



Heavy Metal Contamination in Surface and Groundwater Near a Landfill: Source Apportionment and Health Risk Assessment

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ABSTRACT

Landfilling remains one of the predominant municipal solid waste disposal methods in the world, however, improperly designed landfills pose severe threats to the surrounding aquatic systems through the leaching of toxic chemicals. This study investigated heavy metals (HMs)- cadmium (Cd), chromium (Cr), copper (Cu), lead (Pb), zinc (Zn) and a metalloid; arsenic (As) in surface and groundwater (25 samples each) around a landfill site in Khanewal District located in Central Punjab. The HMs were analyzed using Flame Atomic Absorption Spectrometer (FAAS) while As was analyzed using Hydride Generation AAS. Results obtained indicated that the mean concentrations of As, Cd, and Pb in both surface (0.05, 0.009, 0.13) mg/l and groundwater (0.029, 0.03, 0.04) mg/l exceeded the World Health Organization (WHO) permissible limits. The correlation, cluster analysis, and principal component analysis (PCA) all showed high positive relationships between most metals. According to the heavy metal pollution index, the groundwater quality classified as poor to unsuitable due to elevated concentrations of Cd, Cu, Pb, Zn, and As. Health Risk Assessments (HQ>1) revealed significant non-carcinogenic risks associated with Cd and As exposure through drinking groundwater. Collectively, these findings highlight the urgent need to strengthen municipal solid waste management through engineered landfill design, effective leachate collection and treatment, continuous groundwater quality monitoring, and risk-based remediation strategies to mitigate landfill-derived heavy metal contamination, protect drinking water resources, and reduce potential human health risks.

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INTRODUCTION

Municipal solid waste (MSW) management remains a major environmental challenge in Punjab, which generates about 47,300 tons of solid waste per day. The improper disposal of MSW poses serious environmental risks to soil and air quality, surface and groundwater, as well as human health (Gupta & Raju, 2023). Many studies have highlighted that improper disposal of MSW and landfills leachates causes surface and ground water contamination (Hussain et al., 2025). The landfill leachate contains many toxic chemicals including organic matter, inorganic compounds, toxic heavy metals, and xenobiotic compounds which could be toxic and carcinogenic (Kulkarni, 2020; Maturi et al., 2022; Mor & Ravindra, 2023). The

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excess quantity of toxic Heavy Metals (HMs) contaminates the surface and groundwater and may cause chronic health impacts not for aquatic life but also to human beings. The permissible level of these HMs is determined by World Health organization (WHO), as well as the National Environmental Quality Standards (NEQs). While some anions also contaminate the water if present above sufficiency level environment (Maturi et al., 2022).

There can be other sources of heavy metal pollution in ecosystem that may include both geogenic (weathering and attrition of bedrocks, ore deposits, and volcanic eruptions) and anthropogenic (solid waste dumping, mining, industries, wastewater irrigation, agriculture smelting) activities (Tahiri et al., 2017; Verma et al., 2015). Such sources may pollute freshwater bodies which include wells, lakes, springs, rivers, and streams. Occurrence of surface water bodies in vicinities of highly populated and industrialized areas results in water pollution and contamination (Selvam et al., 2011). The movement of landfill leachate into surface or groundwater at both uncontrolled and engineered municipal dump sites is seen as a significant environmental issue (Kulkarni, 2020). For the past few years, groundwater poisoning by arsenic (As) has been a major environmental and health concern in numerous parts of the world (Shahid et al., 2017). A study investigated that the groundwater of Pakistan is extremely polluted and dangerous for drinking purposes because most of the pollutants surpass their standard limit based on the WHO and NEQS (Raza et al., 2017). Pakistan ranks fourth globally among Arsenic pollution (Masood et al., 2021). The Rural Sindh, and majority areas of Punjab including Quetta, Lahore, Kasur, Gujrat, Swabbi, and Umerkot are worst affected with As pollution (Ehsan et al., 2020).

Khanewal is situated between the coordinates (30.2864° N, 71.9320° E), carrying a population of 3,364,077 (PSB, 2023) in district Punjab, Pakistan. According to the latest survey, 90% of the households in this district have access to drinking water inside the homes and groundwater is their major water source. Khanewal hosts many industries and the effluents from these industries often contain HMs which end up in the water bodies that may cause severe water and environmental problems. The foremost issue triggered by the landfill is the outflow of a huge amount of toxins, especially the HMs into freshwater channels, which eventually end up in our homes for daily use. This landfill is located near large bodies of freshwater sources that frequently results in the pollutants being overlooked. A number of studies have been conducted in different regions of Punjab regarding the identification of groundwater pollution sources, impacts on environment and human health, as well as the mitigation strategies; however, very few studies have been conducted regarding the source apportionments in Punjab (Hussain et al., 2022; Iqbal et al., 2024), and no such study has been conducted in this district. Moreover, no such research has evaluated the level of leachate and its contamination in the ground and surface, and the ultimate chronic health impacts on human bodies through exposure to this water. Therefore, this study investigates the source apportionment of Cd, Cr, Cu, Pb, Zn, and As, characterizes their occurrence in surface and groundwater, and evaluates the potential chronic human health risks associated with exposure to contaminated water.

MATERIALS AND METHODS

Study Site and Sampling Techniques

The current study was conducted in Khanewal, a District situated in central Punjab. Khanewal District lies within the Lower Bari Doab of the central Indus Plain and is characterized by a flat Quaternary alluvial landscape. The surface geology consists mainly of unconsolidated sand, silt, clay, and gravel deposits, which overlie deeply buried Tertiary sedimentary formations and Precambrian crystalline basement rocks, forming a highly productive alluvial aquifer (Hussain & Karuppannan, 2023). The surface and groundwater samples (25 each) were collected from

the landfill site situated near Fazal Park, Kot Alla Singh. The samples were collected through composite sampling to ensure true representation of area between 8:00 A.M to 4:00 P.M. with help of pre-washed 50mL bottles. To ensure the quality, appropriate labeling of sample site was done using permanent marker, and caps were sealed using tape, and transported to the laboratory for preservation and lab analysis. Water samples were stored at 4 °C before analysis.

Sample Preparation and Analysis

100 ml of well mixed acid preserved water sample was transferred into a beaker and 5 ml of concentrated nitric acid was added. The beaker was placed on a heater and allowed to evaporate to about 5 ml without boiling. This took about 35 min, diluted to 100 ml in a volumetric flask and was ready for analysis. (Nouri et al., 2008). Same digestion procedure was followed for all the collected surface and ground water samples for the analysis of each metal. FAAS (Vario 6, Analytical Jena GmbH, Germany) was used to examine the heavy metals (Cd, Cr, Cu, Pb, and Zn) in collected water samples, while HGAAS was used to detect As. Before analysis system was calibrated by using aqueous standards of analytical grade for each of the elements. Furthermore, the quality of the results was assured by using the spike recovery method for the samples to be analyzed (Tahiri et al., 2017; Winkel et al., 2008). The detection limit was 1 ppb for collected water samples.

Hazards Assessment

The following parameters were used to assess the extent of risk involved by the use of heavy metals contaminated drinking water.

Pollution index (Wang et al. 2008) was applied to compare temporal–spatial variations of water quality in surface and ground water as follows:

$$PI_i = \frac{C_i}{C_{si}} (i = 1, 2, \dots, n) \quad (1)$$

Where PI_i is the pollution index of i^{th} variable, C_i is the arithmetic mean concentration of i^{th} variable, and C_{si} is the standard concentration value of i^{th} variable. When PI is greater than 1, the variable is regarded as characteristic pollutant.

Human health risk assessment

The health risk via ingestion of HMs present in contaminated water of the study area was assessed using health risk equations such as daily intake of metals (DIMs) and health risk index (HRI).

The DIM through water drinking is calculated according to the following modified from Muhammad et al. (2011).

$$DIM = \frac{C_m \times DI_w}{BW} \quad (2)$$

Where the concentration of HMs in water (mg /L), DI_w is the average daily intake of water i.e 2 L/day for adult and 1 L/day for children (US-EPA 2011), while BW is the average body weight (72 kg for adult and 32.7 kg for children) (Nawab et al., 2015, Khan et al., 2013).

The HRI of metals through water consumption was calculated using the following equation (Khan et al., 2013; Nawab et al., 2015).

$$HRI = \frac{DIM}{RfD} \quad (3)$$

Whereas, the DIM is the average daily intake of a selected metal and RfD is the oral toxicity reference dose. The value of $HRI < 1$ for selected metal is considered to be safe (Khan et al.,

2013; US-EPA, 2005)

Pollution Source Apportionment

The coefficient of Correlation was used to discover the correlation among metals (HMs). The leading factors of contamination were identified using principal component analysis (PCA), while hierarchical cluster analysis (HCA) was employed to recognize homogeneous clusters of sampling sites (Heberger et al., 2005). A detailed description of PCA techniques and absolute component score can be found elsewhere in the literature (Guo et al., 2004).

RESULTS AND DISCUSSION

Heavy Metals in Surface Water

The concentration of HMs in surface and reference water samples is shown in Table 1. The concentration of Chromium (Cr) in surface water samples ranged from 0.01 to 0.34 mg/l, substantially exceeding the WHO of 0.05mg/L. High Cr levels in most of the samples (63%) may result due to industrial effluents, particularly from the wood and beverage sectors, residential waste, or surface runoff

The amount of As in surface and reference water ranged from 0.01 to 0.21 mg/l and 0.004 to 0.007 mg/l respectively. The As concentrations of 19 samples out of 22 (86.36%) were greater than WHO permissible level i.e. 0.01 mg/l. It was observed that the concentration of Cd in surface water samples ranged from 0.001 to 0.019 mg/l and whereas in reference samples it ranged from 0.001 to 0.003 mg/l. The 17 samples out of 22 (77.27%) collected from canal water showed the concentration higher than the WHO permissible level for Cd, i.e., 0.003 mg/l. The concentration of Pb in surface water samples collected from the canal ranged from 0.01 to 0.23 mg/l. These values were higher than the WHO permissible level of Lead in water i.e., 0.010 mg/l. High lead (Pb) concentrations may stem from paper and wood discharges, domestic and industrial effluents, road runoff from Pb fuel residues, traffic emissions, and residential waste. The concentration of Cu in all of the canal water samples ranged from 0.001 to 0.02 mg/l. None of the samples depicted concentrations higher than WHO permissible level of Cu and Zn in canal water.

Heavy Metals in Ground Water

The concentration of HMs in ground and reference water samples is shown in Table 1. It was observed that concentration of Cd in groundwater samples ranged from 0.01 to 0.05 mg/l. All samples showed concentrations higher than WHO permissible level for Cd. The results of the analysis show that the level of As in groundwater ranged from 0.01 to 0.08 mg/l and 0.004 to 0.007 mg/l in ground water and the reference samples, respectively. The As level of 16 samples out of 22 (72.7%) were higher than the WHO permissible level for water, i.e., 0.01 mg/l. Heavy rainfall-induced erosion near the Khanewal landfill likely caused high concentrations. It was observed that Cr level in all the water samples collected from groundwater around the landfill

Table 1. Concentration (mg/l) of heavy metals in collected and reference surface and groundwater samples

Sample Type	Surface Water Average (range)	Ground Water Average (range)	Permissible value	Canal Water (R)	Ground water (R)
As	0.05(0.01-0.21)	0.029(0.01-0.08)	0.01	0.005	0.005
Cd	0.009(0.002-0.02)	0.03(0.01-0.05)	0.003	0.002	0.002
Cr	0.09(0.01-0.34)	0.04(0.001-0.08)	0.05	0.06	0.06
Cu	0.01(0.001-0.02)	0.02(0.001-0.06)	2.0	0.002	0.002
Pb	0.13(0.01-0.22)	0.04(0.01-0.08)	0.01	0.004	0.004
Zn	0.04(0.01-0.08)	0.03(0.002-0.05)	3.0	0.002	0.002

Table 2. Correlation of heavy metals in surface water

	As	Cd	Cr	Cu	Pb
Cd	0.403 0.046				
Cr	0.294 0.154	-0.149 0.477			
Cu	-0.067 0.749	-0.14 0.504	0.185 0.375		
Pb	0.337 0.1	0.086 0.683	0.107 0.611	0.41 0.042	
Zn	0.471 0.017	0.375 0.065	-0.024 0.908	0.093 0.657	0.576 0.003

site ranged from 0.011 to 0.078 mg/l. The 7 samples out of 22 show a higher level than the WHO permissible level for Cr. One out of three reference samples also exceeded the WHO level of 0.05 mg/l. The concentration of Cu in groundwater samples ranged from 0.006 to 0.055 mg/l. The results demonstrated that the concentration of Pb in groundwater samples collected around the landfill site ranged from 0.013 to 0.079 mg/l. These values were higher than WHO permissible level of Lead in water, 0.010 mg/l. It was also observed that Zn concentrations ranged from 0.02 to 0.052 mg/l in samples collected from ground water lying within WHO permissible level for Zn.

The concentrations of HMs in surface and groundwater highlighted the influence of leachate penetration from the improperly designed landfill site and anthropogenic impacts (urban-industrial runoff). The observed As and Pb concentrations are consistent with the findings of (Malik et al., 2014), who reported Pb (0.079 mg/L) and Cd (0.051 mg/L) near Kot Lakhpat Landfill, Lahore. Some other studies of (Ahmad et al., 2013; Ehsan et al. 2020; Hussain et al., 2022; Najam et al. 2015) also highlighted the accelerated concentrations of HMs and As in other regions of Punjab. The soil texture of Punjab plains is mostly loamy alluvial soil having high hydraulic conductivity (1.2×10^{-4} to 3.5×10^{-3} m/s), which percolates HMs and other metalloids in the groundwater, especially during the monsoon season. Moreover, the other possible sources of contamination are industrial effluents, vehicular emissions, batteries, and fertilizers. The studies have highlighted that the elevated concentrations of As (>0.01 mg/L), for a long term, is strongly associated with cardiovascular diseases, skin lesions, and higher risks of chronic diseases including cancer (Mouine, 2022). The higher Cd concentrations (>0.003 mg/L) may contribute to renal dysfunctioning, and bioaccumulation in food chain. While even the minor concentrations of Pb may cause neurological disorders, hypertension, and anemia (Ehsan et al., 2025).

Source Apportionment of Heavy Metals Using Multivariate Statistical Analysis

The findings of the Pearson correlation analysis of the gathered data for surface water are displayed in Table 2. It depicts complex correlations exist among all the investigated heavy metals in the collected canal water samples. From the results it can be observed that the correlation coefficients of Pb-Zn (0.576) show a strong positive correlation indicating that these metals are likely originated from similar sources. The correlation coefficients of Zn-Cd (0.375), As-Cd (0.402), As-Zn (0.471), Pb-Cu (0.41), and Pb-As (0.337) depicted a moderate positive correlation, indicating that these pairs may be coming from the same source of pollution. Correlation coefficients among Cr-Cu (0.185), As-Cr (0.294), and Pb-Cr (0.107) indicate a small positive correlation. Correlation coefficients for Cu-Cd (-0.14), Cr-Cd (-0.149), Cr-Zn (-0.024), and As-Cu (-0.067) were generally negative suggesting that the origins of these metal pairings were probably distinct. The links between these items and their major sources were further examined using a principal component and cluster analysis.

The dendrogram of sites attained by Complete Linkage technique in canal water from

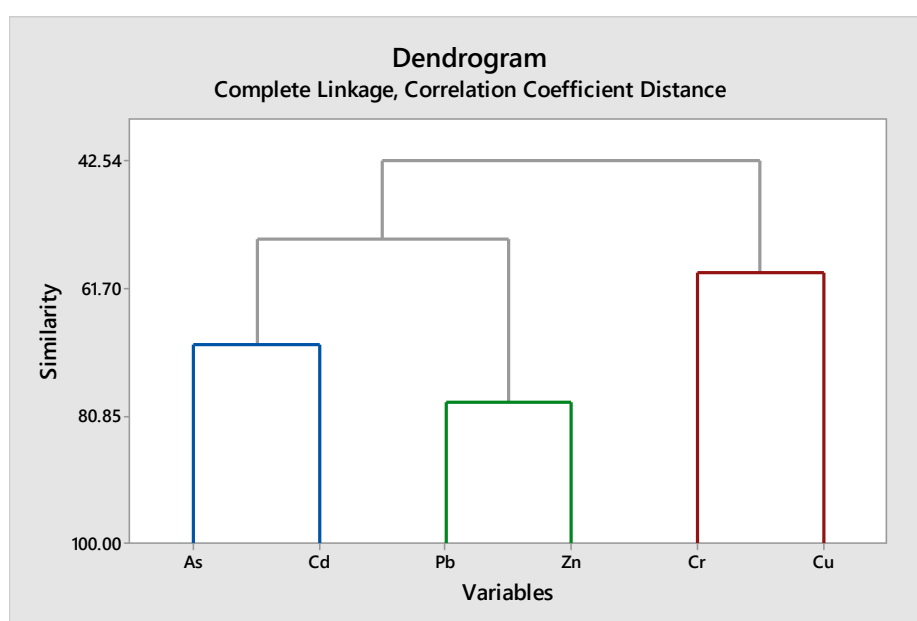


Fig. 1. Dendrogram hierarchical cluster analysis of six heavy metals in surface water

Table 3. PCA for surface water

Variable	PC1	PC2	PC3	PC4	PC5	
Cd	0.345	0.528	0.033	0.688	0.205	
Cu	0.171	-0.639	0.295	0.581	-0.16	
Zn	0.562	0.106	0.22	-0.312	0.518	
Cr	0.142	-0.412	-0.766	0.093	0.443	
As	0.506	0.174	-0.441	-0.06	-0.675	
Pb	0.509	-0.318	0.286	-0.283	-0.111	
EIGENVALUE	2.1974	1.4428	1.0712	0.621	0.3617	0.3059
PROPORTION	0.366	0.24	0.179	0.104	0.06	0.051
CUMULATIVE	0.366	0.607	0.785	0.889	0.949	1

Khanewal District is shown in Figure 1. Based on dendrogram, 6 variables can be clustered into three main clusters. First group includes Cd and As while group 2 comprises of Zn and Pb. The third group contains Cu and Cr. Certain variations in the behavior and reactivity of certain metals in water, which impact their mobility, may be the cause of these variations in spatial distribution.

The five principal components (PC) were extricated for the canal water for the studied database, and they are presented in Table 3. The results show that 78.5 percent of the variance is explained by Eigen values greater than 1, which is helpful in determining the primary causes of variation in the hydrochemistry of trace metals in all water samples.

PC 1 defines 36.6 % of variance with positive loadings of all metals and metalloid like Cd, Cu, Zn, Pb, Cr and As. These are also confirmed by cluster analysis and correlation analysis where they share the same clusters and in Pearson correlation analysis, they also exhibit the positive correlation indicate that they may originate from similar source of distribution. Thus, PC 1 can be accredited to rising urban activities as well as growing household and industrial waste in the catchment area revealing the anthropogenic sources of contamination. PC 2 with 60.7 % of the total variance loads positive scores of Zn, Cd, and As with major contribution of As and Cd sharing the same cluster in CA (Figure 2). The main causes of high Cd levels are surface runoff from agricultural lands and surface water contamination brought on by farmers' use of different fertilizers (Singh & Kumar, 2017). The primary cause of As contamination in

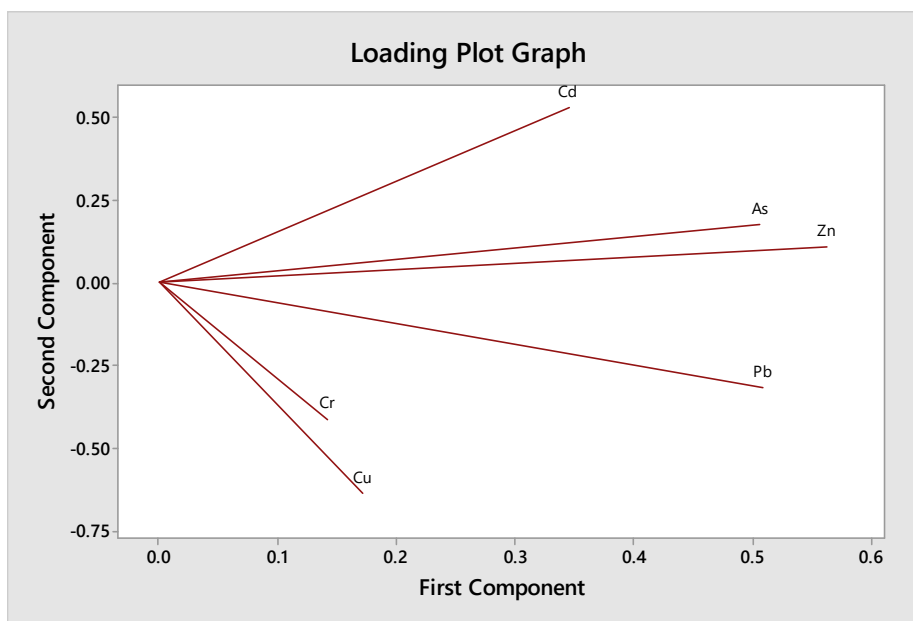


Fig. 3. Principal Component Analysis (PCA) plot for Heavy Metals in surface water

Table 4. Correlation of heavy metals in ground water

	As	Cd	Cr	Cu	Pb
Cd	0.57 0.003				
Cr	0.418 0.038	0.161 0.442			
Cu	0.111 0.598	0.381 0.06	0.189 0.365		
Pb	0.269 0.194	0.427 0.033	0.017 0.937	0.298 0.148	
Zn	0.426 0.034	0.599 0.002	0.451 0.024	0.342 0.095	0.365 0.073

rural regions is agricultural practices like fertilizer and pesticide use. PC 3 displays positive scores for Cu, Cd, Pb, and Zn, accounting for 78.5% of the total variance loads. Since the vast majority of people in the study region consume beverages, the beverage industry plays a key role in this area. Cd, Pb, and Zn seemed to originate from the beverage industry (Tripathi & Singh, 2016).

For groundwater samples, the outcomes of the Pearson correlation analysis are displayed in Table 4. Strong positive correlations were found between element pairs: Zn-Pb (0.599) and As-Cd (0.57). This finding indicated that Zn, Pb, As and Cd might originate from common sources. Seven element pairs, Cu-Cd (0.381), Zn-Cu (0.342), Pb-Cd (0.427), Pb-Zn (0.365), As-Zn (0.426), Cr-Zn (0.451) and Cr-As (0.418), exhibited a moderate positive correlation. This finding indicated that these metals pairs might originate from common sources.

Similarly, Pb-Cu (0.298), As-Cu (0.111), As-Pb (0.269), Cr-Cd (0.161), Cr-Cu (0.189), and Cr-Pb (0.017) shown the weak positive correlation between metal pairs. None of the metal pairs exhibited a negative correlation. The CA score plots outlined the samples' properties and assisted in figuring out their temporal distribution; it can be used to categorize different types of pollution sources. The data sets used for this investigation are shown in Figure 3. As a result, we can distinguish between two groups of heavy metals in the groundwater surrounding the waste.

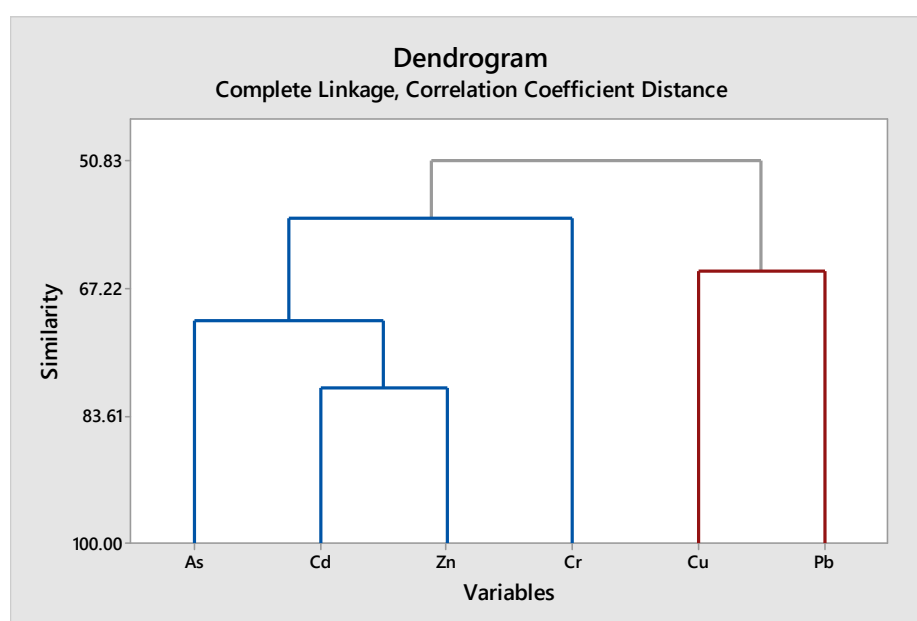


Fig 3. Dendrogram hierarchical cluster analysis of six heavy metals in ground water

Table 5. PCA for groundwater

VARIABLES	PC1	PC2	PC3	PC4	PC5	
As	0.431	-0.314	0.462	0.228	0.5	
Cd	0.495	0.186	0.242	0.476	-0.183	
Cr	0.315	-0.67	-0.346	-0.372	0.163	
Cu	0.325	0.352	-0.741	0.274	0.335	
Pb	0.349	0.534	0.225	-0.702	0.212	
Zn	0.493	-0.094	-0.096	-0.124	-0.73	
EIGENVALUE	2.7462	1.1019	0.8493	0.58	0.4942	0.2285
PROPORTION	0.458	0.184	0.142	0.097	0.082	0.038
CUMULATIVE	0.458	0.641	0.783	0.88	0.962	1

Cu and Pb make up one cluster, whereas Cd, Zn, Cr, and As make up the other. It has clarified that there are two types of possible sources for the five heavy metals and As contamination.

The principal component loadings of the heavy metals in samples from canal water are given in Table 5, whereas the corresponding CA is shown in Figure 4. Total five PCs were extracted. Two PCs are extracted with eigenvalues more than 1, explaining about 64.1 % of the total variance.

Elevated loadings of Zn, As, and Cd are shown in the first PC (45.8% variance), which is confirmed by the fact that these metals share a cluster in CA with Cr. In the cluster analysis, Pb and Cu also exhibit positive loadings in the first PC, which is supported by the same cluster. High amounts of zinc suggest that waste fluorescent light bulbs are being dumped in the landfill (Gunawardhana et al., 2024). The leachate and adjacent groundwater wells have higher levels of chromium and lead, which could be caused by plastics, batteries, leather, paint, metallic objects, fluorescent lights, wood preservatives, and metal scrap that were disposed of at the solid waste disposal site. Inorganic As contamination originates from the uncontrolled disposal of electronic trash found in computer chips, LCD screens, and circuit boards (Maturi et al. 2022). The same cluster in CA confirms the considerable loadings of Pb and Cu in the second PC (64.1% variance). Plant protection products, fertilizers, or copper salts used to break down biofilms in water pipes can all be sources of copper in groundwater (Wagner, 2009). Photographic films, outdated lead-based paints, and lead pipes dumped in landfills are potential

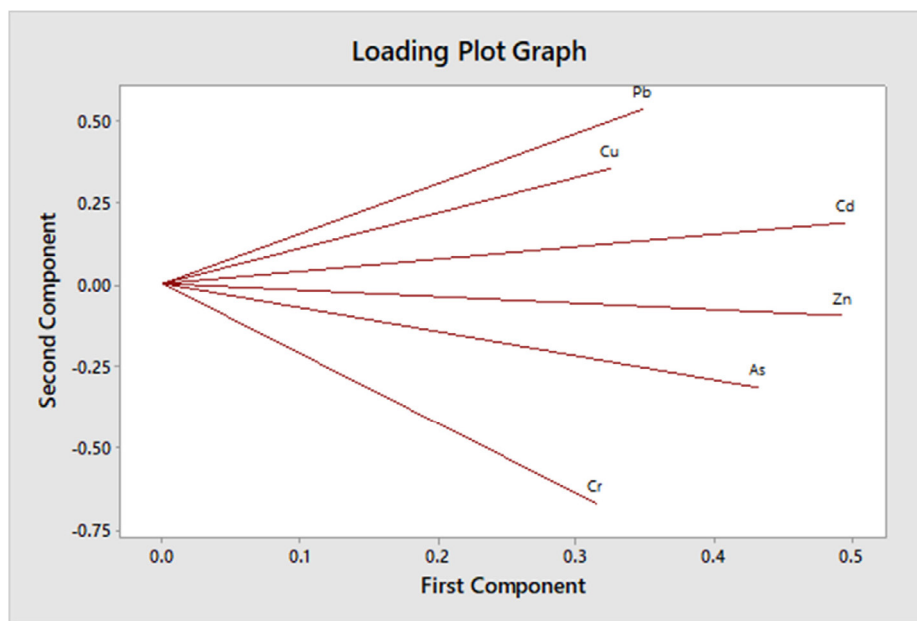


Fig. 5. Principal Component Analysis (PCA) plot for Heavy Metals in ground water

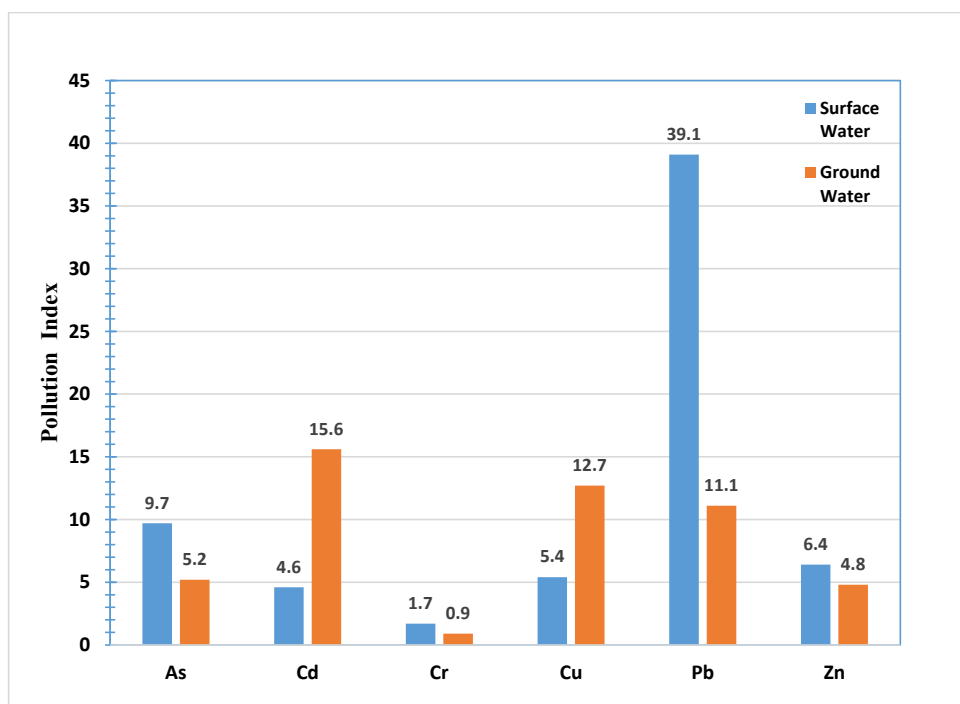


Fig. 6. Pollution Index for studied heavy metals in collected surface and groundwater samples.

sources of lead pollution, which is poisonous to all life at this level (Organization, 2004)(WHO, 2004). Third PC (78.3% variance) exhibits positive loadings for As and Cd. The cluster analysis also displays a mutual cluster for As and Cd metals. PC4 (88 % variance) reveals the positive loadings of Cd, Cu, and As in which As and Cd share the same cluster. PC5 (96.2 % variance) shows positive loadings of Cu, Cr, Pb and As. In cluster analysis, Cu-Pb falls in same cluster and As-Cr lies in another cluster. These seemed to originate from anthropogenic sources.

The PI values of known characteristic pollutants at various sample locations are presented in Figures 6. Here, results show that Pb has highest PI (39.1), followed by As (9.7), while Cr shows the lowest (1.7), indicating Pb as the dominant pollutant of concern in surface water.

Table 7. Health risk index for studied surface and groundwater

Heavy Metal	Surface water		RfD	Ground Water	
	Adult	Children		Adult	Children
Cd	4.38E-01	4.82E-01	0.0005	1.47E+00	1.62E+00
Cu	5.11E-02	5.63E-02	0.005	1.20E-01	1.32E-01
Zn	3.37E-03	3.71E-03	0.3	2.57E-03	2.83E-03
Pb	9.04E-01	9.96E-01	0.0036	2.58E-01	2.84E-01
As	4.50E+00	4.96E+00	0.0003	2.44E+00	2.69E+00
Cr	7.67E-01	8.44E-01	0.0031	3.94E-01	4.34E-01

While Cd shows the highest PI (15.6), followed by Cu (12.7) and Pb (11.1), while Cr shows the lowest (0.9), indicating Cd as the dominant pollutant of concern in groundwater. It is obvious that in the groundwater, the water quality was largely loaded on Pb, As, Zn, and Cu, and moderately loaded on Cr and Cd.

The HRIs values of selected metals and metalloid in drinking water samples are shown in Table 7.

CONCLUSION

This study employed multivariate statistical approaches for source identification and health risk assessment. A thorough investigation was carried out to analyse the levels of arsenic (As) and specific heavy metals in surface and groundwater near the landfill site in Khanewal District, Central Punjab. The findings revealed that while Cu and Zn were within the WHO permitted levels, the As, Cd, Cr, and Pb in the canal water exceeded the permissible limits. While Cu and Cr stayed under acceptable levels, As, Cd, Pb, and Zn were over the limits in groundwater. All tested HMs and As in surface water had $PI > 1$, indicating that they were important pollutants, according to the Pollution Index (PI) values. All but Cr had $PI > 1$ in groundwater, and As, Cd, Cu, Pb, and Zn were categorized as major contaminants. The overall quality of the water varied from inadequate to inappropriate. Health Risk Assessment indicated potential non-carcinogenic and carcinogenic risks associated primarily with As and Cd in groundwater. The PCA, cluster analysis, and Pearson correlation suggested a major source as anthropogenic inputs, particularly from industrial discharges, waste leachate, and improper MSW disposal. Two factors in groundwater accounted for 64.1% of the variation, suggesting a combination of natural and human inputs. To mitigate further degradation to Khanewal's water quality, Appropriate implementation of the MSW management plan, including industrial waste management, engineering landfill leachate control, and periodic water quality monitoring, is recommended.

GRANT SUPPORT DETAILS

The present research did not receive any financial support.

CONFLICT OF INTEREST

The authors declare that there is not any conflict of interest regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/ or falsification, double publication and/or submission, and redundancy have been completely observed by the authors.

LIFE SCIENCE REPORTING

No life science threat was practiced in this research.

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