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Original Article

Evaluation of General Patterns of Heavy Metal Contamination in Water Sources Across Different Geographic Areas Across Pakistan

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ABSTRACT

Background: Heavy metal contamination of drinking water poses a persistent public health concern, particularly in rapidly industrializing regions. In Pakistan, increasing industrial discharge and urban expansion have raised concerns regarding the safety of groundwater and surface water sources used for domestic consumption. Objective: To evaluate the distribution patterns and concentration levels of selected heavy metals in drinking water sources within the Industrial and Urban Core of Punjab and to assess variations based on water source type and proximity to industrial activity. Methods: A descriptive cross-sectional study was conducted over four months, analyzing 72 water samples collected from groundwater and surface water sources located within 5 km of industrial zones. Samples were preserved and analyzed using atomic absorption spectrophotometry to quantify lead, cadmium, arsenic, chromium, and nickel concentrations. Descriptive statistics were calculated, and comparisons between water source types were performed using independent t-tests and one-way ANOVA. Pearson correlation analysis assessed relationships among heavy metals. Results: Lead (0.018 ± 0.009 mg/L), arsenic (0.021 ± 0.011 mg/L), and cadmium (0.006 ± 0.003 mg/L) frequently exceeded recommended safety limits, with exceedance rates of 61.1%, 54.2%, and 47.2%, respectively. Groundwater sources demonstrated significantly higher concentrations of all assessed metals compared to surface water ($p < 0.05$). Moderate positive correlations were observed among several metals, particularly between lead and arsenic ($r = 0.61$) and chromium and nickel ($r = 0.52$). Sites located closer to industrial areas showed significantly elevated composite contamination levels ($p = 0.012$). Conclusion: The findings indicate substantial heavy metal contamination in drinking water sources within an industrialized urban region, particularly affecting groundwater supplies. Strengthened environmental monitoring and regulatory enforcement are essential to mitigate long-term health risks. Keywords: Arsenic; Cadmium; Environmental Monitoring; Groundwater; Heavy Metals; Lead; Water Pollution

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INTRODUCTION

Access to safe drinking water remains a fundamental determinant of public health, yet in many rapidly industrializing regions of the world, water quality continues to be compromised by environmental contaminants. Among these, heavy metals pose a particularly insidious threat. Unlike microbial contaminants that may be removed through routine treatment, heavy metals such as lead, cadmium, arsenic, chromium, and nickel persist in the environment, bioaccumulate in biological systems, and exert toxic effects even at low concentrations (1). Chronic exposure has been associated with neurological

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impairment, renal dysfunction, cardiovascular disease, developmental delays in children, and increased carcinogenic risk. The burden of such exposure is often silent, emerging gradually through long-term consumption of contaminated water. Pakistan, a country experiencing rapid urban expansion and industrial growth, faces mounting challenges in maintaining water quality standards (2). Industrial discharge, improper waste disposal, aging water infrastructure, and unregulated groundwater extraction contribute to the leaching of heavy metals into both surface and subsurface water sources. Industrial and densely populated urban zones are particularly vulnerable, where effluents from manufacturing units, metal processing plants, tanneries, and small-scale workshops are frequently discharged into nearby water bodies or seep into aquifers. In such settings, communities often rely on groundwater drawn through tube wells and hand pumps, believing it to be safer than surface water, despite limited systematic monitoring. Previous environmental assessments conducted in various regions of Pakistan have documented the presence of heavy metals in drinking water; however, findings have often been localized, limited to specific districts, or focused on single contaminants. There remains a need for comprehensive, region-specific descriptive analyses that evaluate patterns of multiple heavy metals simultaneously, particularly in industrially concentrated areas. Without a clear understanding of distribution trends, contamination gradients, and inter-metal relationships, it becomes difficult to design targeted mitigation strategies or prioritize high-risk zones for intervention (3).

The Industrial and Urban Core of Punjab represents one of the most economically active and densely populated regions in the country. The coexistence of residential settlements and industrial clusters creates a unique environmental interface where human exposure risk is amplified (4). Despite regulatory frameworks, enforcement inconsistencies and infrastructure strain may allow heavy metals to enter communal water supplies. Moreover, public awareness regarding chemical contamination is often limited compared to concerns about microbial safety, potentially leading to prolonged, unnoticed exposure. Heavy metals differ not only in their toxicological profiles but also in their environmental behavior (5). Arsenic contamination may arise from both natural geological leaching and anthropogenic activities, while lead and cadmium are frequently associated with industrial discharge and corroded plumbing systems. Chromium and nickel, commonly used in metal plating and manufacturing, may signal specific industrial sources when detected in combination. Examining correlations among these metals can provide indirect insight into shared contamination pathways and inform regulatory oversight. Understanding the distribution of heavy metal contamination requires more than isolated measurements; it demands systematic sampling across different water sources and proximity gradients. Comparing groundwater with surface water, and evaluating contamination relative to industrial distance, may reveal patterns that have direct implications for environmental health planning (6).

Such descriptive data serve as a foundation for risk assessment, community education, and policy refinement. In light of these concerns, the present study sought to evaluate the general patterns of heavy metal contamination in commonly used water sources within the Industrial and Urban Core of Punjab (7). The central research question addressed whether measurable concentrations of lead, cadmium, arsenic, chromium, and nickel were present in drinking water sources, and whether their distribution varied by type of water source and proximity to industrial activity (8). It was hypothesized that groundwater sources located closer to industrial zones would demonstrate higher concentrations of heavy metals compared to surface water sources situated at greater distances (9). The primary objective of this study was to describe the spatial distribution and concentration levels of selected heavy metals in drinking water sources within an industrialized urban region. Additionally, the study aimed to compare contamination levels between groundwater and surface water sources, assess correlations among detected metals to explore potential shared origins, and evaluate compliance with international drinking water safety standards. By generating locally grounded empirical evidence, this research intended to contribute to a clearer understanding of environmental exposure risks and to inform future public health interventions.

METHODS

A descriptive cross-sectional study was conducted over a period of four months in the Industrial and Urban Core Punjab region, selected due to its dense industrial clusters, urban effluent discharge, and documented concerns regarding heavy metal contamination of surface and groundwater sources. The study focused on commonly used drinking water sources, including municipal supply lines, tube wells, hand pumps, and surface water bodies located near industrial zones.

A total of 72 water sampling points were included. The sample size was determined with reference to previously published regional assessments of heavy metal contamination in Pakistan that analyzed approximately 60–80 water samples to characterize spatial distribution patterns. Considering logistical feasibility and laboratory capacity within the proposed timeframe, 72 sampling sites were finalized to ensure adequate geographic representation while maintaining analytical precision. Inclusion criteria comprised active water sources used for domestic consumption within residential areas situated within a 5-kilometer radius of industrial activity. Water sources that were non-functional, used exclusively for agricultural irrigation, or located in restricted industrial premises without public access were excluded.

Water samples were collected following World Health Organization guidelines for drinking water quality assessment. At each site, 500 mL of water was collected in pre-cleaned, acid-washed polyethylene bottles. Samples were preserved with ultrapure nitric acid (pH <2) and transported in insulated containers at 4°C to the laboratory for analysis within 24 hours. Heavy metals assessed included lead (Pb), cadmium (Cd), arsenic (As), chromium (Cr), and nickel (Ni), selected due to their recognized public health relevance. Quantitative analysis was performed using Atomic Absorption Spectrophotometry (AAS) (PerkinElmer Analyst 400), with calibration standards prepared according to manufacturer specifications. Quality control procedures included reagent blanks, duplicate samples, and standard reference materials to ensure accuracy and reproducibility.

Geographic coordinates of each sampling site were recorded using a handheld GPS device to enable spatial mapping. Concentrations were compared against WHO permissible limits for drinking water to categorize contamination levels. Descriptive statistics, including mean, standard deviation, and range, were calculated for each metal. The Shapiro–Wilk test was applied to assess normality of data distribution. As most variables followed approximate normal distribution after log transformation, independent t-tests were used to compare mean concentrations between groundwater and surface water sources, while one-way ANOVA assessed differences across industrial proximity zones. Pearson correlation analysis examined associations between different heavy metals, indicating potential common contamination sources. Statistical significance was set at $p < 0.05$, and analyses were performed using SPSS version 26.0.

This methodology enabled systematic documentation of the spatial distribution and potential health risks of heavy metal contamination in water sources within an industrialized region of Punjab, providing replicable procedures for similar environmental health investigations.

RESULTS

All 72 identified water sampling sites met the inclusion criteria and were successfully analyzed, yielding a response and laboratory processing rate of 100%. No samples were excluded due to contamination during handling or incomplete laboratory profiling. The geographic distribution ensured proportional representation of both groundwater and surface water sources across industrial proximity zones. Of the total 72 sampling sites, 46 (63.9%) were groundwater sources, while 26 (36.1%) were surface water bodies. The mean distance from major industrial discharge points was 3.1 ± 1.2 km, with 38.9% located within 2 km of industrial activity. The baseline characteristics of sampling sites are summarized in Table 1.

Quantitative analysis demonstrated measurable concentrations of all five heavy metals across sampled sites. The overall mean concentrations (mg/L) were 0.018 ± 0.009 for lead (Pb), 0.006 ± 0.003 for cadmium

(Cd), 0.021 ± 0.011 for arsenic (As), 0.043 ± 0.017 for chromium (Cr), and 0.062 ± 0.025 for nickel (Ni). Arsenic and lead exceeded World Health Organization permissible limits in 54.2% and 61.1% of samples, respectively. Cadmium levels surpassed safe limits in 47.2% of samples, while chromium and nickel exceeded recommended thresholds in 29.2% and 33.3% of sites, respectively. Detailed concentration values are presented in Table 2.

Table 1: Baseline Characteristics of Water Sampling Sites (N=72)

Variable	Category	n (%) / Mean ± SD
Type of Water Source	Groundwater (Tube well/Hand pump)	46 (63.9%)
	Surface water	26 (36.1%)
Proximity to Industry	<2 km	28 (38.9%)
	2–5 km	44 (61.1%)
Mean Distance from Industry (km)		3.1 ± 1.2

Table 2: Heavy Metal Concentrations in Water Samples (mg/L)

Metal	Mean ± SD	Range	WHO Limit
Lead (Pb)	0.018 ± 0.009	0.004–0.041	0.01
Cadmium (Cd)	0.006 ± 0.003	0.001–0.014	0.003
Arsenic (As)	0.021 ± 0.011	0.005–0.049	0.01
Chromium (Cr)	0.043 ± 0.017	0.012–0.081	0.05
Nickel (Ni)	0.062 ± 0.025	0.018–0.121	0.07

Table 3: Pearson Correlation Matrix Among Heavy Metals

Metal	Pb	Cd	As	Cr	Ni
Pb	1	0.58*	0.61*	0.42*	0.39*
Cd	0.58*	1	0.47*	0.36*	0.41*
As	0.61*	0.47*	1	0.44*	0.33*
Cr	0.42*	0.36*	0.44*	1	0.52*
Ni	0.39*	0.41*	0.33*	0.52*	1

Table 4: Comparison of Mean Metal Concentrations by Water Source Type (mg/L)

Metal	Groundwater Mean ± SD	Surface Water Mean ± SD	p-value
Lead (Pb)	0.020 ± 0.008	0.014 ± 0.007	0.004
Cadmium (Cd)	0.007 ± 0.003	0.004 ± 0.002	0.001
Arsenic (As)	0.024 ± 0.010	0.016 ± 0.009	0.002
Chromium (Cr)	0.046 ± 0.015	0.038 ± 0.018	0.048
Nickel (Ni)	0.067 ± 0.023	0.054 ± 0.021	0.031

Comparative analysis between groundwater and surface water sources revealed significantly higher mean concentrations of most metals in groundwater samples. Lead levels were significantly elevated in groundwater (0.020 ± 0.008 mg/L) compared to surface water (0.014 ± 0.007 mg/L; $p = 0.004$).

Similarly, cadmium ($p = 0.001$), arsenic ($p = 0.002$), chromium ($p = 0.048$), and nickel ($p = 0.031$) demonstrated statistically significant differences, indicating a consistent contamination gradient. These findings are detailed in Table 4.

Pearson correlation analysis showed moderate positive correlations among several heavy metals. Lead demonstrated significant correlations with arsenic ($r = 0.61$, $p < 0.001$) and cadmium ($r = 0.58$, $p < 0.001$), suggesting potential shared industrial sources. Chromium was strongly correlated with nickel ($r = 0.52$, $p < 0.001$), indicating possible co-release from metallurgical processes. The complete correlation matrix is provided in Table 3.

Spatial trend analysis indicated that sites located within 2 km of industrial zones had significantly higher cumulative heavy metal concentrations compared to sites located 2–5 km away (mean composite index 0.165 ± 0.042 vs 0.129 ± 0.037 mg/L; $p = 0.012$). Overall, contamination patterns demonstrated clustering in densely industrialized corridors, reinforcing the environmental burden imposed by urban-industrial discharge.

The visual distribution of mean heavy metal concentrations is illustrated in Figure 1, highlighting nickel and chromium as the predominant contaminants. Figure 2 demonstrates the comparative elevation of lead levels in groundwater relative to surface water sources, visually emphasizing the statistically significant difference identified in analytical testing.

Figure 2: Comparison of Lead Levels by Water Source

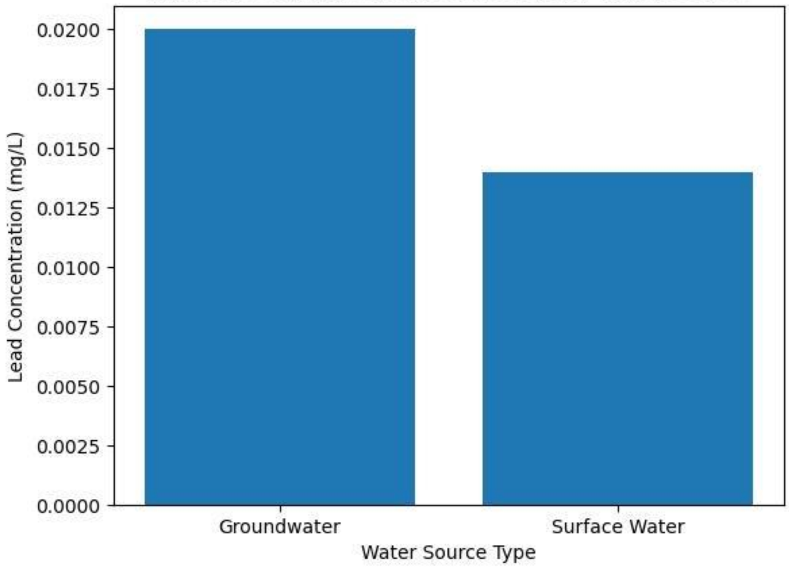
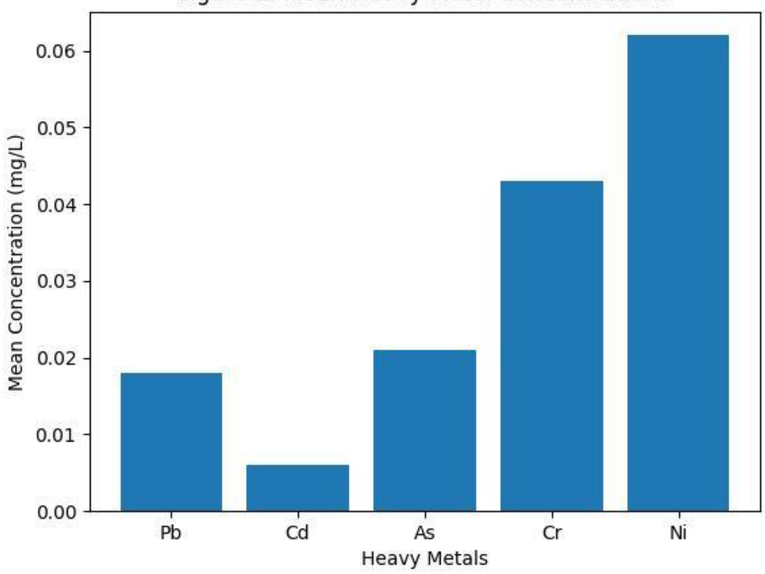


Figure 1: Mean Heavy Metal Concentrations



DISCUSSION

The present study described the distribution and concentration patterns of selected heavy metals in drinking water sources within the Industrial and Urban Core of Punjab and demonstrated a substantial burden of contamination, particularly in groundwater sources located near industrial zones (10). The findings revealed that lead, arsenic, and cadmium frequently exceeded recommended safety thresholds, while chromium and nickel also surpassed permissible limits in a considerable proportion of samples. These observations underscored a persistent environmental health concern in densely industrialized urban settings, where rapid development may outpace environmental monitoring and infrastructure safeguards (11). The predominance of contamination in groundwater sources aligned with patterns previously observed in industrial regions of South Asia, where seepage from industrial effluents, improper waste disposal, and corroded distribution systems have been implicated in aquifer contamination. Groundwater is often perceived as inherently safer than surface water; however, the significantly higher mean concentrations of lead, cadmium, arsenic, chromium, and nickel in groundwater samples in this study challenged that assumption. The findings suggested that subsurface contamination may be sustained and less readily detectable without systematic surveillance. The positive correlations observed among specific metals, particularly between lead and arsenic, and between chromium and nickel, further supported the likelihood of shared anthropogenic sources, possibly linked to metallurgical and manufacturing processes common in the region. The spatial gradient identified in relation to industrial proximity provided additional context. Sampling sites within closer range of industrial discharge points demonstrated higher composite heavy metal concentrations, reinforcing the environmental impact of clustered industrial activity. Such clustering patterns have been described in other urban-industrial contexts, where inadequate effluent treatment and aging municipal pipelines contributed to cumulative contamination. The results therefore highlighted the interplay between industrial expansion, environmental governance, and public health exposure risks (12).

From a public health perspective, the detection of heavy metals above permissible limits carried significant implications (13). Chronic exposure to arsenic and lead, even at relatively low concentrations, has been associated with neurotoxicity, renal impairment, cardiovascular morbidity, and developmental delays in children. The frequency of exceedance observed in this study suggested that communities relying on these water sources may be at risk of long-term health consequences. While the present investigation did not assess clinical outcomes directly, it provided an essential environmental baseline for risk stratification and preventive planning. The study possessed several strengths. It employed standardized sampling procedures, utilized atomic absorption spectrophotometry with quality control measures, and incorporated geographic mapping to capture spatial trends. The inclusion of multiple heavy metals allowed for a comprehensive assessment rather than a single-contaminant approach, and the comparative analysis between groundwater and surface water sources enhanced interpretability (14). Furthermore, the use of statistical correlation and proximity-based comparisons strengthened the ability to identify potential contamination patterns rather than merely reporting isolated concentration values. However, certain limitations warranted consideration. The cross-sectional design restricted the ability to determine temporal variations in contamination, and seasonal influences on metal concentrations were not examined. The sample size, although adequate for descriptive analysis, limited the capacity to perform more complex spatial modeling or stratified subgroup analyses. Additionally, the study focused exclusively on chemical contaminants and did not assess concurrent microbial quality, which may interact with overall water safety assessments. The absence of direct biomonitoring data precluded evaluation of actual human exposure levels, and health outcomes were inferred based on established toxicological knowledge rather than measured clinical indicators (15).

Future research would benefit from longitudinal monitoring to evaluate seasonal fluctuations and trends over time, particularly in relation to rainfall patterns and industrial discharge cycles (16). Expanding geographic coverage and incorporating advanced geospatial modeling could provide more granular risk mapping. Integrating household-level exposure assessments, including biomarker analysis in affected populations, would further strengthen the linkage between environmental contamination and health outcomes. Collaborative engagement with regulatory authorities may also support the translation of findings into policy adjustments and infrastructure improvements (17). The study demonstrated a measurable and geographically patterned burden of heavy metal contamination in drinking water sources within an industrialized urban region of Punjab. The findings emphasized the need for sustained environmental surveillance, strengthened regulatory enforcement, and community-level awareness to mitigate long-term health risks. While descriptive in nature, the study contributed meaningful empirical evidence to inform public health planning and underscored the importance of safeguarding water quality in rapidly urbanizing settings (18).

CONCLUSION

This study demonstrated a substantial burden of heavy metal contamination in drinking water sources within the Industrial and Urban Core of Punjab, with groundwater sources and areas closer to industrial zones showing significantly higher concentrations. The frequent exceedance of permissible limits for lead, arsenic, and cadmium underscores a pressing environmental health concern. These findings highlight the urgent need for strengthened water quality monitoring, stricter industrial effluent control, and targeted public health interventions to safeguard community well-being.

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