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Assessment of Heavy Metal Contamination in Surface Water and Associated Health Risks

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ABSTRACT

Background: Surface water contamination by heavy metals has become a major environmental and public health concern due to their persistence, toxicity, and bioaccumulative nature.

Objective: To assess the level of heavy metal contamination in surface water and evaluate the associated health risks.

Methodology: This was a cross-sectional analytical study conducted from April 2025 to October 2025. A total of 65 surface water samples were collected using non-probability purposive sampling from rivers, lakes, and reservoirs near industrial, agricultural, and urban areas of Karachi. Samples were analyzed for lead (Pb), cadmium (Cd), arsenic (As), mercury (Hg), and chromium (Cr) using atomic absorption spectrophotometry.

Results: The mean concentrations of Pb, Cd, As, Hg, and Cr were 0.048 ± 0.021 mg/L, 0.012 ± 0.006 mg/L, 0.031 ± 0.014 mg/L, 0.006 ± 0.003 mg/L, and 0.057 ± 0.025 mg/L, respectively. Concentrations exceeding permissible limits were observed in 58.5% (n=38) for Pb, 36.9% (n=24) for Cd, 44.6% (n=29) for As, 26.2% (n=17) for Hg, and 61.5% (n=40) for Cr. Pollution index analysis showed that 52.3% (n=34) of samples were moderately polluted and 30.8% (n=20) were highly polluted. Health risk assessment indicated that HQ values exceeded 1 for Pb in 49.2% (n=32) and for Cr in 53.8% (n=35) of samples, while the hazard index exceeded 1 in 46.2% (n=30) of cases.

Conclusion: Surface water in the study area is significantly contaminated with heavy

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metals, posing considerable health risks.

Keywords: Heavy Metals, Surface Water, Contamination, Health Risk Assessment, Hazard Quotient, Carcinogenic Risk

Introduction

Water is a precious resource used for drinking, irrigation, and industrial purposes; but its quality is under threat due to environmental pollution, especially contamination by heavy metals [1]. Metals such as lead (Pb), cadmium (Cd), mercury (Hg), arsenic (As), and chromium (Cr) are non-biodegradable and persist in the environment, often accumulating in water bodies, posing environmental and health hazards [2]. These metals are non-degradable, persistent and can bioaccumulate in the food chain, resulting in chronic toxicity even at low levels. Contamination of surface water with heavy metals can come from various natural and human sources. Weathering of rocks, volcanic eruptions, and other natural phenomena add to the natural background levels of metals, but the sharp increase in contamination is primarily due to industrial effluents, agricultural runoff, mining, improper disposal of waste, and urbanization [3]. In developing nations like Pakistan, poor wastewater management and lack of environmental regulations add to the plight by allowing untreated water to flow into rivers, lakes and reservoirs [4]. Contaminated water containing heavy metals has been associated with numerous health problems. Lead exposure can cause neurological impairment and developmental impairments, particularly in children, and cadmium causes kidney failure and bone demineralisation [5]. Arsenic exposure is known to cause skin lesions and cancers, while mercury exposure damages the nervous system, resulting in impaired cognitive and motor functions. Chromium, especially its hexavalent form, is known to cause cancer. These health issues underline the need to regulate and control the presence of heavy metals in surface water [6].

Contamination by heavy metals is usually assessed by determining metal concentrations in water samples using sophisticated analytical methods, including atomic absorption spectrometry (AAS), inductively coupled plasma mass spectrometry (ICP-MS), and spectrophotometry. Apart from measuring contamination, health risk models are used to assess potential risks [7]. These include chronic daily intake (CDI), hazard quotient (HQ), hazard index (HI), and carcinogenic risk (CR), which provide useful information on the potential risks of non-carcinogenic and carcinogenic health effects from exposure [8]. Over the years, industrial growth and urbanisation have exacerbated heavy metal contamination in surface water. Urbanisation and the release of untreated industrial waste have resulted in higher levels of toxic metals in surface waters. And farming activities play a significant role in this regard through the overuse of fertilizers and pesticides, which can contain minute quantities of heavy metals, which eventually find their way into water bodies [9]. Additionally, changes in climate and weather patterns, including heavy rain and flooding, can also flush contaminants from land into water bodies, exacerbating water quality problems [10]. The other main concern of heavy metal contamination is its ecological implications. Plants and animals in aquatic ecosystems, such as fish, algae, and invertebrates, are particularly vulnerable to changes in water quality, and can take

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up and retain heavy metals [11]. This impacts biodiversity, ecosystem health, and also indirectly affects human health via consumption of contaminated organisms. Bioconcentration and biomagnification occur, leading to higher metal concentrations at higher trophic levels, and potential exposure of top predators, such as humans [12].

Objective

To assess the level of heavy metal contamination in surface water and evaluate the associated health risks.

Methodology

This was a cross-sectional analytical study conducted from April 2025 to October 2025. A total of 65 surface water samples were collected and analyzed to determine the concentration of selected heavy metals and assess their potential health risks. A non-probability purposive sampling technique was employed to collect water samples. Water samples were collected in clean, acid-washed polyethylene bottles following standard protocols. Each sample was obtained from a depth of approximately 20–30 cm below the water surface to minimize surface contamination. Immediately after collection, samples were acidified with nitric acid to preserve the integrity of heavy metals and were transported to the laboratory under appropriate conditions. Surface water samples collected from rivers, lakes, and reservoirs situated near potential contamination sources, including industrial discharge points, agricultural runoff areas, and urban regions of Karachi, during the study period were included. Groundwater and drinking water samples were excluded from the study. Additionally, samples collected from areas without identifiable contamination sources or those that were improperly collected or contaminated during handling were not included.

Laboratory Analysis

Collected samples were filtered and subjected to acid digestion using standard procedures prior to analysis. The concentrations of heavy metals, including lead (Pb), cadmium (Cd), arsenic (As), mercury (Hg), and chromium (Cr), were determined using atomic absorption spectrophotometry (AAS). Calibration was carried out using standard reference solutions, and quality control was maintained through the use of blanks and duplicate samples. Health risk assessment was performed by calculating chronic daily intake (CDI), hazard quotient (HQ), hazard index (HI), and carcinogenic risk (CR) using standard equations. Exposure parameters such as ingestion rate, body weight, exposure duration, and frequency were considered. HQ values greater than 1 were interpreted as indicative of potential non-carcinogenic risk, while CR values exceeding acceptable limits suggested significant carcinogenic risk.

Statistical Analysis

Data were entered and analyzed using Statistical Package for the Social Sciences (SPSS) version 26. Continuous variables such as heavy metal concentrations were presented as mean $\pm$ standard deviation, while categorical variables were expressed as frequencies and percentages. Appropriate statistical tests were applied to determine

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associations, and a p-value ≤ 0.05 was considered statistically significant.

Results

A total of 65 surface water samples were analyzed for heavy metal contamination. The mean concentrations of lead (Pb), cadmium (Cd), arsenic (As), mercury (Hg), and chromium (Cr) were 0.048 ± 0.021 mg/L, 0.012 ± 0.006 mg/L, 0.031 ± 0.014 mg/L, 0.006 ± 0.003 mg/L, and 0.057 ± 0.025 mg/L, respectively.

Table 1: Mean Concentration of Heavy Metals in Surface Water (n=65)

Heavy Metal	Mean $\pm$ SD (mg/L)
Lead (Pb)	0.048 ± 0.021
Cadmium (Cd)	0.012 ± 0.006
Arsenic (As)	0.031 ± 0.014
Mercury (Hg)	0.006 ± 0.003
Chromium (Cr)	0.057 ± 0.025
Pollution Category	
Safe	11 (16.9)
Moderately Polluted	34 (52.3)
Highly Polluted	20 (30.8)

A substantial proportion of samples exceeded permissible limits, particularly for chromium (61.5%, n=40) and lead (58.5%, n=38). Arsenic levels were above safe limits in 44.6% (n=29) of samples, while cadmium exceeded limits in 36.9% (n=24) and mercury in 26.2% (n=17). However, a higher percentage of samples remained within acceptable limits for mercury (73.8%, n=48), cadmium (63.1%, n=41), and arsenic (55.4%, n=36), compared to lead and chromium.

Table 2: Frequency of Samples Exceeding Permissible Limits (n=65)

Heavy Metal	Above Limit n (%)	Within Limit n (%)
Lead (Pb)	38 (58.5)	27 (41.5)
Cadmium (Cd)	24 (36.9)	41 (63.1)
Arsenic (As)	29 (44.6)	36 (55.4)
Mercury (Hg)	17 (26.2)	48 (73.8)
Chromium (Cr)	40 (61.5)	25 (38.5)

Non-carcinogenic health risk assessment revealed that hazard quotient (HQ) values exceeded 1 in 53.8% (n=35) of samples for chromium and 49.2% (n=32) for lead, indicating potential health risks. The cumulative hazard index (HI) was greater than 1 in 46.2% (n=30) of samples, suggesting combined toxic effects from multiple metals, while 53.8% (n=35) of samples remained within safe limits.

Table 3: Health Risk Assessment (Non-Carcinogenic Risk) (n=65)

Parameter	Condition	n (%)
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HQ (Lead)	>1	32 (49.2)
HQ (Lead)	≤1	33 (50.8)
HQ (Chromium)	>1	35 (53.8)
HQ (Chromium)	≤1	30 (46.2)
Hazard Index (HI)	>1	30 (46.2)
Hazard Index (HI)	≤1	35 (53.8)

Carcinogenic risk analysis demonstrated that chromium posed a higher risk, with 41.5% (n=27) of samples exceeding acceptable limits, followed by arsenic in 38.5% (n=25) of samples. Despite this, the majority of samples were within acceptable carcinogenic risk limits for arsenic (61.5%, n=40) and chromium (58.5%, n=38).

Table 4: Carcinogenic Risk Assessment (n=65)

Heavy Metal	CR Above Acceptable Limit n (%)	CR Within Acceptable Limit n (%)
Arsenic (As)	25 (38.5)	40 (61.5)
Chromium (Cr)	27 (41.5)	38 (58.5)

The Heavy Metal Pollution Index (HPI) distribution indicated that 38.5% (n=25) of samples were moderately polluted, while 27.7% (n=18) were highly polluted, and 33.8% (n=22) were classified as having low pollution levels.

Table 5: Heavy Metal Pollution Index (HPI) Distribution (n=65)

HPI Range	Interpretation	n (%)
< 100	Low Pollution	22 (33.8)
100–120	Moderate Pollution	25 (38.5)
> 120	High Pollution	18 (27.7)

Discussion

This study examined the levels of heavy metal pollution in surface water and its potential human health impacts, and found that contamination is high in a significant number of samples. The study showed that average levels of the main heavy metals, such as lead and chromium, were high, and that numerous samples exceeded the safe limits. These findings reflect the continued environmental impact of heavy metal pollution and the potential health risks to humans, particularly in areas where raw surface water is widely used. The most conspicuous pollutants in this study were lead and chromium, with 58.5% and 61.5% of samples above the permissible limits, respectively [13]. These high concentrations are likely due to industrial effluents, inadequate waste disposal, and urban runoff, recognised sources of surface water contamination. This finding is in line with other studies that have shown lead and chromium as predominant contaminants in surface water systems owing to their industrial applications. The non-biodegradability and persistence of these metals also contribute to their accumulation in water bodies [14].

Significant levels of arsenic and cadmium were also found, with 44.6% and 36.9% of

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samples, respectively, exceeding safe levels. Arsenic is a known carcinogen, and its contamination is thus of particular concern, while cadmium is known for its kidney toxicity and bone lesions. While mercury concentrations were relatively low, the detection of mercury above permissible levels in 26.2% of samples is concerning, given its high toxicity, even at low levels [15]. These results are consistent with other studies demonstrating that even low concentrations of heavy metals can have significant health implications over time due to cumulative exposure. The use of pollution indices in the current study also highlighted the extent of pollution, with more than 50% of the samples falling in the moderately polluted category and almost 30% in the highly polluted category [16,17]. These results suggest a significant fraction of surface water bodies can't be used directly by humans without treatment. Comparable findings of elevated pollution index values in surface water bodies adjacent to industrial and agricultural areas highlight the impact of human activities on water pollution [18].

The results of the human health risk assessment showed considerable non-carcinogenic risks, particularly for lead and chromium, with hazard quotients exceeding 1 in the majority of samples. The hazard index was also above the safe limit in almost half of the samples, indicating the combined effect of multiple heavy metals. These results align with other studies that have shown the potential for additive or synergistic toxic effects from exposure to multiple metals, and greater risk of adverse health effects [19]. The carcinogenic risk assessment also revealed the potential long-term health risks, with arsenic and chromium exhibiting carcinogenic risk values exceeding acceptable levels in a significant proportion of samples. This indicates a higher likelihood of cancer in communities exposed to contaminated water over a long time [20,21]. Other studies have also highlighted the role of arsenic and chromium in the carcinogenic risk of contaminated water, suggesting the need for rigorous monitoring and remediation measures. This study has some limitations. The cross-sectional nature of the study limits the evaluation of temporal changes in contaminant concentrations, which can vary with seasonal variations and discharge. Moreover, the limited sample size and spatial representation may impact the representativeness of the findings. This study did not consider other potential contaminants and confounding factors, such as microbial contamination and physicochemical characteristics, which can affect water quality.

Conclusion

It is concluded that surface water in the studied area is significantly contaminated with heavy metals, particularly lead and chromium, with a considerable proportion of samples exceeding permissible limits. The findings demonstrate that a large number of water sources fall into moderately to highly polluted categories, posing potential non-carcinogenic and carcinogenic health risks to exposed populations. Elevated hazard quotient and carcinogenic risk values further indicate the likelihood of adverse health outcomes with prolonged exposure.

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