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HEALTH RISK ASSESSMENT OF TRACE AND TOXIC METALS IN DRINKING WATER OF THE COASTAL AREA OF TALUKA MIRPUR SAKRO, SINDH

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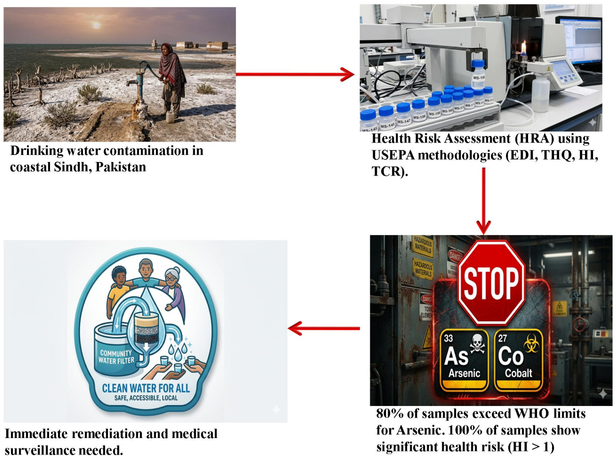
Abstract

Contamination of drinking water with trace and toxic metals is a significant public health concern, particularly in coastal areas where natural and anthropogenic factors may elevate metal concentrations. This study assesses the levels of eight metals (Arsenic, Cadmium, Chromium, Cobalt, Manganese, Nickel, Copper, and Zinc) in drinking water samples collected from the coastal area of Taluka Mirpur Sakro, Sindh. A total of 30 water samples (MS-145 to MS-174) were collected and prepared using the wet digestion method. Analysis was performed using Atomic Absorption Spectrophotometry (AAS). The concentrations were compared with WHO permissible limits. Health risk assessment was conducted by calculating Estimated Daily Intake (EDI), Target Hazard Quotient (THQ), Hazard Index (HI), and Cancer Risk for carcinogenic metals (As, Cd, Cr, Ni) using standard USEPA methodologies. The results revealed that concentrations of As exceeded the WHO limit (10 μg/L) in 24 out of 30 samples (80%), with values ranging from 5 to 75 μg/L. Co exceeded the WHO limit (0.1 mg/L) in 12 samples, with a maximum of 0.340 mg/L (MS-154). The EDI values ranged from 10^{-5} to 10^{-2} mg/kg-day. THQ analysis indicated that all samples had THQ > 1 for multiple metals, with Co showing the highest THQ values (up to 32.38). The Hazard Index (HI) for all samples exceeded the safe level of 1, ranging from 3.35 to 34.85, indicating significant non-carcinogenic health risks. Total Cancer Risk (TCR) for all samples exceeded the USEPA acceptable limit of 1×10^{-4}, ranging from 6.62×10^{-4} to 3.88×10^{-3}, with As being the primary contributor. The drinking water of Taluka Mirpur Sakro is contaminated with toxic metals, particularly As and Co, posing significant non-carcinogenic and carcinogenic health risks to the local population. Immediate remediation measures and regular monitoring are recommended.



Drinking water contamination in coastal Sindh, Pakistan

Health Risk Assessment (HRA) using USEPA methodologies (EDI, THQ, HI, TCR).

80% of samples exceed WHO limits for Arsenic. 100% of samples show significant health risk (HI > 1)

Immediate remediation and medical surveillance needed.

Figure: 1 Graphical Abstract

INTRODUCTION

Access of safe and clean drinking water is a basic human need and a significant factor in the public health (Shar, et al., 2021). Although, synthetic as well as natural contaminants are making water unsafe for drinking purpose, and trace and toxic metals are particularly unsafe since they reside in the body, build up, and have serious health issues (Sharma, et al., 2023). However, heavy metals are extremely difficult to control since they can only move from one chemical state to another and cannot be broken down or eliminated (El-Sharkawy, et al., 2025). Arsenic (As), cadmium (Cd), lead (Pb), chromium (Cr), and nickel (Ni) contamination of freshwater resources has been linked globally to a number of chronic ailments, including cancer, renal difficulties, neurological disorders, and developmental abnormalities (Teschke, and Xuan, 2025). Rapid population increase, unplanned industrialisation, agricultural runoff, and a lack of water treatment facilities exacerbate the problem in Pakistan (Fida, et al., 2023). The province of Sindh, particularly its coastline region, is experiencing a distinct and escalating environmental catastrophe (Haider, et al., 2025). Changes in water flow, enclosing from upstream, and infiltration of seawater are major sources of stress for the Indus Delta, one of the world's biggest deltas with a dry environment (Inam, et al., 2022). This delicate coastal habitat includes Taluka Mirpur Sakro, which is located in District Thatta. Its groundwater and surface water reservoirs are very susceptible to salinisation and metal contamination due to its proximity to the Arabian Sea, abundance of creeks, marshy area, and other bodies of water (Arain, et al., 2026).

In this region, hazardous and trace metals come from a variety of sources. Geologically speaking, sedimentary rocks and coastal alluvial deposits in the Indus plain naturally allow arsenic and other metals to enter the aquifer (Naseem, and Rafi, 2024). Through the Indus River and its tributaries, the region receives contaminated runoff from industrial waste from Hyderabad, Karachi, and Kotri. Lead, cadmium, and chromium levels are further increased by the extensive use of agrochemicals on the surrounding agriculture and improper disposal of waste from residences and medical facilities (Gadhi, et al., 2026). These contaminants are further dispersed by monsoon runoff and tidal backflows, which trap them in the shallow drinking water sources that the local population relies on (Singh, et al., 2024).

In the coastal Taluka Mirpur Sakro, farmers make up the majority of the population. They obtain their water from untreated surface water, privately installed reverse osmosis (RO) facilities, hand pumps, and shallow drilled wells. Two factors put these populations at risk: the poisonous metals themselves, as well as the high salinity and other co-contaminants that exacerbate the problem. Regular use of water containing even trace concentrations of hazardous metals can lead to long-term health issues. Until the organ damage is severe, these issues are frequently undetectable (Wu, et al., 2025). For instance, prolonged exposure to arsenic can result in keratosis, skin lesions, and ultimately lung, bladder, and skin malignancies (arsenicosis). Exposure to lead elevates blood pressure in adults and harms children's brain development. Conversely, itai-itai illness and renal tubular injury result from cadmium accumulation in the kidneys and bones (Ganie, et al., 2024).

Heavy metal contamination in Sindh's major cities (Karachi, Hyderabad) and the Manchar Lake region has been documented in numerous studies; however, there is still a substantial lack of information regarding the quantitative health risk assessment of trace metals in the drinking water of the remote, underprivileged coastal communities of Taluka Mirpur Sakro (Khan, et al., 2025). The majority of earlier research has focused on microbiological contamination or physicochemical characteristics (salinity, pH, TDS), ignoring the long-term, non-communicable dangers linked to low-level metal exposure. Therefore, by conducting a comprehensive Health Risk Assessment (HRA) of trace and hazardous metals in Taluka Mirpur Sakro's drinking water, this study seeks to close this gap. The HRA framework is described as follows by the US Environmental Protection Agency (US EPA):

1. Hazard Identification: Determining which harmful elements (such as As, Cd, Pb, Cr, Ni, Fe, and Zn) are present in the local drinking water.
2. Exposure Assessment: Determining the daily amounts of these metals that various populations (adults and children) consume and come into contact with.
3. 3. Dose-Response Assessment: To determine potential non-carcinogenic hazards, use the Hazard Quotient (HQ) and Hazard Index (HI); to determine potential carcinogenic risks, use cancer risk (CR) and Total Cancer Risk (TCR).

The ultimate objective is to estimate the likelihood of negative health impacts for the local population and to provide a scientific basis for the concerning levels of metal contamination. In order to protect the health of one of Pakistan's most ecologically vulnerable and neglected coastal populations, policymakers, the Sindh Environmental Protection Agency (SEPA), the Pakistan Council of Research in Water Resources (PCRWR), and local health authorities will need to prioritise interventions like the installation of community-scale treatment systems, the provision of alternative safe water sources, and the start of medical surveillance programs.

MATERIAL AND METHODS

Study Area

Located in District Thatta, Sindh, Pakistan, the coastline region of Taluka Mirpur Sakro is an essential component of the Indus Delta, one of the largest desert deltas in the world. This low-lying, level region is extremely susceptible to seawater intrusion because of its marshy terrain, closeness to the Arabian Sea, and network of creeks. The approximately 17,500 residents of the area, who live in dispersed rural communities, get their drinking water via hand pumps, shallow dug wells, and sometimes reverse osmosis plants. However, due to a combination of natural geological processes and man-made pressures like upstream dam construction, decreased clean water flow from the Indus River, runoff from agriculture, and tidal backflows, groundwater is extremely saline and contaminated with trace and toxic metals, in particular cadmium, lead, and arsenic. As a result, the majority of drinking water is unfit for human consumption, leading to a high prevalence of chronic and waterborne illnesses. Salinisation has also had an impact on livelihoods, with many locals giving up farming and thousands of acres of farmland becoming desert. Although the infrastructure is still rudimentary, work is being done on a coastal highway that will connect Mirpur Sakro and Keti Bandar. Mirpur Sakro is a significant location for the study of health concerns related to metal poisoning of drinking water because of its distinct environmental and socioeconomic context (Figure: 1) (Masood, et al., 2024).

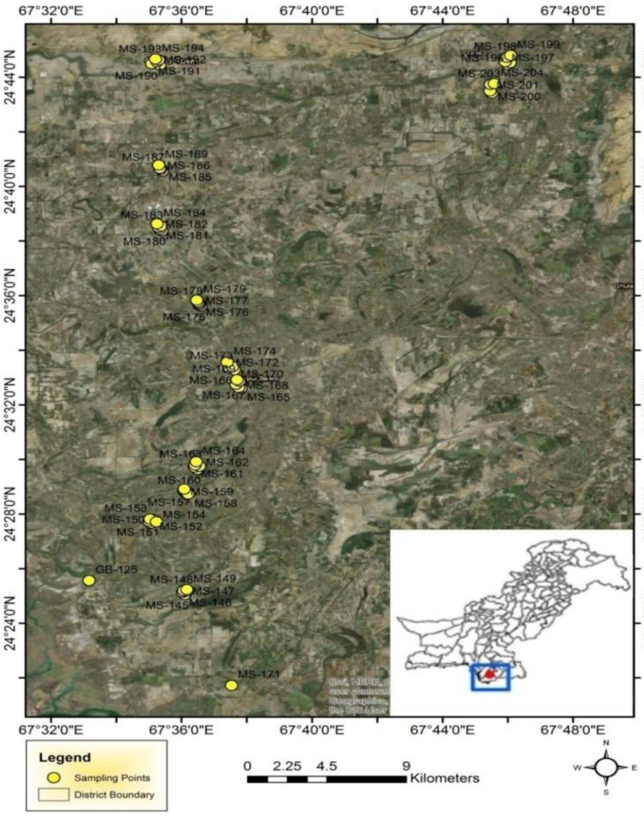


Figure 2: Map of the study area of Taluka Mirpur Sakro

Sample Collection

In order to determine the presence and quantity of trace and hazardous metals, sixty drinking water samples were methodically collected from the coastline area of Taluka Mirpur Sakro, District Thatta, Sindh. Each sample was obtained in triplicate from each of the chosen locations to ensure accuracy and analytical reliability, yielding 180 distinct water specimens. In order to capture the variety of drinking water sources that the community actually uses, sampling locations included shallow dug wells, hand pumps, boreholes, and, in a few instances, stored rainwater or water from small-scale reverse osmosis units. To prevent cross-contamination, all samples were gathered in 1.0 L high-density polyethylene plastic bottles that had been previously washed and rinsed with the source water before being filled. Each bottle was labelled with a unique sample code, date and time of collection, source type, and GPS coordinates as soon as it was collected. The labelled samples were then placed in insulated coolers with ice packs to preserve the chemical integrity of the water and minimise any microbial or chemical degradation during transit. The precise geographic location of each of the sixty sampling locations was recorded using a hand-held Global Positioning System (GPS) unit with data loggings to ensure the authenticity, traceability, and spatial accuracy of the results. Before being prepared and examined, the samples were later moved to the Research Laboratory of the Institute of Chemistry at Shah Abdul Latif University in Khairpur and kept under controlled refrigeration at 4°C. To stabilise the dissolved metal species and stop adsorption to the container walls, each sample was acidified with ultrapure nitric acid to a pH of less than 2.0 after being filtered through 0.45 µm membrane filters in the lab to eliminate suspended particles. The prepared samples were digested using a hot plate or microwave digestion system in compliance with standard protocols (such as APHA methods) to ensure complete solubilisation of metals before being quantified using techniques like atomic absorption spectrophotometry or inductively coupled plasma mass spectrometry. Strict quality control methods were also employed during the preparation and analytical stages to confirm the precision and correctness of the results. Reagent blanks, injected samples, and verified reference materials were used in these methods (Table: 1) (Lee, et al., 2022).

Table 1: ***Collection of water samples from various Union Councils of Taluka Mirpur Sakro with their sample ID***

S. No:	UCs of Mirpur Sakro	Sample ID	No: of Samples
1	Gharo	MS-145 to MS-151	7
2	Dhabeji	MS-152 to MS-158	7
3	Chowbandi	MS-159 to MS-165	7
4	MirpurSakro	MS-166 o MS-172	7
5	Bhuhara	MS-173 to MS-179	7
6	Gujjo	MS-180 to MD-186	7
7	Ghulamullah	MS-187 to MS-192	6
8	Haji Gharano	MS-193 to MS-198	6
9	Sukhpur	MS-199 to MS-204	6

Sample Analysis

A 250 mL aliquot of each collected drinking water sample was placed in a 500 mL borosilicate beaker and placed on an electric hot plate in order to pre-concentrate the dangerous and trace metals. Two to three drops of strong nitric acid were added in order to initiate the digestive process and maintain the metals in solution. The temperature was carefully maintained between 70 and 80 °C, which is under the boiling point of water, to escape the water slowly neither violent boiling or analyte loss. After the volume had been appropriately reduced, the remains were dissolved using 2N nitric acid. To obtain a ten-fold pre-concentration factor compared to the original 250 mL sample, all of the beaker's contents were quantitatively transferred into a 25 mL volumetric flask, which was then filled to the brim with deionised water. All prepared samples were immediately delivered under the proper chain-of-custody protocols for instrumental analysis to the National Water Quality Laboratory (NWQL) of the Pakistan Council of Research in Water Resources (PCRWR), Ministry of Science and Technology, Islamabad. Following standard operating protocols, the concentrations of cadmium (Cd), chromium (Cr), cobalt (Co), copper (Cu), manganese (Mn), iron (Fe), nickel (Ni), and zinc (Zn) were measured using an Analytik Jena atomic absorption spectrophotometer (AAS). The sample absorbance readings were then interpolated onto the associated calibration graphs to calculate the amount of each metal in the water used for drinking samples. Several standard solutions with known concentrations were run in order to develop calibration curves for each metal. Strict quality assurance measures, such as the analysis of reagent blanks and authorised reference materials, were also employed during the AAS runs to ensure the accuracy and reliability of the reported metal concentrations (Kassim, et al., 2022).

Standard Default Values for Calculation of Risk Assessment

The sample absorbance readings were then interpolated onto the respective calibration graphs in order to calculate the concentration of each metal in the drinking water samples. Several standard solutions with known concentrations were run to develop calibration curves for each metal. Strict quality assurance protocols, including the analysis of reagent blanks and approved reference materials, were also employed during the AAS runs to ensure the accuracy and reliability of the reported metal concentrations (Shar, et al., 2026). An adult's average body weight (BW) is assumed to be 70 kg. Lastly, the duration over which the cumulative dose is averaged, usually in days, is known as the averaging time (AT). For carcinogenic risks, AT is usually set at 70 years multiplied by 365 days per year (i.e., 25,550 days), which represents a whole lifespan; for non-carcinogenic risks, AT is computed as ED multiplied by 365 days per year. The daily intake, resulting hazard quotients, and cancer risks are then calculated using these parameters in established US EPA calculations (Shar, et al, 2025; Shar, et al., 2022) (Table: 2 & 3).

Table 2: *Health Risk Assessment Parameters for Drinking Water*

Parameter	Symbol	Formula	Unit	Description
Estimated Daily Intake	EDI	$EDI = \frac{C \times IR \times EF \times ED}{BW \times AT}$	mg/kg/day	The daily amount of a specific element ingested via drinking water.
Hazard Quotient	THQ	$THQ = \frac{EDI}{RfD}$	Unitless	Ratio of daily intake to the safe reference dose (RfD).
Hazard Index	HI	$HI = \sum THQn$	Unitless	The sum of HQ values for all elements to assess cumulative risk.
Cancer Risk	CR	$CR = EDI \times CSF$	Unitless	The probability of developing cancer over a lifetime (70 years).
Total Cancer Risk	TCR	$TCR = \sum CRn$	Unitless	The combined cancer risk from all carcinogenic elements.

Table 3: *Classification of Elements Based on Toxicity and Essentiality*

Element	Unit	Classification	Reasoning
As	µg/L	Toxic Metal	Carcinogen; no essential function in humans.
Cd	mg/L	Toxic Metal	Highly toxic; classified as a human carcinogen.
Cr	mg/L	Toxic Metal	Hexavalent form is highly toxic/carcinogenic.
Co	mg/L	Toxic Metal	Toxic in free ionic form; essential only as part of Vitamin B12.
Ni	mg/L	Toxic Metal	Carcinogenic; causes allergies.
Mn	mg/L	Trace Metal	Essential nutrient (though neurotoxic in excess).
Cu	mg/L	Trace Metal	Essential nutrient.
Zn	mg/L	Trace Metal	Essential nutrient.

RESULTS AND DISCUSSIONS

Concentration of Trace and Toxic Metals

A comparison of the trace and toxic metal concentrations in drinking water from the coastal region of Taluka Mirpur Sakro with the permissible limits set by the Food and Agriculture Organization (FAO) and the World Health Organization (WHO) using the data shown in Table 1 reveals serious health risks for a number of metals. The WHO limit for arsenic (As) is 10 µg/L. The vast majority of the 30 samples on the list surpass this recommendation. Samples for example; MS- 145 (35 µg/L), MS- 146 (45 µg/L), MS- 149 (23 µg/L), MS- 155 (21 µg/L), MS- 156 (34 µg/L), MS- 160 (75 µg/L), MS- 161 (66 µg/L), MS- 162 (55 µg/L), MS- 170 (75 µg/L), MS- 171 (45 µg/L), MS- 172 (57 µg/L), and MS- 173 (63 µg/L) show values well above the safe limit, with MS- 160 and MS- 170 reaching 75 µg/L – seven times the permissible level. Long-term use of such water increases the risk of internal malignancies, skin sores, and arsenicosis.

Cadmium (Cd) has a WHO limit of 0.003 mg/L. Many samples exceed this, including MS- 146 (0.0052), MS- 147 (0.0042), MS- 148 (0.0042), MS- 149 (0.0112), MS- 150 (0.0062), MS- 151 (0.0052), MS- 152 (0.0082), MS- 153 (0.0092), MS- 157 (0.0092), MS- 159 (0.0092), MS- 161 (0.0102), MS- 162 (0.0062), MS- 163 (0.0062), MS- 164 (0.0042), MS- 165 (0.0092), MS- 167 (0.0102), MS- 168 (0.0072), MS- 169 (0.0052), MS- 170 (0.0092), MS- 171 (0.0092), MS- 172 (0.0062), MS- 173 (0.0052), and MS- 174 (0.0102). The highest concentrations (0.0112 and 0.0102 mg/L) are more than three times. The highest readings (0.0112 and 0.0102 mg/L) exceed the WHO limit by more than three times. Because it is nephrotoxic, cadmium builds up in the urinary tract and bones.

With the significant exception of MS-154 (0.061 mg/L) which above the limit, chromium (Cr) often stays below the WHO standard of 0.05 mg/L for the majority of samples. Other samples such as MS- 145 (0.030), MS- 152 (0.030), MS- 153 (0.035), and MS- 165 (0.043) are within the permissible range. As a result, only a few areas are contaminated by chromium.

The WHO has set a limit of 0.1 mg/L for cobalt (Co). MS-148 (0.098, near the limit), MS-154 (0.340, above three times higher), MS-156 (0.121), MS-165 (0.161), and MS-155 (0.031 is safe) are among the samples with elevated levels. MS-154 (0.340) is especially concerning. Polycythaemia, thyroid damage, and cardiomyopathy can result from long-term cobalt exposure.

Manganese (Mn) exceeds the WHO limit of 0.05 mg/L in multiple samples: MS- 145 (0.06), MS- 147 (0.20), MS- 150 (0.10), and MS- 169 (exactly 0.05, borderline). Neurological consequences are linked to high manganese intake, particularly in youngsters.

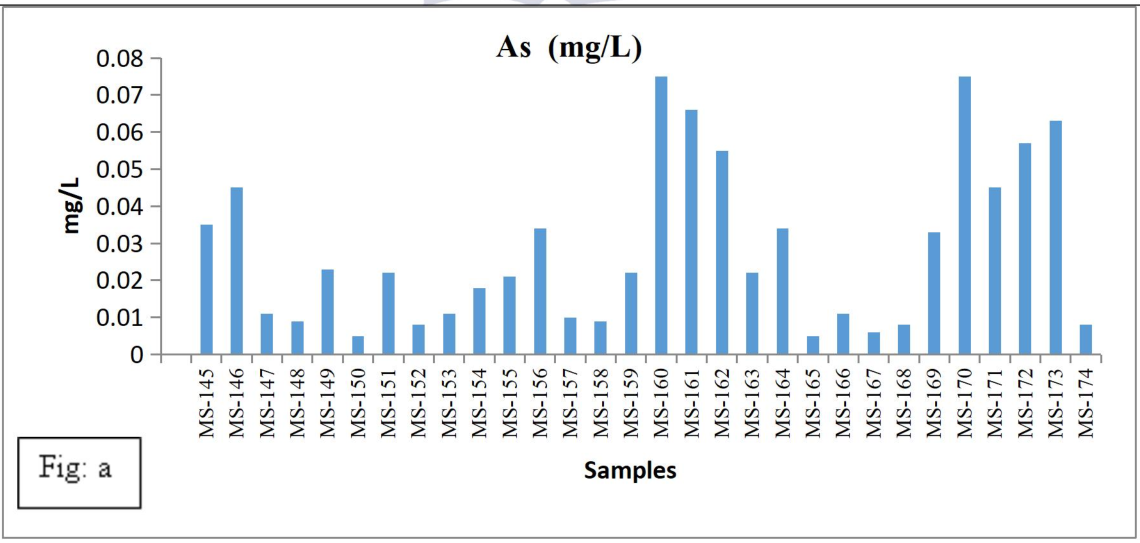
The WHO limit for nickel (Ni) is 0.02 mg/L. Exceedances are observed in MS- 148 (0.033), MS- 166 (0.033), MS- 168 (0.033), and MS- 167 (0.021) slightly above. These numbers are between 1.5 and 1.65 times the recommended amount. A known allergy and possible cause of cancer is nickel. All of the samples for copper (Cu) and zinc (Zn) are well within the WHO standards of 2.0 mg/L and 3.0 mg/L, respectively, suggesting that there is no health risk associated with these vital trace elements in the water sources under investigation.

In summary, arsenic, cadmium, cobalt, manganese, and nickel levels in the drinking water of coastal Taluka Mirpur Sakro are severely contaminated, often exceeding WHO/FAO recommendations. Arsenic and cadmium are the most common and severe exceedances, followed by manganese and cobalt in some areas. These results necessitate immediate public health measures, such as monitoring the local population's health and providing alternate safe water sources (Table: 4; Figure: 3 (a - h).

Table 4: ***The level of Trace and toxic metals in drinking water of coastal area of Taluka Mirpur Sakro, Sindh***

CODE NO:	As (µg/L)	Cd (mg/L)	Cr (mg/L)	Co (mg/L)	Mn (mg/L)	Ni (mg/L)	Cu (mg/L)	Zn (mg/L)
WHO Limit	10	0.003	0.05	0.1	0.05	0.02	2.0	3.0
MS-145	35	0.0012	0.030	0.031	0.06	0.013	0.700	0.170
MS-146	45	0.0052	0.011	0.046	0.04	0.014	0.014	0.054
MS-147	11	0.0042	0.021	0.067	0.20	0.019	0.015	0.021
MS-148	9	0.0042	0.026	0.098	0.03	0.033	0.015	0.024
MS-149	23	0.0112	0.017	0.046	0.01	0.015	0.014	0.018
MS-150	5	0.0062	0.009	0.023	0.10	0.013	0.800	0.180
MS-151	22	0.0052	0.009	0.021	0.03	0.013	0.021	0.028

MS-152	8	0.0082	0.03	0.054	0.04	0.017	0.012	0.082
MS-153	11	0.0092	0.035	0.023	0.04	0.016	0.017	0.017
MS-154	18	0.0022	0.061	0.340	0.02	0.020	0.020	0.025
MS-155	21	0.0012	0.01	0.031	0.02	0.019	0.700	0.280
MS-156	34	0.0032	0.009	0.121	0.02	0.008	0.019	0.023
MS-157	10	0.0092	0.015	0.033	0.03	0.015	0.049	0.019
MS-158	9	0.0012	0.009	0.067	0.03	0.017	0.016	0.020
MS-159	22	0.0092	0.008	0.053	0.02	0.015	0.019	0.020
MS-160	75	0.0022	0.008	0.087	0.02	0.014	0.900	0.230
MS-161	66	0.0102	0.009	0.053	0.02	0.012	0.017	0.020
MS-162	55	0.0062	0.016	0.042	0.02	0.014	0.023	0.026
MS-163	22	0.0062	0.018	0.031	0.03	0.013	0.077	0.017
MS-164	34	0.0042	0.015	0.021	0.03	0.01	0.012	0.022
MS-165	5	0.0092	0.043	0.161	0.02	0.017	0.800	0.250
MS-166	11	0.0012	0.024	0.028	0.02	0.033	0.016	0.018
MS-167	6	0.0102	0.016	0.021	0.02	0.021	0.012	0.018
MS-168	8	0.0072	0.011	0.041	0.02	0.033	0.027	0.023
MS-169	33	0.0052	0.008	0.031	0.05	0.014	0.015	0.022
MS-170	75	0.0092	0.027	0.041	0.01	0.017	0.800	0.220
MS-171	45	0.0092	0.01	0.051	0.03	0.021	0.016	0.021
MS-172	57	0.0062	0.013	0.048	0.02	0.015	0.017	0.026
MS-173	63	0.0052	0.016	0.053	0.03	0.016	0.013	0.017
MS-174	8	0.0102	0.009	0.057	0.02	0.018	0.017	0.018



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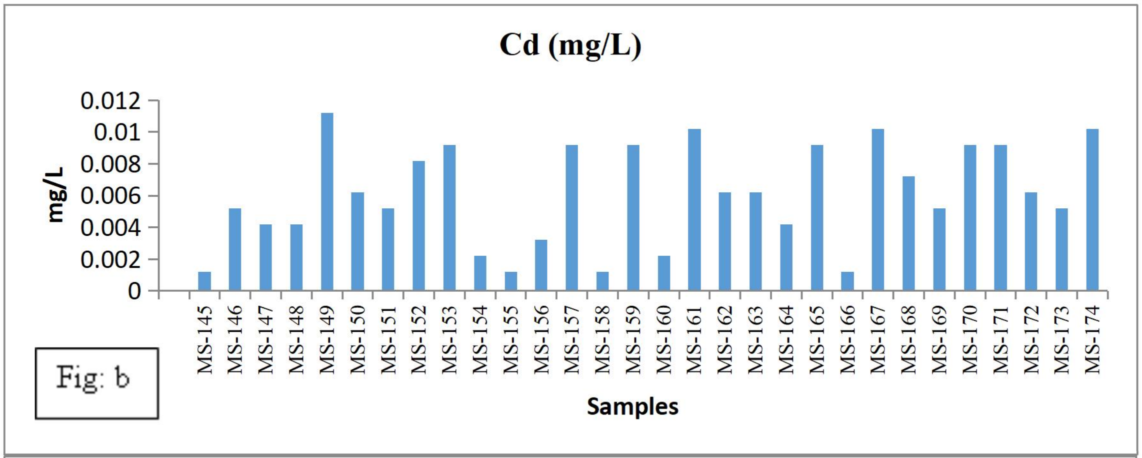

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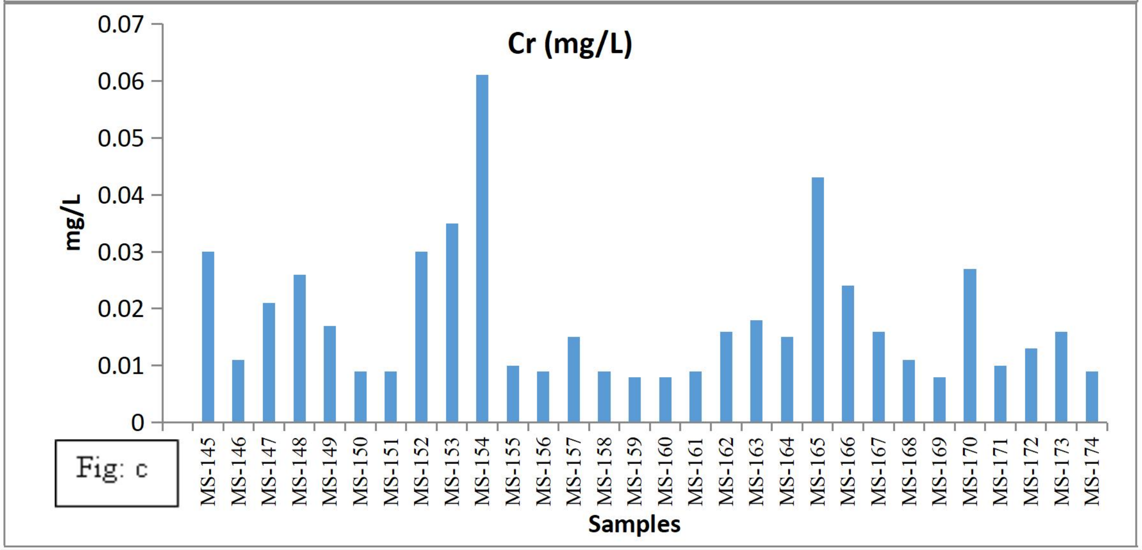

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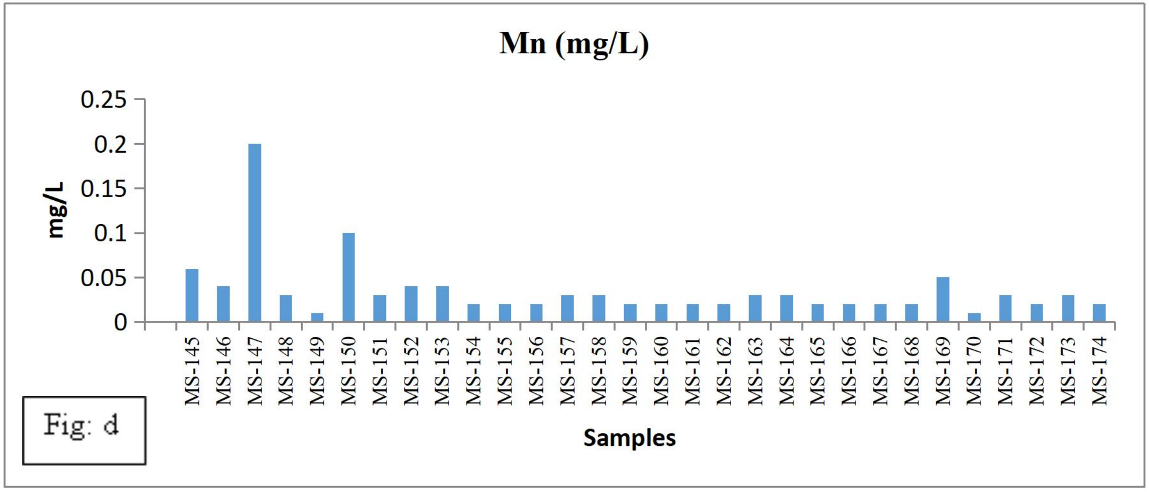

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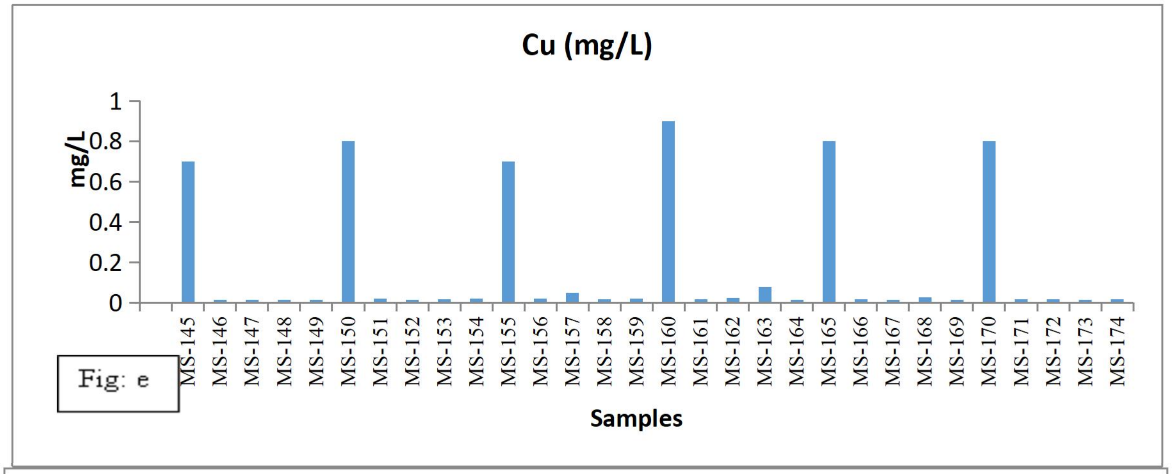

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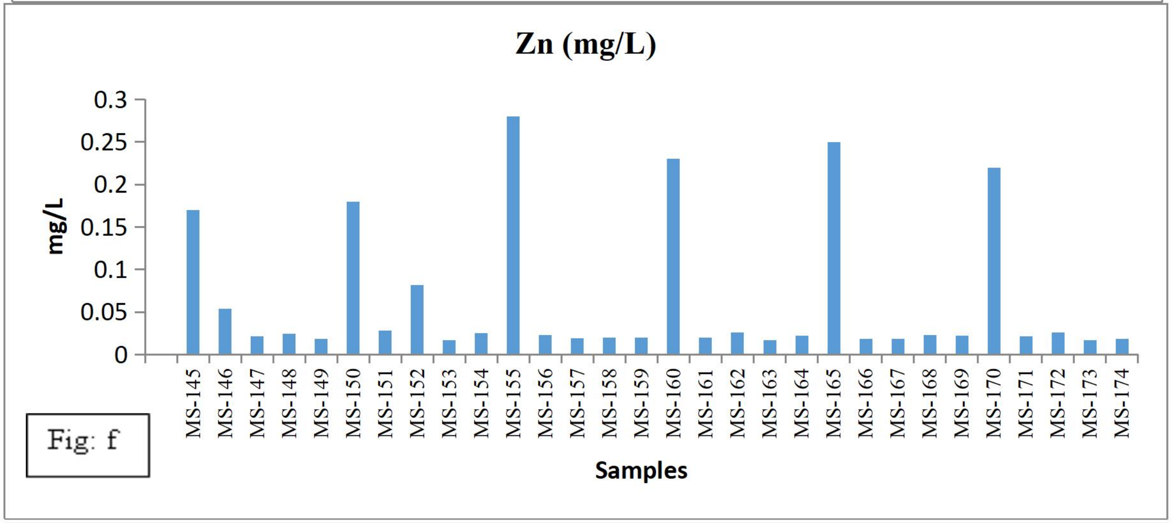

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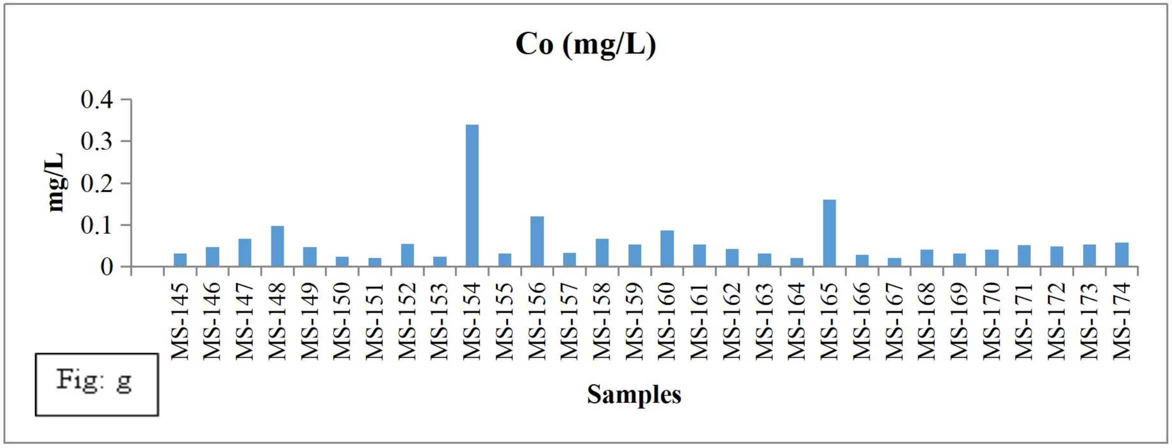

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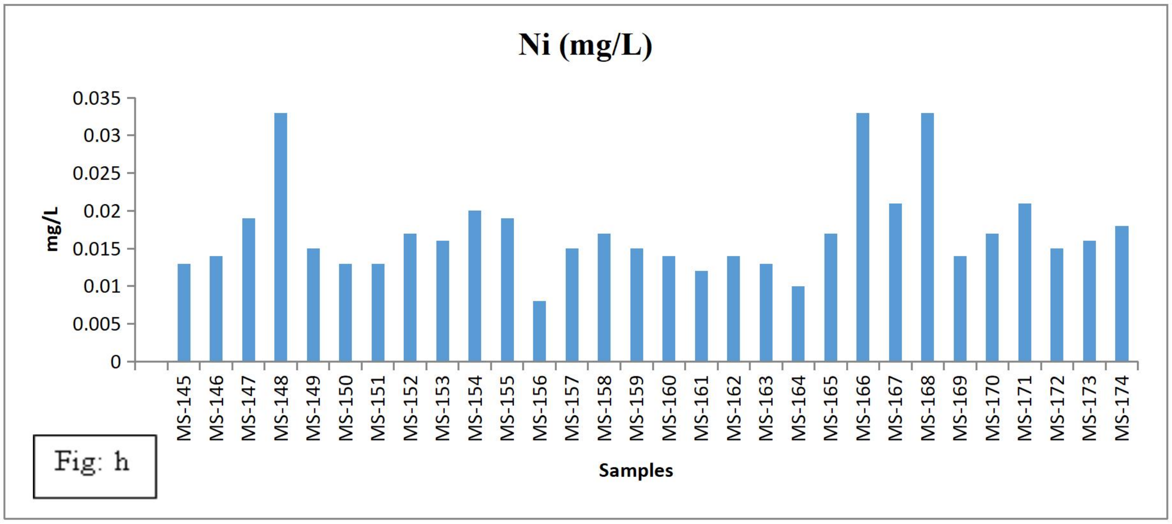

Fig: h

Figure: 3 (a - h) Concentration of trace and toxic metals in water of the coastal area of Taluka Mirpur Sakro

Estimated Daily Intake (EDI) values

An adult's daily intake of each metal per kilogram of body weight is directly measured by the Estimated Daily Intake (EDI) values for hazardous and trace metals in drinking water from Taluka Mirpur Sakro's coastline area. The EDI figures show the possibility of negative health consequences when compared to established oral reference doses (RfD) or tolerated daily intake (TDI) levels from the US EPA or WHO.

For **arsenic** (As), the EDI values range from 1.43 × 10^{-4} to 2.14 × 10^{-3} mg/kg- day. The oral RfD for arsenic set by the US EPA is 3.0 × 10^{-2} mg/kg per day. Many samples, including MS- 145 (1.00 × 10^{-3}), MS- 146 (1.29 × 10^{-3}), MS- 149 (6.57 × 10^{-4}), MS- 160 (2.14 × 10^{-3}), MS- 161 (1.89 × 10^{-3}), MS- 162 (1.57 × 10^{-3}), MS- 170 (2.14 × 10^{-3}), MS- 171 (1.29 × 10^{-3}), MS- 172 (1.63 × 10^{-3}), and MS- 173 (1.80 × 10^{-3}), show EDIs exceeding the RfD by a factor of 2 to 7. This suggests that, in addition to its well-known carcinogenic potential, arsenic poses a substantial non-carcinogenic risk. For Cd**,** the EDI ranges from 3.43 × 10^{-5} to 3.20 × 10^{-4} mg/kg- day. For cadmium, the US EPA's RfD is 1.0 × 10^{-3} mg/kg per day. Interestingly, all of the cadmium EDI values are below the RfD, with the highest value (MS 149, 3.20 × 10^{-2}) being roughly one-third of the RfD. As a result, daily Cd consumption does not surpass the safety threshold; but, cumulative impacts with other metals may still be dangerous.

For Cr, all EDIs (range from 2.29 × 10^{-1} to 1.74 × 10^{-3}) are significantly below the RfD of 1.5 mg/kg day, assuming the trivalent form (Cr III). With the exception of MS 154 (1.74 × 10^{-3}) and MS 153 (1.00 × 10^{-3}), which are still below 3.0 × 10^{-3}, most samples stay below that limit even if hexavalent chromium were present (with a substantially lower RfD of 3.0 × 10^{-3} mg/kg day for Cr VI). Therefore, chromium EDI is not a cause for immediate alarm. For **cobalt** (**Co**), the EDI values range from 6.00 × 10^{-4} to 9.71 × 10^{-3} mg/kg- day. Although there isn't a generally recognised RfD for cobalt, the WHO TDI is approximately 0.01 mg/kg day (10 µg/kg- day). Several samples approach or exceed this: MS- 147 (1.91 × 10^{-3}), MS- 148 (2.80 × 10^{-3}), MS- 154 (9.71 × 10^{-3} – very close to 0.01), MS- 156 (3.46 × 10^{-3}), MS- 165 (4.60 × 10^{-3}), and MS- 174 (1.63 × 10^{-3}). The greatest value (9.71 × 10^{-3}) is close to the TDI, suggesting a possible risk of thyroid dysfunction and cobalt-induced cardiomyopathy.

For manganese (Mn)**,** the EDIs range from 2.86 × 10^{-4} to 5.71 × 10^{-3} mg/kg- day. The US EPA RfD for manganese is 1.4 × 10^{-1} mg/kg- day (0.14 mg/kg- day). Manganese by itself does not present a non-carcinogenic risk by ingesting because all EDI values are orders of magnitude below this RfD, yet neurological consequences from long-term high exposure are still a worry at lower levels for susceptible groups. For Ni, the EDI ranges from 2.29×10^{-4} to 9.43×10^{-4} mg/kg- day. Nickel has an oral RfD of 2.0×10^{-2} mg/kg per day. There is no discernible non-carcinogenic danger from nickel consumption, as all levels are well below this. The EDIs for Zn and Cu are within acceptable bounds. Cu EDI ranges from 3.43×10^{-4} to 2.57×10^{-2} mg/kg- day, and the RfD is 4.0×10^{-2} mg/kg- day; only a few samples (e.g., MS- 145, MS- 150, MS- 155, MS- 160, MS- 165, MS- 170) have EDIs around $2.0–2.57 \times 10^{-2}$, still below the RfD. Zinc EDI ranges from 4.86×10^{-4} to 8.00×10^{-3} mg/kg- day, far below the RfD of 0.3 mg/kg- day.

In conclusion, the EDI analysis verifies that arsenic is the most essential metal, with numerous samples surpassing the RfD by multiple times. In certain places, cobalt also approaches or sometimes surpasses its TDI. The cumulative intake of several metals may nevertheless contribute to total health risk, which is usually assessed using the Hazard Index, even though individual EDIs for cadmium, chromium, manganese, nickel, copper, and zinc are still below their respective safety limits. This coastal area's high EDI values for cobalt and arsenic necessitate prompt corrective action as well as ongoing health monitoring for the local populace (Table: 5).

Table 5: ***Calculated EDI (mg/kg-day) for all drinking water samples collected from coastal area of Taluka Mirpur Sakro***

CODE	As EDI	Cd EDI	Cr EDI	Co EDI	Mn EDI	Ni EDI	Cu EDI	Zn EDI
MS-145	1.00×10^{-3}	3.43×10^{-5}	8.57×10^{-4}	8.86×10^{-4}	1.71×10^{-3}	3.71×10^{-4}	2.00×10^{-2}	4.86×10^{-3}
MS-146	1.29×10^{-3}	1.49×10^{-4}	3.14×10^{-4}	1.31×10^{-3}	1.14×10^{-3}	4.00×10^{-4}	4.00×10^{-4}	1.54×10^{-3}
MS-147	3.14×10^{-4}	1.20×10^{-4}	6.00×10^{-4}	1.91×10^{-3}	5.71×10^{-3}	5.43×10^{-4}	4.29×10^{-4}	6.00×10^{-4}
MS-148	2.57×10^{-4}	1.20×10^{-4}	7.43×10^{-4}	2.80×10^{-3}	8.57×10^{-4}	9.43×10^{-4}	4.29×10^{-4}	6.86×10^{-4}
MS-149	6.57×10^{-4}	3.20×10^{-4}	4.86×10^{-4}	1.31×10^{-3}	2.86×10^{-4}	4.29×10^{-4}	4.00×10^{-4}	5.14×10^{-4}
MS-150	1.43×10^{-4}	1.77×10^{-4}	2.57×10^{-4}	6.57×10^{-4}	2.86×10^{-3}	3.71×10^{-4}	2.29×10^{-2}	5.14×10^{-3}
MS-151	6.29×10^{-4}	1.49×10^{-4}	2.57×10^{-4}	6.00×10^{-4}	8.57×10^{-4}	3.71×10^{-4}	6.00×10^{-4}	8.00×10^{-4}
MS-152	2.29×10^{-4}	2.34×10^{-4}	8.57×10^{-4}	1.54×10^{-3}	1.14×10^{-3}	4.86×10^{-4}	3.43×10^{-4}	2.34×10^{-3}
MS-153	3.14×10^{-4}	2.63×10^{-4}	1.00×10^{-3}	6.57×10^{-4}	1.14×10^{-3}	4.57×10^{-4}	4.86×10^{-4}	4.86×10^{-4}
MS-154	5.14×10^{-4}	6.29×10^{-5}	1.74×10^{-3}	9.71×10^{-3}	5.71×10^{-4}	5.71×10^{-4}	5.71×10^{-4}	7.14×10^{-4}
MS-155	6.00×10^{-4}	3.43×10^{-5}	2.86×10^{-4}	8.86×10^{-4}	5.71×10^{-4}	5.43×10^{-4}	2.00×10^{-2}	8.00×10^{-3}
MS-156	9.71×10^{-4}	9.14×10^{-5}	2.57×10^{-4}	3.46×10^{-3}	5.71×10^{-4}	2.29×10^{-4}	5.43×10^{-4}	6.57×10^{-4}
MS-157	2.86×10^{-4}	2.63×10^{-4}	4.29×10^{-4}	9.43×10^{-4}	8.57×10^{-4}	4.29×10^{-4}	1.40×10^{-3}	5.43×10^{-4}

MS-158	2.57×10^{-4}	3.43×10^{-5}	2.57×10^{-4}	1.91×10^{-3}	8.57×10^{-4}	4.86×10^{-4}	4.57×10^{-4}	5.71×10^{-4}
MS-159	6.29×10^{-4}	2.63×10^{-4}	2.29×10^{-4}	1.51×10^{-3}	5.71×10^{-4}	4.29×10^{-4}	5.43×10^{-4}	5.71×10^{-4}
MS-160	2.14×10^{-3}	6.29×10^{-5}	2.29×10^{-4}	2.49×10^{-3}	5.71×10^{-4}	4.00×10^{-4}	2.57×10^{-2}	6.57×10^{-3}
MS-161	1.89×10^{-3}	2.91×10^{-4}	2.57×10^{-4}	1.51×10^{-3}	5.71×10^{-4}	3.43×10^{-4}	4.86×10^{-4}	5.71×10^{-4}
MS-162	1.57×10^{-3}	1.77×10^{-4}	4.57×10^{-4}	1.20×10^{-3}	5.71×10^{-4}	4.00×10^{-4}	6.57×10^{-4}	7.43×10^{-4}
MS-163	6.29×10^{-4}	1.77×10^{-4}	5.14×10^{-4}	8.86×10^{-4}	8.57×10^{-4}	3.71×10^{-4}	2.20×10^{-3}	4.86×10^{-4}
MS-164	9.71×10^{-4}	1.20×10^{-4}	4.29×10^{-4}	6.00×10^{-4}	8.57×10^{-4}	2.86×10^{-4}	3.43×10^{-4}	6.29×10^{-4}
MS-165	1.43×10^{-4}	2.63×10^{-4}	1.23×10^{-3}	4.60×10^{-3}	5.71×10^{-4}	4.86×10^{-4}	2.29×10^{-2}	7.14×10^{-3}
MS-166	3.14×10^{-4}	3.43×10^{-5}	6.86×10^{-4}	8.00×10^{-4}	5.71×10^{-4}	9.43×10^{-4}	4.57×10^{-4}	5.14×10^{-4}
MS-167	1.71×10^{-4}	2.91×10^{-4}	4.57×10^{-4}	6.00×10^{-4}	5.71×10^{-4}	6.00×10^{-4}	3.43×10^{-4}	5.14×10^{-4}
MS-168	2.29×10^{-4}	2.06×10^{-4}	3.14×10^{-4}	1.17×10^{-3}	5.71×10^{-4}	9.43×10^{-4}	7.71×10^{-4}	6.57×10^{-4}
MS-169	9.43×10^{-4}	1.49×10^{-4}	2.29×10^{-4}	8.86×10^{-4}	1.43×10^{-3}	4.00×10^{-4}	4.29×10^{-4}	6.29×10^{-4}
MS-170	2.14×10^{-3}	2.63×10^{-4}	7.71×10^{-4}	1.17×10^{-3}	2.86×10^{-4}	4.86×10^{-4}	2.29×10^{-2}	6.29×10^{-3}
MS-171	1.29×10^{-3}	2.63×10^{-4}	2.86×10^{-4}	1.46×10^{-3}	8.57×10^{-4}	6.00×10^{-4}	4.57×10^{-4}	6.00×10^{-4}
MS-172	1.63×10^{-3}	1.77×10^{-4}	3.71×10^{-4}	1.37×10^{-3}	5.71×10^{-4}	4.29×10^{-4}	4.86×10^{-4}	7.43×10^{-4}
MS-173	1.80×10^{-3}	1.49×10^{-4}	4.57×10^{-4}	1.51×10^{-3}	8.57×10^{-4}	4.57×10^{-4}	3.71×10^{-4}	4.86×10^{-4}
MS-174	2.29×10^{-4}	2.91×10^{-4}	2.57×10^{-4}	1.63×10^{-3}	5.71×10^{-4}	5.14×10^{-4}	4.86×10^{-4}	5.14×10^{-4}

Target Hazard Quotient (THQ)

The non-carcinogenic health risks associated with drinking water from Taluka Mirpur Sakro's coastline area are quantitatively evaluated by the Target Hazard Quotient (THQ) and Hazard Index (HI) values shown in Table 4. A THQ value higher than 1.0, according to the US EPA risk assessment system, means that daily exposure to a single metal surpasses the oral reference dose (RfD), potentially posing a non-carcinogenic health risk. In a similar vein, a Hazard Index (HI) greater than 1.0, which is the total of all THQs for a particular sample, indicates a cumulative danger from several metals.

In most samples, arsenic (As) exhibits THQ values greater than 1.0. For instance, MS- 145 (3.33), MS- 146 (4.29), MS- 147 (1.05), MS- 149 (2.19), MS- 151 (2.10), MS- 156 (3.24), MS- 160 (7.14), MS- 161 (6.29), MS- 162 (5.24), MS- 164 (3.24), MS- 169 (3.14), MS- 170 (7.14), MS- 171 (4.29), MS- 172 (5.43), and MS- 173 (6.00) all have THQ- As > 1. The highest arsenic THQ values (7.14 at MS- 160 and MS- 170) are more than seven times the safe threshold, indicating a very high probability of adverse effects such as skin lesions, cardiovascular disease, and various internal cancers. Only a few samples (e.g., MS- 148, MS- 150, MS- 152, MS- 157, MS- 158, MS- 165, MS- 166, MS- 167, MS- 168, MS- 174) have THQ- As below 1.0, though some are still close (e.g., MS- 148: 0.86).

Cobalt (Co) also exhibits remarkably high THQ values. Many samples exceed the safe limit of 1.0: MS- 145 (2.95), MS- 146 (4.38), MS- 147 (6.38), MS- 148 (9.33), MS- 149 (4.38), MS- 152 (5.14), MS- 154 (32.38 – extremely high), MS- 156 (11.52), MS- 157 (3.14), MS- 158 (6.38), MS- 159 (5.05), MS- 160 (8.29), MS- 161 (5.05), MS- 162 (4.00), MS- 165 (15.33), MS- 166 (2.67), MS- 168 (3.90), MS- 169 (2.95), MS- 170 (3.90), MS- 171 (4.86), MS- 172 (4.57), MS- 173 (5.05), and MS- 174 (5.43). The highest cobalt THQ (32.38 at MS- 154) is 32 times the safe limit, implying severe risk of cobalt- induced cardiomyopathy, hypothyroidism, and polycythemia. The widespread exceedance for cobalt is second only to arsenic in severity.

For Cadmium (Cd) THQ values are all below 1.0 (maximum 0.64 at MS- 149). Although no single sample exceeds the threshold for cadmium alone, the cumulative HI includes this contribution. For Chromium (Cr) THQ values are all well below 1.0 (maximum 0.58 at MS- 154), indicating no significant non- carcinogenic risk from chromium in these samples, assuming trivalent form. THQ values for Manganese (Mn)are negligible (all ≤ 0.04), well below 1.0. THQ values for Nickel (Ni) are also very low (maximum 0.05), far below the safe limit. Copper (Cu). THQ values remain below 1.0 (maximum 0.64 at MS- 160), though a few samples (MS- 145, MS- 150, MS- 155, MS- 160, MS- 165, MS- 170) show values between 0.50 and 0.64, indicating a moderate but still acceptable risk.

Zinc (Zn), THQ values are negligible (all ≤ 0.03). Hazard Index (HI) – the sum of all THQs for each sample – exceeds the safe limit of 1.0 for every single sample. The lowest HI is 3.35 (MS- 167) and the highest is 34.85 (MS- 154). All 30 samples have HI values far above 1.0, indicating that the cumulative exposure to multiple metals presents a serious non- carcinogenic health risk to the local population. The order of contribution to HI is dominated by arsenic and cobalt, with minor contributions from cadmium, copper, and others. For instance, cobalt alone accounts for 32.38 of 34.85 (93% of the HI) in MS-154. Arsenic (7.14) and cobalt (8.29) combined make up the majority of the HI of 16.32 in MS-160. Arsenic (4.29) and cobalt (4.38) contribute almost equally to MS-146.

In summary, the THQ and HI investigation clearly shows that the drinking water in Taluka Mirpur Sakro's coastline area presents a serious non-carcinogenic health risk to adults. The main elements causing this risk are cobalt and arsenic; numerous samples had cumulative HI values between three and thirty-five times the acceptable limit and individual THQ values that are several times higher than 1.0. There is an urgent need for immediate public health actions, such as medical screening for diseases linked to metals and the supply of alternative safe drinking water sources. Additionally, the high cobalt levels (up to 0.34 mg/L in raw water, corresponding to THQ > 32) are uncommon for drinking water and call for additional research into potential industrial or geological sources of cobalt pollution in the area (Table: 6).

Table 4: *Calculated THQ for each metal and the HI for each sample collected from drinking water of coastal area of Taluka Mirpur Sakro*

CODE	THQ As	THQ Cd	THQ Cr	THQ Co	THQ Mn	THQ Ni	THQ Cu	THQ Zn	HI (ΣTHQ)
MS-145	3.33	0.07	0.29	2.95	0.01	0.02	0.50	0.02	**7.19**
MS-146	4.29	0.30	0.10	4.38	0.01	0.02	0.01	0.01	**9.11**
MS-147	1.05	0.24	0.20	6.38	0.04	0.03	0.01	0.00	**7.95**

MS-148	0.86	0.24	0.25	9.33	0.01	0.05	0.01	0.00	**10.74**
MS-149	2.19	0.64	0.16	4.38	0.00	0.02	0.01	0.00	**7.41**
MS-150	0.48	0.35	0.09	2.19	0.02	0.02	0.57	0.02	**3.73**
MS-151	2.10	0.30	0.09	2.00	0.01	0.02	0.02	0.00	**4.52**
MS-152	0.76	0.47	0.29	5.14	0.01	0.02	0.01	0.01	**6.71**
MS-153	1.05	0.53	0.33	2.19	0.01	0.02	0.01	0.00	**4.14**
MS-154	1.71	0.13	0.58	32.38	0.00	0.03	0.01	0.00	**34.85**
MS-155	2.00	0.07	0.10	2.95	0.00	0.03	0.50	0.03	**5.68**
MS-156	3.24	0.18	0.09	11.52	0.00	0.01	0.01	0.00	**15.06**
MS-157	0.95	0.53	0.14	3.14	0.01	0.02	0.04	0.00	**4.83**
MS-158	0.86	0.07	0.09	6.38	0.01	0.02	0.01	0.00	**7.44**
MS-159	2.10	0.53	0.08	5.05	0.00	0.02	0.01	0.00	**7.79**
MS-160	7.14	0.13	0.08	8.29	0.00	0.02	0.64	0.02	**16.32**
MS-161	6.29	0.58	0.09	5.05	0.00	0.02	0.01	0.00	**12.04**
MS-162	5.24	0.35	0.15	4.00	0.00	0.02	0.02	0.00	**9.79**
MS-163	2.10	0.35	0.17	2.95	0.01	0.02	0.06	0.00	**5.66**
MS-164	3.24	0.24	0.14	2.00	0.01	0.01	0.01	0.00	**5.65**
MS-165	0.48	0.53	0.41	15.33	0.00	0.02	0.57	0.02	**17.37**
MS-166	1.05	0.07	0.23	2.67	0.00	0.05	0.01	0.00	**4.08**
MS-167	0.57	0.58	0.15	2.00	0.00	0.03	0.01	0.00	**3.35**
MS-168	0.76	0.41	0.10	3.90	0.00	0.05	0.02	0.00	**5.26**
MS-169	3.14	0.30	0.08	2.95	0.01	0.02	0.01	0.00	**6.51**
MS-170	7.14	0.53	0.26	3.90	0.00	0.02	0.57	0.02	**12.45**
MS-171	4.29	0.53	0.10	4.86	0.01	0.03	0.01	0.00	**9.81**
MS-172	5.43	0.35	0.12	4.57	0.00	0.02	0.01	0.00	**10.52**
MS-173	6.00	0.30	0.15	5.05	0.01	0.02	0.01	0.00	**11.54**
MS-174	0.76	0.58	0.09	5.43	0.00	0.03	0.01	0.00	**6.90**

Cancer risks (CR) and Total The cancer risk (TCR)

The cancer risk values for arsenic, cadmium, hexavalent chromium, and nickel, along with the total cancer risk (TCR) presented in Table 5, reveal an alarming carcinogenic hazard for the population consuming drinking water from the coastal area of Taluka Mirpur Sakro. A lifetime cancer risk of more than 1.0×10^{-2} (one extra cancer case per 10,000 persons) is deemed unacceptable, according to US EPA rules; the allowed range is normally between 1.0×10^{-1} and 1.0×10^{-2}. Every sample examined in this study had a TCR that is significantly higher than 1.0×10^{-1}; in fact, all TCR values exceed 6.0×10^{-1}, with many above 1.0×10^{-3} (one in a thousand) and the largest reaching 3.88×10^{-3} (about four in a thousand). In every sample, arsenic is the main factor influencing the overall risk of cancer. The individual cancer risk for arsenic ranges from 2.14×10^{-4} (MS-150, MS-165) to 3.21×10^{-3} (MS-160, MS-170). With the exception of MS-150, MS-165, MS-167, and a few others, all arsenic risk estimates are greater than 1.0×10^{-3}. The US EPA's permissible level of 1.0×10^{-3} is 32 times lower than the highest arsenic dangers (3.21×10^{-3}). This suggests that during a lifetime of exposure, there is a very high chance of developing cancers caused by arsenic, such as skin, bladder, lung, and kidney cancers. The second-highest cancer risk is associated with nickel, which ranges from 2.08×10^{-2} to 8.58×10^{-2}. The permissible level of 1.0×10^{-1} is exceeded by all nickel hazards, and several exceed 3.0×10^{-2}. The existence of such higher nickel hazards exacerbates the overall carcinogenic load because nickel is a known human carcinogen linked to lung and nasal malignancies. Cadmium cancer risks range from 1.30×10^{-5} to 1.22×10^{-4}. While most cadmium risks are at or slightly above the acceptable limit (some are just below 1.0×10^{-4}, e.g., MS-145: 1.30×10^{-5}), a few samples (MS-149: 1.22×10^{-4}, MS-152: 8.90×10^{-5}, MS-153: 9.99×10^{-5}) approach or exceed the threshold. Cadmium increases the cumulative danger even if its impact is less than that of arsenic and nickel.

Hexavalent chromium (Cr VI) risks range from 3.78×10^{-5} to 2.87×10^{-4}. Most values are below 1.0×10^{-4}, though some exceed it (MS-145: 1.41×10^{-4}, MS-148: 1.23×10^{-4}, MS-152: 1.41×10^{-4}, MS-153: 1.65×10^{-4}, MS-154: 2.87×10^{-4}, MS-165: 2.03×10^{-4}, MS-166: 1.13×10^{-4}, MS-170: 1.27×10^{-4}). At MS-154, the maximum Cr VI risk (2.87×10^{-2}) is almost three times higher than the permitted limit. Chromium hence presents a non-negligible carcinogenic risk in a number of places. The total of the four metal dangers determines each sample's Total Cancer Risk (TCR). The lowest TCR is 6.62×10^{-4} (MS-150) and the highest is 3.88×10^{-3} (MS-170). Every TCR number is at least 6.6 times higher than the 1.0×10^{-1} US EPA permissible limit, and many are 10–30 times higher. For instance, MS-170 has a TCR of 3.88×10^{-3}, meaning that after a 70-year lifetime, there are roughly 388 excess cancer incidences per 100,000 persons (or 3.9 per 1,000). The impact on public health is really significant.

In conclusion, arsenic, nickel, cadmium, and hexavalent chromium are the main causes of the unacceptable and serious carcinogenic risk that the drinking water in coastal Taluka Mirpur Sakro poses to the local population. Each and every sampling site significantly showed over the acceptable cancer risk level. There is an urgent need for immediate corrective measures, such as the supply of safe alternative water sources (such as large-scale reverse osmosis plants, rainwater collection, or piped treated water). A thorough health surveillance program for cancer screening in the exposed population should also be started very away. It is impossible to overlook the public health emergency represented by the high TCR values recorded here (Table: 7).

Table 7: *Cancer Risk and Total Cancer Risk (TCR) for carcinogenic metals in drinking water of coastal area of Taluka Mirpur Sakro*

CODE NO	As Risk	Cd Risk	Cr(VI) Risk	Ni Risk	Total Cancer Risk (TCR)
MS-145	1.50×10^{-3}	1.30×10^{-5}	1.41×10^{-4}	3.38×10^{-4}	**1.99×10^{-3}**
MS-146	1.93×10^{-3}	5.65×10^{-5}	5.18×10^{-5}	3.64×10^{-4}	**2.39×10^{-3}**
MS-147	4.71×10^{-4}	4.56×10^{-5}	9.90×10^{-5}	4.94×10^{-4}	**1.11×10^{-3}**
MS-148	3.86×10^{-4}	4.56×10^{-5}	1.23×10^{-4}	8.58×10^{-4}	**1.41×10^{-3}**
MS-149	9.86×10^{-4}	1.22×10^{-4}	8.02×10^{-5}	3.90×10^{-4}	**1.58×10^{-3}**
MS-150	2.14×10^{-4}	6.73×10^{-5}	4.24×10^{-5}	3.38×10^{-4}	**6.62×10^{-4}**
MS-151	9.43×10^{-4}	5.65×10^{-5}	4.24×10^{-5}	3.38×10^{-4}	**1.38×10^{-3}**
MS-152	3.43×10^{-4}	8.90×10^{-5}	1.41×10^{-4}	4.42×10^{-4}	**1.02×10^{-3}**
MS-153	4.71×10^{-4}	9.99×10^{-5}	1.65×10^{-4}	4.16×10^{-4}	**1.15×10^{-3}**
MS-154	7.71×10^{-4}	2.39×10^{-5}	2.87×10^{-4}	5.20×10^{-4}	**1.60×10^{-3}**
MS-155	9.00×10^{-4}	1.30×10^{-5}	4.72×10^{-5}	4.94×10^{-4}	**1.45×10^{-3}**
MS-156	1.46×10^{-3}	3.47×10^{-5}	4.24×10^{-5}	2.08×10^{-4}	**1.74×10^{-3}**
MS-157	4.29×10^{-4}	9.99×10^{-5}	7.08×10^{-5}	3.90×10^{-4}	**9.90×10^{-4}**
MS-158	3.86×10^{-4}	1.30×10^{-5}	4.24×10^{-5}	4.42×10^{-4}	**8.84×10^{-4}**
MS-159	9.43×10^{-4}	9.99×10^{-5}	3.78×10^{-5}	3.90×10^{-4}	**1.47×10^{-3}**
MS-160	3.21×10^{-3}	2.39×10^{-5}	3.78×10^{-5}	3.64×10^{-4}	**3.64×10^{-3}**
MS-161	2.83×10^{-3}	1.11×10^{-4}	4.24×10^{-5}	3.12×10^{-4}	**3.30×10^{-3}**
MS-162	2.36×10^{-3}	6.73×10^{-5}	7.54×10^{-5}	3.64×10^{-4}	**2.86×10^{-3}**
MS-163	9.43×10^{-4}	6.73×10^{-5}	8.48×10^{-5}	3.38×10^{-4}	**1.43×10^{-3}**
MS-164	1.46×10^{-3}	4.56×10^{-5}	7.08×10^{-5}	2.60×10^{-4}	**1.84×10^{-3}**
MS-165	2.14×10^{-4}	9.99×10^{-5}	2.03×10^{-4}	4.42×10^{-4}	**9.59×10^{-4}**
MS-166	4.71×10^{-4}	1.30×10^{-5}	1.13×10^{-4}	8.58×10^{-4}	**1.46×10^{-3}**
MS-167	2.57×10^{-4}	1.11×10^{-4}	7.54×10^{-5}	5.46×10^{-4}	**9.90×10^{-4}**
MS-168	3.43×10^{-4}	7.82×10^{-5}	5.18×10^{-5}	8.58×10^{-4}	**1.33×10^{-3}**
MS-169	1.41×10^{-3}	5.65×10^{-5}	3.78×10^{-5}	3.64×10^{-4}	**1.87×10^{-3}**
MS-170	3.21×10^{-3}	9.99×10^{-5}	1.27×10^{-4}	4.42×10^{-4}	**3.88×10^{-3}**
MS-171	1.93×10^{-3}	9.99×10^{-5}	4.72×10^{-5}	5.46×10^{-4}	**2.63×10^{-3}**
MS-172	2.44×10^{-3}	6.73×10^{-5}	6.12×10^{-5}	3.90×10^{-4}	**2.97×10^{-3}**
MS-173	2.70×10^{-3}	5.65×10^{-5}	7.54×10^{-5}	4.16×10^{-4}	**3.25×10^{-3}**
MS-174	3.43×10^{-4}	1.11×10^{-4}	4.24×10^{-5}	4.68×10^{-4}	**9.65×10^{-4}**

Principal Component Analysis

Your research area's underlying environmental dynamics can be viewed via a sophisticated lens thanks to the PCA results. The research finds that two different contamination profiles account for more than half of the variability in the data by lowering the dimensionality of the eight metals. The close coupling of copper and zinc dominates the first main trend, which is represented by PC1. This strong link indicates that these two components are probably coming into the water system from a common human source, like brass fittings, galvanised plumbing, or particular fertilisers used in agriculture. The biggest risk regions for this particular metal signature are shown by samples that appear on the far right of the figure; these samples often correspond with excessive levels of arsenic. The second tendency, denoted as PC2, emphasises an entirely distinct industrial or geochemical influence. The vertical climb of the vectors for nickel, cobalt, and chromium shows that these metals fluctuate independently of the copper-zinc group but together. The sample MS-154, which functions as a significant statistical outlier, best illustrates this. Its exceptional placement at the top of the graph, where its concentrations of cobalt and chromium differ significantly from the rest of the dataset, suggests a localised pollution event or a particular geological pocket. In this model, arsenic exhibits distinctive behaviour, with a negative orientation on the second axis. This suggests that although arsenic is more common in samples with a high copper content, it is often less common in samples with an industrial character dominated by chromium and cobalt. The Arsenic-Copper hotspots (MS-160 and MS-170), the Chromium-Cobalt industrial sites (MS-154), and the comparatively compliant "clean" cluster (centred on the left) are the three danger zones that this geographical division on the graph helps classify your sampling locations into. In this PCA space, manganese is essentially neutral, indicating that its presence is more consistent or less indicative of the main pollution causes impacting the other metals. All things considered, this PCA does more than simply group samples; it creates a chemical geography that differentiates between isolated industrial discharge and pervasive contamination (Figure: 4).

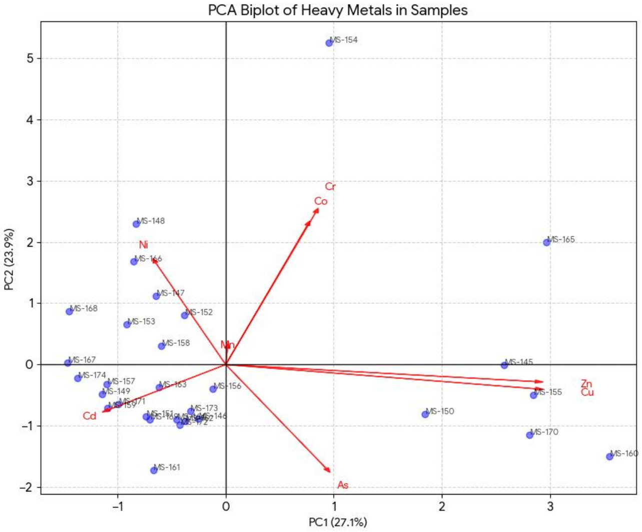

Figure: 4 PCA Biplot of trace and toxic Metals in drinking water samples collected from Taluka Mirpur Sakro

Pearson Correlation Matrix

A statistical basis for comprehending how different heavy metals interact in your sampling environment is provided by the Pearson correlation matrix. The analysis's most notable finding is the remarkably strong positive correlation between copper and zinc, which is highly significant at the 0.01 level with a coefficient of 0.959. This almost linear relationship strongly suggests that these two metals are not independent variables in your study area but rather come from a single anthropogenic source, like the wear of brass alloys or galvanised materials, or a particular industrial discharge that uses both metals at the same time. With a positive correlation of 0.677, which is likewise significant at the 0.01 level, chromium and cobalt are found to have a secondary but still strong association. This implies that although these metals are different from the Copper-Zinc group, they have a similar industrial origin or transport route, which may be connected to metallurgical processes or electronic waste. There is a high degree of confidence that these factors are fluctuating simultaneously as a result of external environmental pressures rather than a random distribution because of the statistical significance in this case. It's interesting to note that at the 0.05 level, the matrix shows a substantial negative association between nickel and arsenic. This negative connection of -0.378 is quite instructive because it implies that the sources or environmental factors that promote high concentrations of arsenic—such as particular groundwater chemistry or agricultural runoff—do not align with those that cause nickel accumulation. Additionally, with no discernible relationships with any other metals, cadmium and manganese seem to be the most "independent" elements in the collection. Their weak and frequently negative coefficients imply that their presence is probably caused by distinct geological leaching or localised point sources that deviate from the more general contamination patterns set by the Copper-Zinc or Chromium-Cobalt clusters. Overall, by measuring precisely which metals are statistically "locked" together and which are moving through the environment independently, these correlations improve the PCA results (Table: 8).

Table 8: ***Correlation coefficient of trace and toxic metals in drinking water of coastal area of Taluka Mirpur Sakro***

	As	Cd	Cr	Co	Mn	Ni	Cu	Zn
As	1							
Cd	-0.038	1						
Cr	-0.232	-0.068	1					
Co	-0.077	-0.215	0.677**	1				
Mn	-0.239	-0.183	0.004	-0.093	1			
Ni	-0.378*	-0.09	0.213	0.087	-0.051	1		
Cu	0.201	-0.179	0.117	0.027	0.038	-0.147	1	
Zn	0.166	-0.191	0.141	0.048	-0.011	-0.113	0.959**	1

CONCLUSION

Arsenic and cobalt concentrations in 80% of samples (up to 75 µg/L) and 40% of samples (up to 0.34 mg/L) surpass WHO permitted limits, indicating a severe contamination of the drinking water. The oral reference dosage is often exceeded by the Estimated Daily Intake (EDI) values for arsenic, indicating a high non-carcinogenic risk. The Hazard Index (HI) ranged from 3.35 to 34.85, much over the acceptable limit of 1, and the Target Hazard Quotient (THQ) study shows that all samples had THQ > 1 for arsenic and/or cobalt, confirming a serious cumulative non-carcinogenic health risk for the local people. Additionally, all samples had a Total Cancer Risk (TCR) between 6.62×10^{-3} and 3.88×10^{-3}, which is 6 to 38 times higher than the US EPA's tolerable level of 1×10^{-1}. The main contributor is arsenic, followed by nickel. These results point to a serious public health emergency. It is urgently advised that alternate safe drinking water sources be made available right away, and that medical surveillance for metal-related illnesses be conducted on a regular basis.

Author Contribution

Dr. Abdul Raheem Shar conceptualized, designed experiments, *Liaquat Ali Shar and Saleem Ahmed Utero* prepared the draft of the article. *Rubina Naz Mirani and Naseem Khatoon Bhatti* interpreted the data. *Ali Raza Rind, Rehana Keerio and Farzana Mangrio* corrected grammatical errors.All authors read, revised, and approved the final version of the manuscript.

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Conflict of Interest

The authors declare no conflict of interest

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