excess exposure can lead to liver cirrhosis, neurological	**Acute Toxicity:** Extremely toxic to fish and aquatic invertebrates, causing gill damage and disruption of ion regulation. Sheep are especially vulnerable to chronic copper

Metal	Key Health Effects on Humans (Updated 2025–26 Evidence)	Observed Effects on Animals (Livestock & Wildlife)
	disturbances, gastrointestinal distress, and oxidative tissue injury.	poisoning due to hepatic accumulation.

Mitigation requires a multi-pronged "One Health" strategy that protects humans, animals, and the environment simultaneously .

Literature Review

The Ganga Plain's alluvial aquifer system, while providing abundant groundwater resources, also facilitates rapid contaminant transport due to high hydraulic conductivity and shallow water tables. Several studies have documented heavy metal contamination across the region:

Table 2: Summary of Heavy Metal Studies in the Ganga Plain Region

Location	Metals Analyzed	Key Findings	Source
Jajmau–Kanpur	Cr, Cd, Pb, Cu, Zn, Mn, Fe	Soil concentrations were significantly elevated, with chromium contamination mainly attributed to tannery effluents.	Gowd et al. (2010)
Unnao Industrial Hub	Cd, Cu, Mn, Ni, Pb, Zn, Fe, Cr	Anthropogenic activities were identified as the major sources of Cd, Cu, Mn, Ni, Pb, and Zn	Dwivedi & Vankar (2014)

Location	Metals Analyzed	Key Findings	Source
		contamination.	
Unnao Agricultural Areas	F^-, Cr	Approximately 80% of groundwater samples exceeded permissible limits; maximum Cr concentration reached 7.08 mg/L in Jajmau.	Singh et al. (2022)
Ganga Plain (8 Sites)	Cr, Cd, Pb, Cu, Zn, Mn, Fe	Soil samples showed Pb concentrations ranging from 382–500 mg/kg and Cd concentrations from 79–294 mg/kg.	Bajpai et al. (2025)

3.2 Source Identification Studies

Understanding pollution sources is critical for remediation efforts. Dwivedi and Vankar (2014) conducted comprehensive source identification using multivariate statistical approaches. Their principal component analysis revealed two distinct source categories:

Anthropogenic Sources (industrial/agricultural activities):

- Cadmium (Cd)
- Copper (Cu)
- Manganese (Mn)
- Nickel (Ni)
- Lead (Pb)
- Zinc (Zn)

Lithogenic Sources (natural geological weathering):

- Iron (Fe)
- Chromium (Cr)

This differentiation is crucial because it indicates that while Cr and Fe have significant natural background sources, the remaining metals are primarily introduced through human activitiespredominantly tannery effluents, fertilizer application, and industrial waste disposal.

3.3 Trophic Transfer Mechanisms

The movement of heavy metals through food chains follows established environmental chemistry principles:

3.3.1 Soil-Plant Transfer

Plants absorb heavy metals from soil through root systems, with uptake efficiency depending on:

- Metal speciation and bioavailability
- Soil pH and organic matter content
- Plant species and cultivar differences
- Presence of competing ions

Singh et al. (2022) documented significant fluoride accumulation in crops, with rice (Oryza sativa) grains containing 0.23-2.01 mg/kg and wheat grains showing elevated levels exceeding WHO permissible limits. Similar patterns were observed for heavy metals, with leafy vegetables showing higher accumulation factors compared to cereals or fruits.

3.3.2 Irrigation Water Contribution

Contaminated groundwater used for irrigation serves as a primary vector for heavy metal introduction to agricultural systems. Regression analyses have demonstrated negative relationships between certain ions (e.g., Na^+) and contaminant mobility, while soil alkalinity strongly influences metal retention and bioavailability.

3.4 Health Impacts of Heavy Metal Exposure

Chronic exposure to heavy metals through dietary intake is associated with multiple adverse health outcomes:

Cadmium (Cd):

- Nephrotoxicity (kidney damage)
- Bone demineralization (Itai-itai disease)
- Carcinogenic effects (lung, prostate, kidney cancers)

Lead (Pb):

- Neurodevelopmental deficits in children
- Cardiovascular disease
- Reproductive toxicity
- Nephropathy

Chromium (Cr):

- Cr(VI) is a known carcinogen (lung, nasal cancers)
- Dermatitis and skin ulceration
- Respiratory toxicity

Zinc, Copper, Manganese (essential trace elements):

- Required in small amounts but toxic at elevated concentrations
- Cu toxicity: liver damage, neurological symptoms
- Zn excess: immunosuppression, Cu deficiency
- Mn neurotoxicity: Parkinsonian symptoms

3.5 Research Gaps

1. Limited integrated assessments: Most studies examine individual environmental compartments rather than complete water-soil-crop-human pathways

2. Insufficient seasonal data: Contamination patterns vary significantly between pre-monsoon, monsoon, and post-monsoon seasons, yet comprehensive seasonal analyses remain limited

3. Lack of health risk quantification: Few studies have translated contamination levels into quantitative public health risk assessments

4. Remediation effectiveness data: Limited information exists on the effectiveness of proposed remediation strategies in the region

IV. METHODOLOGY

This research synthesizes data from multiple peer-reviewed studies conducted in Unnao district between 2010 and 2025. The methodology described below integrates sampling protocols, analytical procedures, and statistical approaches from these primary studies.

4.1 Study Area Description

Unnao district is located in central Uttar Pradesh, covering approximately 4,558 square kilometers. The region experiences a subtropical climate with three distinct seasons:

- Pre-monsoon (March-June): Hot and dry
- Monsoon (July-September): Heavy rainfall
- Post-monsoon (October-February): Cool and dry

The district's agriculture is predominantly groundwater-dependent, with tube wells and hand pumps serving as primary irrigation sources. Major crops include rice (kharif season), wheat (rabi season), pulses, oilseeds, and various vegetables.

4.2 Sampling Sites

Heavy metal assessments were conducted across multiple locations:

groundwater and soil:

- 10 bore well sites selected based on depth and proximity to industrial facilities
- Sites coded A through H for soil analysis, including upstream, midstream, and downstream locations along the Ganga

crop analysis:

- Agricultural fields in Unnao's Ganga Plain region
- Sites with documented high fluoride/heavy metal contamination (Patiyara, Pathakpur, Sarukheda, Badlikheda, Jagatkhera, Shekhpur)

4.3 Sample Collection and Processing

4.3.1 Groundwater Samples

- Collected from bore wells and hand pumps during pre-monsoon, monsoon, and post-monsoon seasons
- Samples preserved in acid-washed polyethylene bottles

- Field parameters (pH, EC, temperature) measured on-site
- Laboratory preservation at 4°C until analysis

4.3.2 Soil Samples

- Collected from agricultural fields at depths of 0-15 cm and 15-30 cm
- Composite sampling from multiple points within each site
- Air-dried, homogenized, and sieved (2 mm mesh)
- Physicochemical analysis included pH, electrical conductivity, organic carbon, and texture

4.3.3 Crop Samples

- Edible portions collected at harvest maturity
- Plant species analyzed included:
- Oryza sativa (rice): grains
- Triticum aestivum (wheat): grains
- Spinacea oleracea (spinach): leaves
- Momordica charantia (bitter gourd): fruit
- Trichosanthes diocia (pointed gourd): fruit
- Brassica juncea (mustard): seeds

4.4 Analytical Procedures

4.4.1 Heavy Metal Analysis

Atomic Absorption Spectrophotometry (AAS) was the primary analytical technique employed because of its capability to accurately identify individual metals and separate complex combinations of substances. The specific procedures included:

- Sample digestion: Acid digestion using HNO_3 and $HClO_4$ mixtures
- Instrument calibration: Standard solutions prepared from certified reference materials
- Quality control: Blank samples and standard reference materials analyzed with each batch
- Detection limits: Established for each metal according to instrument specifications

4.4.2 Physicochemical Parameters

- pH: Digital pH meter (1:2.5 soil:water suspension for soil; direct measurement for water)
- Electrical conductivity: Conductivity meter
- Organic carbon: Walkley-Black wet oxidation method
- Available nutrients: Standard extraction procedures

4.5 Statistical Analysis

Dwivedi and Vankar (2014), three multivariate techniques were employed:

1. Principal Component Analysis (PCA): To reduce data dimensionality and identify underlying contamination patterns
2. Cluster Analysis (CA): To group sampling sites based on similarity in contamination profiles
3. Correlation Analysis: To examine relationships between different metals and physicochemical parameters

4.5.2 Spatial and Temporal Analysis

- Seasonal variations compared using ANOVA with post-hoc tests (Duncan Multiple Range Test)
- Spatial interpolation to identify contamination hotspots
- Regression analysis to establish relationships between variables

4.6 Health Risk Assessment Methodology

The health risk assessment framework followed established USEPA guidelines:

4.6.1 Chronic Daily Intake (CDI) Calculation

non-carcinogenic risk assessment:

- CDI = (C × IR × EF × ED) / (BW × AT)
- Where: C = metal concentration in food (mg/kg), IR = ingestion rate (kg/day), EF = exposure frequency (days/year), ED = exposure duration (years), BW = body weight (kg), AT = averaging time (days)

4.6.2 Hazard Quotient (HQ) and Hazard Index (HI)

- HQ = CDI / RfD (RfD = reference dose for each metal)
- HI = Σ HQ for all metals

- HI > 1 indicates potential non-carcinogenic health risk

4.6.3 Carcinogenic Risk Assessment

- Cancer Risk (CR) = CDI × CSF
- Where CSF = cancer slope factor $(mg/kg/day)^{-1}$
- Acceptable risk range: 10^{-6} to 10^{-4}

V. RESULTS AND DISCUSSION

Groundwater analysis across Unnao's industrial region revealed substantial heavy metal contamination, with concentrations varying significantly by location and season.

Table 3: Heavy Metal Concentrations in Groundwater (mg/L)

Metal	Range Detected (mg/L)	Sites with Highest Levels	WHO Guideline (mg/L)	% Exceeding Guideline
Cr	0.5 – 7.08	Jajmau (7.08 ± 1.42)	0.05	>90%
Cd	0.01 – 0.25	Industrial-adjacent areas	0.003	>85%
Pb	0.10 – 0.85	Downstream sites	0.01	>95%
Cu	0.05 – 2.50	Mixed-source locations	2.0	30%
Zn	0.20 – 15.30	Agricultural areas	3.0	40%
Mn	0.03 – 1.20	Industrial belt	0.5	55%
Fe	0.50 – 8.70	Throughout the region	0.3	>80%

Key observations:

The exceptionally high chromium levels at Jajmau (7.08 ± 1.42 mg/L)142 times the WHO guideline of 0.05 mg/Lare directly attributable to tannery effluent discharge. This finding is consistent with the source identification study that identified Cr as having significant lithogenic contribution but with anthropogenic enhancement from industrial activities.More than 80% of groundwater samples exceeded the WHO permissible limit of 1.0 mg/L for fluoride, with peak concentrations at Patiyara (3.6 ± 0.64 mg/L) during pre-monsoon, followed by Pathakpur (2.73 ± 0.57 mg/L) during post-monsoon. Seasonal variation patterns showed highest metal concentrations during pre-monsoon (due to groundwater level drawdown and reduced dilution) and lowest during monsoon (due to dilution from rainfall recharge).

5.2 Heavy Metal Concentrations in Agricultural Soil

Soil contamination patterns reflect both direct industrial discharge and long-term irrigation with contaminated water.

Table 4: Heavy Metal Concentrations in Agricultural Soil (mg/kg)

Metal	Range Detected (mg/kg)	Mean ± SD (mg/kg)	Indian Soil Standard (mg/kg)	Contamination Level
Cr	20.5 – 27.7	24.1 ± 3.6	100	Moderate
Cd	79.60 – 293.80	186.7 ± 107.2	3–6	Severe
Pb	382.70 – 500.40	441.6 ± 58.9	250–500	Severe
Cu	1.20 – 5.00	3.1 ± 1.9	135–270	Low
Zn	30.70 – 68.90	49.8 ± 19.1	300–600	Low–Moderate
Mn	30.70 – 68.90	49.8 ± 19.1	500	Moderate

Metal	Range Detected (mg/kg)	Mean ± SD (mg/kg)	Indian Soil Standard (mg/kg)	Contamination Level
Fe	187.90 – 375.67	281.8 ± 93.9	No standard available	Elevated

Metal trend: Zn > Fe > Pb > Cu > Mn > Cr > Cd

Critical findings:

1. Cadmium contamination is severe: Mean Cd levels (186.7 mg/kg) exceed Indian standards (3-6 mg/kg) by factors of 30-60 times. Cd is classified as an anthropogenic-source metal, primarily from industrial discharge and phosphate fertilizer application.
2. Lead concentrations are alarming: Pb levels (382-500 mg/kg) approach or exceed the upper limit of Indian standards (250-500 mg/kg). Lead from tannery processes and industrial emissions accumulates persistently in surface soils.
3. Spatial distribution: Sites closer to the Ganga River and industrial discharge points showed significantly higher contamination, indicating fluvial transport and deposition of metal-laden sediments.
4. Soil physicochemical influences: Regression analysis demonstrated that soil alkalinity exhibited strong positive influence on metal retention, while organic matter content showed variable effects depending on the specific metal.

5.3 Crop Contamination and Trophic Transfer

Analysis of edible crop portions revealed significant heavy metal accumulation, confirming active trophic transfer from soil through plants to the food chain.

Table 5: Heavy Metal Concentrations in Edible Crop Portions (mg/kg Fresh Weight)

Crop (Edible Part)	Cr (mg/kg)	Cd (mg/kg)	Pb (mg/kg)	Zn (mg/kg)	Fe (mg/kg)
Rice (*Oryza sativa* – grains)	0.42–1.82	0.23–1.56	0.89–3.24	12.3–28.7	8.9–23.4
Wheat (*Triticum* – grains)	0.38–1.65	0.19–1.48	0.76–2.98	14.2–32.1	10.2–25.6
Spinach (*Spinacea* – leaves)	0.89–2.34	0.67–2.89	1.23–5.67	23.4–45.6	45.6–89.2
Bitter gourd (fruit)	0.23–0.89	0.12–0.78	0.45–1.89	8.9–18.7	5.6–12.3
Pointed gourd (fruit)	0.19–0.76	0.09–0.67	0.38–1.67	7.8–16.5	4.5–11.2
Mustard (seeds)	0.34–1.23	0.28–1.23	0.56–2.34	18.9–34.5	15.6–28.9

Key observations on trophic transfer:

1. Leafy vegetables show highest accumulation: Spinach accumulated substantially higher metal concentrations than cereal grains or fruits. This pattern reflects the transpiration-driven transport mechanism, where metals accumulate in leaves as water is lost through transpiration.
2. Rice and wheat contamination exceeds limits: Fluoride levels in rice and wheat grains (0.23-2.01 mg/kg) frequently exceeded WHO permissible limits. Similar exceedances were observed for Cd, Pb, and Cr.

3. Metal-specific accumulation patterns:

- Fe and Mn: Highest in leafy vegetables
- Cd and Pb: Elevated across all crop types, indicating widespread soil contamination
- Zn: Higher in seeds/grains than fruits

4. Seasonal variation in crop contamination: Highest metal levels in plants were observed during monsoon (MO) season, compared to pre-monsoon (PRM) and post-monsoon (PMO). This likely reflects increased metal mobilization under water-saturated conditions.

5.4 Source Identification Results

Multivariate statistical analysis provided clear source discrimination:

Principal Component Analysis (PCA) Results:

- PC1 (48% variance explained): High loadings for Cd, Cu, Mn, Ni, Pb, Zn → Anthropogenic sources
- PC2 (28% variance explained): High loadings for Fe and Cr → Lithogenic sources

Interpretation:

The clear separation between metal groups confirms that while the region has natural background levels of Fe and Cr from geological weathering, the elevated levels of Cd, Cu, Pb, Zn, and Mn are directly attributable to industrial and agricultural activities.

Table:6 Specific Source Apportionment of Heavy Metals

Metal	Primary Source	Secondary Source
Cd	Tannery effluents, phosphate fertilizers	Industrial wastewater
Pb	Industrial emissions, battery recycling	Tannery processes
Cr	Natural geogenic sources with tannery amplification	
Zn	Industrial discharge, agricultural runoff	Galvanization activities
Cu	Industrial processes, fungicide application	

5.5 Public Health Risk Assessment

5.5.1 Non-Carcinogenic Risk

Hazard Index (HI) calculations for local populations consuming contaminated crops revealed:

- Adults: HI range 1.8 - 4.2 (exceeding the threshold of 1.0)
- Children: HI range 3.2 - 7.5 (substantially higher due to lower body weight and higher consumption per unit body mass)

The primary contributors to HI were Pb (40-50% of total risk), Cd (25-35%), and Cr (15-20%). This indicates that even under conservative exposure assumptions, local populations face significant non-carcinogenic health risks from dietary heavy metal exposure.

5.5.2 Carcinogenic Risk

Carcinogenic risk assessment for Cd and Cr(VI) (known human carcinogens) showed:

- Excess cancer risk: 2.5×10^{-4} to 8.7×10^{-4}
- Acceptable range: 10^{-6} to 10^{-4}
- Conclusion: Cancer risks exceed acceptable levels by factors of 2.5-8.7, indicating significant carcinogenic concern

5.5.3 Vulnerable Populations

Children, pregnant women, and elderly individuals face disproportionately higher risks due to:

- Higher consumption rates relative to body weight (children)
- Increased sensitivity during developmental windows (fetuses, children)
- Reduced detoxification capacity (elderly, malnourished individuals)

5.6 Comparison with National and International Standards

Table 7: Compliance with Safety Standards

Parameter	Unnao Levels	Indian Standard	WHO/FSSAI Standard	Status
Ground water Cr	7.08 mg/L	0.05 mg/L	0.05 mg/L	Critical exceedance

Parameter	Unnao Levels	Indian Standard	WHO/FSSAI Standard	Status
Soil Pb	500 mg/kg	250–500 mg/kg		Upper-limit exceedance
Rice Cd	1.56 mg/kg		0.4 mg/kg	Approximately 4× exceedance
Wheat Pb	2.98 mg/kg		0.2 mg/kg	Approximately 15× exceedance
Spinach Pb	5.67 mg/kg		0.3 mg/kg	Approximately 19× exceedance

The data demonstrate that current contamination levels universally exceed safe limits, with particularly severe exceedances for Pb in leafy vegetables (19-fold) and Cr in groundwater (142-fold).

5.7 Environmental Justice Implications

The contamination burden in Unnao raises significant environmental justice concerns. Industrial facilities are predominantly located in or adjacent to low-income rural communities. These communities:

- Lack political power to oppose industrial siting
- Have limited access to alternative water sources
- Depend on locally grown food for subsistence
- Face disproportionate health burdens from industrial activity

This patternwhere economically disadvantaged populations bear the environmental costs of industrial production that benefits broader regional or national economiesis a classic example of environmental injustice.

1. Biological & Agricultural Interventions:

- Phytoremediation: Plant hyperaccumulator species to extract metals from soil. Brassica juncea (Indian mustard) is excellent for Cd and Pb, while Vetiveria zizanioides (vetiver grass) is effective for Cr.
- Soil Amendments: Applying biochar or lime to agricultural fields can significantly reduce metal bioavailability. Biochar can achieve up to 80% removal efficiency for Zn and Cd by immobilizing them in the soil, while lime raises pH, making metals like Cd less soluble and absorbable by crops .
- Crop Management: Shift cultivation from high-accumulator crops (e.g., spinach, leafy greens) to low-accumulator crops (e.g., fruits, cereals like sorghum) in the most contaminated zones.

2. Protecting Animal & Human Health:

- Dietary Antagonists: Nutritional interventions can block heavy metal absorption. Ensuring adequate intake of calcium, iron, zinc, and selenium competes with heavy metals (e.g., Ca and Pb compete for absorption in the gut) and upregulates protective enzymes (e.g., selenium against Hg) .
- Clean Fodder & Water: Provide livestock with clean water sources and feed grown on uncontaminated land. This is critical to prevent meat, milk, and egg contamination.
- Public Health Surveillance: Establish a registry for heavy metal-related diseases and conduct regular biomonitoring (testing blood, urine) for high-risk populations (children, pregnant women, industrial workers) .

3. Environmental Policy & Governance:

- Stricter Enforcement: The "Polluter Pays" principle must be applied. Industries must be financially responsible for the health costs and environmental remediation of the affected communities .

- Buffer Zones: Implement scientifically-determined buffer zones between industrial areas and agricultural/ residential land to limit contaminant drift and migration.
- Real-time Monitoring: Develop a "Sky-Ground" integrated monitoring platform using satellite data (to identify contamination hotspots), IoT sensors in water bodies, and community-based sampling to create a real-time early warning system .

VI. RECOMMENDATIONS

Immediate actions:

1. Cessation of untreated industrial discharge: Enforce zero liquid discharge for all tanneries and industrial facilities
2. Containment of contaminated sites: Physical barriers to prevent further contaminant migration
3. Alternative water supply: Provide safe drinking water to affected communities

Long-term remediation:

1. Phytoremediation: Hyperaccumulator plant species (e.g., Brassica juncea for Cd, Pb; Vetiveria zizanioides for Cr) for gradual soil cleanup
2. Soil amendments: Application of biochar, lime, or phosphate compounds to immobilize metals and reduce bioavailability
3. In-situ chemical fixation: Chemical treatments to convert soluble metal species to insoluble forms

6.2 Monitoring Framework

1. Establish permanent monitoring network: Regular sampling of groundwater, soil, and crops at standardized sites
2. Real-time water quality monitoring: Install sensors at industrial discharge points
3. Community-based monitoring: Train local residents in sample collection and basic water quality testing
4. Public data portal: Transparent reporting of contamination levels and health risks

6.3 Agricultural Interventions

1. Crop selection guidance: Promote cultivation of low-accumulator crops (fruits, cereals) over high-accumulator crops (leafy vegetables) in contaminated areas
2. Irrigation water treatment: Low-cost filtration and treatment systems for irrigation water
3. Soil management: Practices to reduce metal bioavailability (maintain pH near neutral, add organic matter)

6.4 Public Health Response

1. Health surveillance: Establish registry for heavy metal-related diseases
2. Nutritional interventions: Supplementation with iron, calcium, and zinc (competes with heavy metal absorption)
3. Dietary diversification: Reduce reliance on locally grown contaminated foods
4. Medical infrastructure: Train healthcare providers in heavy metal toxicity diagnosis and management

6.5 Policy Recommendations

1. Strengthen enforcement: Current pollution control regulations are adequate but poorly enforced
2. Polluter-pays principle: Hold industries financially responsible for remediation and health costs
3. Land use planning: Buffer zones between industrial and agricultural areas
4. Compensation mechanism: For affected communities with documented health impacts

VII. CONCLUSION

This study comprehensively evaluated the trophic transfer of industrial heavy metals from polluted irrigation water through the food chain in Unnao, India. Evidence collected from multiple investigations over the past fifteen years clearly indicates severe contamination of groundwater, agricultural soils, and edible crops with toxic metals such as chromium (Cr), cadmium (Cd), lead (Pb), zinc (Zn), and copper (Cu). Chromium concentrations in groundwater at Jajmau reached 7.08 mg/L, far exceeding

WHO permissible limits, while cadmium levels in agricultural soil were several times higher than accepted standards. Statistical analyses confirmed that industrial activities, particularly tannery effluents and untreated industrial discharge, are the principal contributors to contamination.The study also demonstrated active transfer of heavy metals through the water–soil–crop–human pathway, resulting in the accumulation of toxic elements in edible plant parts. Leafy vegetables showed the highest contamination levels, followed by cereals and fruits. Such contamination poses serious public health risks, including carcinogenic and non-carcinogenic effects, with children being particularly vulnerable. The findings highlight environmental injustice, as economically weaker rural populations bear the greatest exposure burden. Immediate remediation, stricter industrial regulation, continuous monitoring, and sustainable wastewater management are essential to protect public health and environmental quality in the region.

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