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Evaluating Heavy Metal Contamination in Burundi's Water Sources and Public Health Implications

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ABSTRACT

Background: Water quality is essential for safe consumption and overall public health. However, contamination by heavy metals can pose significant risks, particularly in countries with limited resources. This study aimed to quantify heavy metals, including chromium, cadmium, copper, and lead, among others, in various water sources in Burundi, and to assess their implications for human and environmental health.

Method: A total of 43 water samples were collected from seven provinces in Burundi, including tap water, river water, Lake Tanganyika surface water, bottled water, and dialysis water. Each sample was analysed for four parameters (chromium, cadmium, copper, and lead), resulting in a total of 172 analyses. The sampling occurred between January and February 2021. Heavy metal concentrations were analyzed using atomic absorption spectrophotometry.

Results: Across all samples analyzed for heavy metals, chromium concentrations were critically elevated, exceeding the World Health Organization (WHO) guideline of 0.05 mg/L. Most of the other heavy metals were below the limit of detection in all sample types; however, one surface water sample collected from Lake Tanganyika showed a lead concentration above the recommended safety threshold. Statistical analysis indicated significant differences in heavy metal concentrations across the various water types.

Conclusion and Recommendations: The findings indicate widespread chromium contamination across all analyzed water samples, with concentrations consistently exceeding the World Health Organization (WHO) recommended guideline value, highlighting potential public health and environmental concerns. Although most other heavy metals remained below detectable levels, the findings highlight a serious issue with heavy metals in Burundi's water sources, particularly chromium. Prolonged exposure to these contaminants poses significant health risks to the population. Immediate monitoring and follow-up efforts are essential to address heavy metal contamination. Public health initiatives should focus on raising awareness and implementing water treatment solutions to ensure safe drinking water. Further research is recommended to explore the long-term health impacts of heavy metal exposure in Burundi.

BACKGROUND

Certain heavy metals have biological importance as trace elements, but the toxic effects of many of them in the human body are very concerning. Therefore, it is necessary to understand the conditions, such as concentrations, health and environmental impacts, and exposure indices to these metals. Literature sources highlight that these metals are released into the environment from natural and anthropogenic sources, particularly mining and industrial activities, automobile exhaust, and traditional cooking.[1–3]

Heavy metals are a group of metals that exhibit toxic properties, including chromium, cadmium, copper, and lead. These elements can enter water bodies through various pathways, such as industrial discharges, agricultural runoff, and improper waste disposal.[1,2] Unlike organic pollutants, heavy metals do not decompose, leading to their accumulation in sediments and organisms over time. This persistence raises significant concerns about its long-term effects on human health.[6] Heavy metals include lead (Pb), cadmium (Cd), zinc (Zn), mercury (Hg), arsenic (As), silver (Ag), chromium (Cr), copper (Cu), iron (Fe), and platinum group elements.[3,4] The tolerance limits for certain heavy metals are indicated in Table 1.[5]

Clean water is considered a fundamental requirement for human health and well-being. Its pollution is a significant threat to global health. Water pollution has consequences for health and

ecosystems, and its economic cost is huge. According to an assessment by the World Health Organization (WHO), the burden of diseases caused by water pollution is immense. Nearly 12 million deaths are attributed to environmental pollution and unsanitary conditions.[10–12]

Water is essential for various bodily functions, including digestion, nutrient transport, and temperature regulation. [13] It is vital for maintaining hygiene and sanitation, which are crucial for preventing waterborne diseases. Clean water is also fundamental for agricultural practices, impacting food security and nutrition. Access to safe drinking water is a cornerstone of public health. In many regions, particularly in developing countries, the lack of clean water sources leads to a reliance on contaminated water, resulting in significant health burdens. [14] The WHO emphasizes that safe drinking water is essential for the prevention of diseases and for overall health improvement.[11]

Heavy metal pollution of surface and groundwater sources leads to significant soil pollution, and pollution increases when extracted ores are dumped on the surface for manual treatment.[15,16] Surface dumping exposes metals to air and rain. When agricultural soils are polluted, these metals are absorbed by plants and thus accumulate in their tissues.[17–19] Animals that graze on these contaminated plants and drink from polluted waters, as well as marine species that reproduce in waters contaminated by heavy metals, also accumulate these metals in their tissues.[20–23] Humans are in turn exposed to heavy metals by consuming contaminated plants and animals, which is known to lead to various biochemical disorders. In summary, all living organisms in a given ecosystem are variously contaminated throughout their food chain cycles.[14,24]

Exposure to heavy metals occurs significantly through occupational exposure. Workers in the extraction and production of cadmium, chromium, lead, mercury, nickel, gold, and silver have been exposed; residents around industrial sites of heavy metal extraction and processing are also exposed through airborne suspended particles.[24–28]

Chemical pollutants present in water can cause congenital malformations and are sources of diseases such as cancers. Groundwater pollution results in the contamination of aquifers with serious health consequences for humans. More than half of this mortality burden is borne by populations in developing countries.[10] The distribution of pollution-related deaths shows that they are related to Chronic Obstructive Pulmonary Disease (COPD) in 22% of cases, lung cancers in 6% of cases, lower respiratory infections in children in 12% of cases, ischemic heart disease in 26% of cases, and stroke in 34%.[10,11]

The pathologies associated with water pollution are diverse, ranging from simple digestive or respiratory discomfort to more serious diseases such as cancer. Thus, water pollution has become a global concern for populations and authorities in light of the increasing pathologies attributed to it. Indeed, developing countries are more affected by water pollution than developed countries.[6–8]

Heavy metal contamination in the water sources of Burundi, notably in Lake Tanganyika, rivers, and streams, mainly arises from untreated industrial and municipal wastewater, mining operations, agricultural runoff (including pesticides and fertilizers), and urban waste.[9–11] Pollutants such as cadmium, lead, and mercury; among other heavy metals, infiltrate aquatic ecosystems through river inflows, soil erosion, and direct atmospheric deposition, posing significant risks of bioaccumulation.[10–13] Despite its critical importance, Lake Tanganyika faces severe pollution challenges, especially near Bujumbura, the largest city along its shores.[12,14] This situation has resulted in the loss of biodiversity, the destruction of habitats, and disruptions to the trophic system.

Heavy metal contamination in Burundi's water sources presents substantial, long-term health risks for the population, primarily due to the accumulation of toxic substances within the body. Key contaminants identified in some regional studies include lead (Pb), cadmium (Cd), mercury (Hg), and arsenic (As), among other which typically originate from mining operations, agricultural runoff, and industrial waste disposal.[9,13,15–18]

In Burundi, according to the Food and Agriculture Organization (FAO), the annual water consumption in the country is estimated at 0.23 km³, of which only 1% is for industry, 17% for domestic use, and 82% for agriculture. By comparison, the same source indicates that only 14% of water consumed in Rwanda is allocated to industry, 39% to agriculture, and 48% to households.[19] Despite discrepancies in global and sectoral estimates (certainly due to a lack of reliable data), various sources clearly show that agriculture remains the main consumer of water. Considering that 82% of water is allocated to agriculture in Burundi, if agricultural soils are polluted, metals are absorbed by plants and accumulate in their tissues; consequently, animals that graze on these contaminated plants and drink from polluted waters, as well as marine species that reproduce in waters polluted by heavy metals, also accumulate these metals in their tissues. Ultimately, humans are exposed to heavy metals by consuming contaminated plants and animals, which may lead to various health disorders.[20–24]

Monitoring and assessing heavy metal contamination in Burundi's water bodies, especially around urban centers like Bujumbura and the northern section of Lake Tanganyika, largely rely on laboratory-based analytical methods. However, national monitoring initiatives often face challenges such as high costs and the necessity for specialized personnel. Various scientific research efforts and regional programs contribute valuable data on contamination levels in these areas.[34,41,42] In Burundi, treating drinking water for heavy metal pollutants employs a combination of conventional methods, industrial techniques, and innovative low-cost point-of-use (POU) solutions, particularly in rural regions and areas affected by mining. The main treatment approaches include chemical precipitation, reverse osmosis, and biosorption, targeting pollutants like lead, cadmium, and arsenic.[25–32]

Burundi has modernized its legal framework to combat environmental degradation, particularly in mining and waste management. Key initiatives include the Mining Code 2023, which enforces stricter compliance measures for heavy metal management and allows for revocation of mining licenses for environmental violations.[33] New regulations from Decree No. 100/006 establish environmental and operational standards for mining.[33,34] In collaboration with the United Nations Environment Programme (UNEP), Burundi is developing a Chemicals and Waste Management Strategy based on circular economy principles to enhance waste management. Environmental Impact Assessments (EIA) are now mandatory for mining projects, requiring detailed Environmental Management Plans to mitigate environmental harm.[34–37] Technical mitigation strategies emphasize eco-friendly methods such as bioremediation, the use of microbial consortia to remove heavy metals, hyperaccumulating plants for pollutant extraction, and advanced wastewater treatment. Recommended improvements include enhancing laboratory capabilities for water quality monitoring, applying the Polluter Pays Principle to hold companies accountable for remediation costs, implementing agricultural best practices to reduce heavy metal runoff, and raising public awareness to promote sustainable mining practices.[34,38,39]

A significant amount of scientific data is currently available on water pollution and its health consequences. Although there are still gaps, differences and uncertainties depending on the country, it constitutes an important basis for specialists. However, most of this database is Western; few studies have been conducted in sub-Saharan Africa, including Burundi. This explains the importance and relevance of the topic. This has prompted us to conduct this study to determine the quality of water consumed in households, river water, and Lake Tanganyika water, as well as dialysis water in Burundi, and to assess the health and environmental impact of heavy metal contamination on the affected population.

Given the critical concerns surrounding heavy metal contamination in water, this study aims to quantify the levels of heavy metals in various water sources across Burundi., especially to determine the concentration of different heavy metals contaminating water, like Copper, Lead, Cadmium and Chromium. By identifying the extent of contamination, we hope to inform public health policies and encourage the implementation of effective water management strategies. The findings will serve as a crucial resource for policymakers, health professionals, and community leaders, emphasizing the need for immediate action to ensure access to safe drinking water and protect public health.

METHODOLOGY

Study Setting

This study was conducted in Burundi, a country in East Africa where water from rivers, lakes, tap systems, and commercial sources is widely used for domestic and medical purposes. Samples were collected from seven provinces, namely Bujumbura, Rumonge, Gitega, Ngozi, Kayanza, Bubanza, and Kirundo. The study included multiple water sources, including tap water, river water, Lake Tanganyika surface water, bottled water, and dialysis water, in order to provide a broad representation of water quality across urban and rural settings.

Study Design

A cross-sectional analytical study was conducted between January and February 2021 to assess heavy metal contamination in different water sources in Burundi. The study focused on determining the concentrations of chromium (Cr), cadmium (Cd), copper (Cu), and lead (Pb) and evaluating their potential implications for human health.

Study Samples

The study analyzed water samples collected from different sources commonly used by the population. These included tap water, river water, Lake Tanganyika surface water, bottled drinking water, and dialysis water. Each sample was collected in clean sterile containers and labeled with a unique identification code before transportation to the laboratory for analysis.

Study Samples

The study analyzed water samples collected from common sources used by the population. These included tap water, river water, Lake Tanganyika surface water, bottled drinking water, and dialysis water. Each sample was collected in clean, sterile containers and labeled with a unique identification code before being transported to the laboratory for analysis.

Sample Size and Sampling Criteria

A total of 43 water samples, as presented in Table 1, were randomly collected from seven provinces in Burundi. The distribution included 17 samples from Bujumbura, 16 from Rumonge, 3 from Gitega, 1 from Ngozi, 1 from Kayanza, 3 from Bubanza, and 1 from Kirundo. Samples were selected to ensure representation of both urban and rural environments and to include the main water sources consumed or used by the population. Water sources accessible during the study period and considered relevant for domestic or medical use were included in the sampling process.

Data Collection and Laboratory Processing

Samples were collected by trained personnel following standardized procedures to minimize contamination. Immediately after collection, the samples were stored in clean containers and placed in insulated coolers before being transported for analyses to the Toxicology Laboratory of the Faculty of Medicine, Pharmacy and Odontology at Cheikh Anta Diop University (UCAD) in Dakar, Senegal.

Sample preparation was carried out according to the manufacturer's recommended procedures[40]. Before analysis, water samples were filtered using a PTFE syringe filter with a pore size of 0.45 µm. The samples were then acidified with a few drops of 67% nitric acid (HNO_3). Calibration standards were prepared using aliquots of a 1000 mg/L Agilent-certified stock standard solution diluted with water acidified to 5% nitric acid. Calibration and rinsing blanks consisting of 5% nitric acid solution

TABLE 1: Water Sample Distribution

		Tap water	Lake Tanganyika water	River water	Bottled water	Dialysis water
1	Bujumbura	4	2	6	2	3
2	Gitega	3	-	-	-	-
3	Ngozi	1	-	-	1	-
4	Rumonge	4	6	6	-	-
5	Kayanya	1	-	-	-	-
6	Bubanza	1	-	2	-	-
7	Kirundo	1	-	-	-	-
Total		15	8	14	3	3

were also prepared under the same conditions as the samples.

Heavy metal concentrations were determined using Atomic Absorption Spectrophotometry (AAS) with an Agilent Technologies 200 Series instrument equipped with a flame atomization system. Calibration curves were established for each metal using five standard concentrations. Pearson correlation coefficients demonstrated strong linearity for cadmium (r = 0.99), chromium (r = 0.977), copper (r = 1.00), and lead (r = 1.00).

Sample analysis was carried out according to the manufacturer's procedures. After calibration and before each analysis, blank samples were analyzed at the beginning of every analytical run. In addition, blank samples were analyzed intermittently throughout the analyses, and the obtained results were consistent, confirming the reliability and accuracy of the procedure.

Data Analysis

All laboratory results were entered into Microsoft Excel for organization and cleaning before statistical analysis. Data analysis was performed using SPSS version 26.0 (Statistical Package for the Social Sciences, Paris, France). Descriptive statistics, including means, standard deviations, minimum values, and maximum values, were calculated. The Kruskal–Wallis test was used to compare heavy metal concentrations among different water types because the data did not necessarily follow a normal distribution. Statistical significance was established at $P<.05$.

Calibration Method

Calibration curves for each heavy metal were established to ensure accurate quantification. The calibration process involved preparing a series of known concentrations for each metal, which were analyzed before each parameter and also alongside the samples analysis process to create a reference for comparison.

The calibration involves five standards with known concentrations of cadmium (in mg/L) ranging from 0.000 mg/L (standard 0) to 2.400 mg/L (standard 4) (Figure 3); of chromium (in mg/L) ranging from 0.000 mg/L (standard 0) to 6.00 mg/L (standard 4) (Figure 2); and of copper and lead (in mg/L) ranging from 0.000 mg/L (standard 0) to 8.00 mg/L (standard 4) (Figure 1 and 4).

FIGURE 1: Cu Calibration Curve

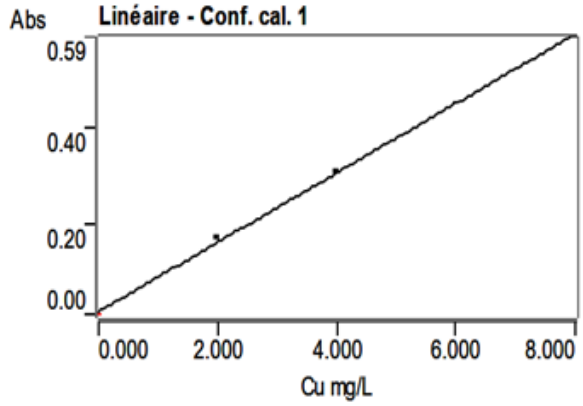


FIGURE 2: Cr Calibration Curve

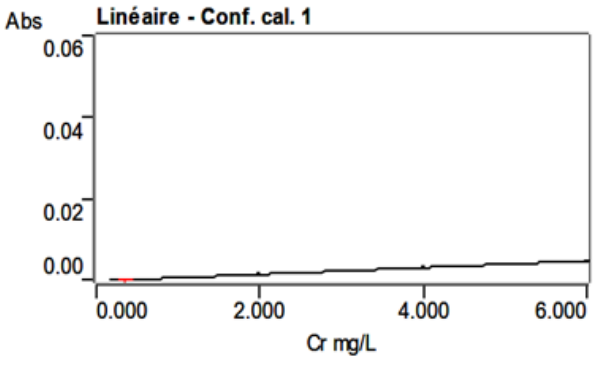


FIGURE 3: Cd Calibration Curve

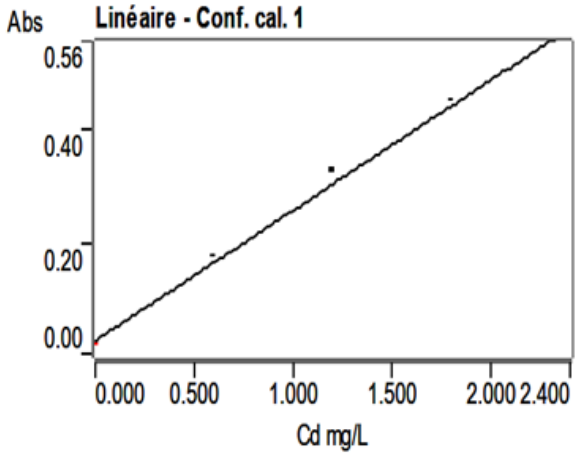
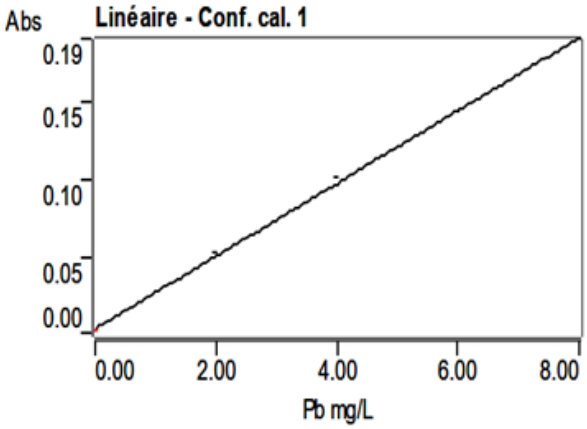


FIGURE 4: Pb Calibration Curve



The values obtained ranged from 0.9880 to 0.9990, indicating very strong linear relationships between concentration and instrumental response for all analyzed metals. Copper (Cu) and lead (Pb) displayed excellent linearity (0.9990), while cadmium (0.9900) and chromium (0.9880) also demonstrated acceptable calibration performance (Table 2). The calibration data shows a clear linear relationship between cadmium, chromium, copper and lead concentration and their respective absorbance, which is essential for quantifying unknown samples based on their absorbance.

Among the analyzed metals (Table 2), chromium (Cr) exhibited the lowest limit of detection (LOD) at 0.0005 mg/L, indicating the highest analytical sensitivity for this element. Lead (Pb) and copper (Cu) followed with LOD values of 0.0068 mg/L and 0.0189 mg/L, respectively, whereas cadmium (Cd) presented the highest LOD (0.0675 mg/L), suggesting comparatively lower sensitivity for its detection.

Similarly, chromium showed the lowest limit of quantification (LOQ) at 0.0015 mg/L (Table 2), followed by Pb and Cu with LOQ values of 0.0206 mg/L and 0.0573 mg/L, respectively. Cadmium again exhibited the highest LOQ (0.2045 mg/L). These results demonstrate that the analytical method is particularly effective and sensitive for the detection and quantification of trace concentrations of chromium, while higher concentrations of cadmium are required to achieve reliable quantification. Overall, the relatively low LOD and LOQ values obtained for most metals confirm the suitability of the method for trace metal analysis in environmental samples.

Ethical Considerations

Ethical approval for the study was obtained from the Ethics Committee of the Faculty of Medicine of the University of Burundi in 2021. All sample collection and laboratory procedures were conducted in accordance with established ethical and scientific standards.

TABLE 2: Limit of Detection and Limit of Quantification

	Cd	Cr	Cu	Pb
LOD (mg/L)	0,0675	0,0005	0,0189	0,0068
LOQ (mg/L)	0,2045	0,0015	0,0574	0,0206
Correlation Coefficient (R^2)	0,9900	0,9880	0,9990	0,9990

TABLE 3: Test Statistics Results [a]

	Concentration in mg/Lb	Concentration in mg/Lc
Chi-Square	148.535	1.975
df	3	4
Asymp. Sig.	0.000	0.740

a. Kruskal Wallis Test
b. Grouping Variable: Heavy metal
c. Grouping Variable: Type of water sample

RESULTS

Results by Location

The findings from Bujumbura (Table 4) indicate widespread chromium (Cr) contamination across all analyzed water sources, while cadmium (Cd), copper (Cu), and lead (Pb) remained below detectable limits or showed negative concentrations, suggesting absence or concentrations below the analytical detection threshold. These findings are detailed as following:

- In tap water, chromium concentrations ranged from 0.447 to 0.660 mg/L, with an average of 0.565 mg/L, exceeding the World Health Organization (WHO) recommended limit for drinking water (0.05 mg/L) by more than tenfold.

- River water samples showed even higher chromium contamination, with concentrations ranging from 0.671 to 1.286 mg/L and an average of 0.994 mg/L. The highest levels were observed in the Ruziba and Kanyosha rivers, indicating that river systems in Bujumbura may be heavily impacted by anthropogenic activities such as industrial discharge, urban runoff, wastewater disposal, and agricultural contamination.

- Lake Tanganyika surface water demonstrated the highest chromium concentrations among the environmental water sources, ranging from 1.595 to 2.24 mg/L, with a mean concentration of 1.918 mg/L. These concentrations are nearly 40 times higher than WHO permissible limits, highlighting severe contamination of the lake near Bujumbura.

- Bottled drinking water samples also contained alarmingly high chromium levels, with concentrations ranging from 1.326 to 1.537 mg/L (average: 1.432 mg/L). The results may indicate contamination of the source water or inadequate treatment during the bottling process, raising concerns about regulatory oversight and consumer safety.

- Dialysis water samples from CHUK hospital exhibited very high chromium concentrations, ranging from 1.609 to 1.664 mg/L, with an average concentration of 1.642 mg/L. The persistence of chromium even after filtration suggests that the dialysis water treatment system may not effectively remove heavy metals.

The results from Rumonge (Table 5) reveal substantial chromium (Cr) contamination across all analyzed water sources, while cadmium (Cd) and copper (Cu) concentrations remained below detectable limits. Lead (Pb) was generally undetectable except in one Lake Tanganyika surface water sample from Magara, which showed an extremely elevated concentration. Overall, chromium was the predominant contaminant and consistently exceeded the World Health Organization (WHO) recommended limit for drinking water (0.05 mg/L), indicating a serious public health concern. These findings are detailed as follow:

- In tap water samples, chromium concentrations ranged from 0.449 to 0.724 mg/L, with an average concentration of 0.572 mg/L. These values are more than ten times higher than the WHO permissible limit, suggesting widespread contamination of municipal and domestic water systems in Rumonge. The highest concentration was detected in Magara (0.724 mg/L), while the lowest was observed in Mbuga (0.449 mg/L).

- River water samples demonstrated even higher chromium concentrations, ranging from 1.225 to 1.428 mg/L, with a mean value of 1.303 mg/L. The highest contamination was recorded in the Rugatu River (1.428 mg/L), followed closely by the Nyaru River (1.354 mg/L). Since rivers are frequently used for domestic activities, irrigation, and livestock, the contamination may contribute to both environmental degradation and human exposure through direct contact and the food chain.

- Lake Tanganyika surface water samples also showed alarmingly high chromium concentrations, varying from 1.287 to 1.538 mg/L, with an average concentration of 1.428 mg/L. These concentrations indicate severe contamination of the lake shoreline areas in Rumonge and Muhuta communes.

- A particularly important finding was the detection of an extremely high lead concentration (4.19 mg/L) in the Magara Lake Tanganyika sample. This value is far above the WHO recommended limit for lead in drinking water (0.01 mg/L), representing acute contamination and a major public health risk.

The findings from Bubanza (Table 6) indicate significant chromium (Cr) contamination in both tap water and river water, while cadmium (Cd), copper (Cu), and lead (Pb) concentrations remained below detectable limits or within negligible ranges. Chromium was the only heavy metal consistently detected at elevated concentrations, greatly exceeding the World Health Organization (WHO)

recommended limit of 0.05 mg/L for drinking water.

- In tap water collected from Muzinda commune, the chromium concentration was 0.53 mg/L, which is more than ten times higher than the WHO permissible limit.

- River water samples collected from Muzazi and Murago also showed high chromium concentrations of 0.887 mg/L and 0.883 mg/L, respectively, with an average concentration of 0.885 mg/L. These levels are substantially higher than international safety standards and indicate severe contamination of local river systems.

- The absence of detectable cadmium, copper, and lead concentrations may indicate either very low environmental levels or concentrations below the analytical detection limits of the instrument used. However, the consistently high chromium concentrations across both tap and river water sources point to chromium as the principal contaminant of concern in Bubanza.

The results from Gitega (Table 7) indicate substantial chromium (Cr) contamination in all analyzed tap water samples, while cadmium (Cd), copper (Cu), and lead (Pb) concentrations remained below detectable limits or at negligible levels. Chromium was therefore identified as the principal heavy metal contaminant in the water supply of the studied areas. Chromium concentrations in tap water ranged from 0.705 mg/L to 0.808 mg/L, with an average concentration of 0.761 mg/L. These levels are more than 14 times higher than the World Health Organization (WHO) recommended limit of 0.05 mg/L for drinking water, indicating serious contamination of the municipal water system in Gitega.

The tap water sample collected from Ngozi commune (Table 8) showed a chromium concentration of 0.671 mg/L, which is more than 13 times higher than the World Health Organization (WHO) recommended limit of 0.05 mg/L for drinking water. An even higher chromium concentration was observed in the bottled drinking water sample, which contained 1.509 mg/L of chromium. This concentration is approximately 30 times higher than the WHO permissible limit and exceeds the chromium level found in tap water. Cadmium, copper, and lead concentrations were below detectable limits in both tap and bottled water samples.

The findings from Kayanza and Kirundo (Table 9) indicate significant chromium (Cr) contamination in tap water samples, while cadmium (Cd), copper (Cu), and lead (Pb) concentrations remained below detectable limits or at negligible levels. Chromium was the only heavy metal consistently detected at concentrations exceeding international drinking water safety standards. In Kayanza, the tap water sample showed a chromium concentration of 0.626 mg/L, while in Kirundo the concentration reached 0.752 mg/L. The average chromium concentration for the two provinces was 0.689 mg/L, which is nearly 14 times higher than the World Health Organization (WHO) recommended limit of 0.05 mg/L for drinking water. Among the two locations, Kirundo presented the highest chromium concentration, suggesting comparatively greater contamination of the local water supply.

Results by samples

Tap water samples

In tap water (Table 10_a), chromium concentrations ranged from 0.447 mg/L to 0.808 mg/L, with a mean concentration of 0.63±0.11 mg/L and all the samples exceeded the maximum permissible concentration for chromium; whereas the concentration of Cd, Cu and Pb were below the detectable limit.

River Water Samples

River water samples (Table 10_b) showed even higher chromium concentrations for all the samples, ranging from 0.67 mg/L to 1.43 mg/L. The rest of the heavy metals tested reported undetectable concentrations.

Tanganyika Water Samples

Chromium concentrations in Lake Tanganyika surface water were alarmingly high, ranging from 1.29 mg/L to 2.24 mg/L. Notably, a single sample, collected from Magara, contained lead at 4.19 mg/L, far exceeding safety limits for both metals (Cr and Pb).

Bottled Water Samples

The bottled drinking water samples presented chromium concentrations between 1.33 mg/L and 1.54 mg/L. These levels are alarming, given that bottled water is often perceived as a safer alternative to tap water.

Dialysis Water Sample

The dialysis water samples also exhibited high chromium concentrations, ranging from 1.61 mg/L to 1.66 mg/L. The other heavy metals reported undetectable concentrations.

TABLE 4: Results of Samples Collected from Bujumbura

	Cd		Cr		Cu		Pb	
	Conc. mg/L	Abs.	Conc. mg/L	Abs.	Conc. mg/L	Abs.	Conc. mg/L	Abs.
Lake Tanganyika surface water								
TAN6	-0,028	0,0187	2,24	0,0009	-0,103	0,0002	-0,26	-0,0027
TAN7	-0,026	0,0191	1,595	0,0012	-0,102	0,0003	-0,24	-0,0023
Average concentration	-0,027	0,0189	1,9175	0,00105	-0,1025	0,00025	-0,25	-0,0025

Continue

TABLE 4: Continued

	Cd		Cr		Cu		Pb	
	Conc. mg/L	Abs.	Conc. mg/L	Abs.	Conc. mg/L	Abs.	Conc. mg/L	Abs.
				Bottled drinking water				
MI1	-0,121	-0,0028	1,326	0,0009	-0,103	0,0002	-0,25	-0,0026
MI3	-0,056	0,0124	1,537	0,0011	-0,102	0,0003	-0,29	-0,0036
Average concentration	-0,0885	0,0048	1,4315	0,001	-0,1025	0,00025	-0,27	-0,0031
				Dialysis water				
DL1	-0,055	0,0124	1,664	0,0012	-0,1	0,0004	-0,28	-0,0033
DL2	-0,056	0,0122	1,609	0,0012	-0,102	0,0003	-0,31	-0,004
DL3	-0,056	0,0123	1,654	0,0012	-0,101	0,0003	-0,3	-0,0037
Average concentration	-0,05567	0,0123	1,64233	0,0012	-0,101	0,000333	-0,2967	-0,0037

TABLE 5: Results of Samples Collected from Rumonge

Code	Cd		Cr		Cu		Pb	
	Conc. mg/L	Abs.	Conc. mg/L	Abs.	Conc. mg/L	Abs.	Conc. mg/L	Abs.
				Tape water				
RB4	-0,031	0,0181	0,602	0,0004	-0,113	0,0005	-0,16	0,0004
RB5	-0,028	0,0187	0,449	0,0002	-0,113	0,0006	-0,19	0,0013
RB6	-0,027	0,0189	0,512	0,0003	-0,096	0,0007	-0,15	0,0003
RB7	-0,037	0,0167	0,724	0,0005	-0,112	0,0004	-0,16	0,0005
Average concentration	-0,031	0,018	0,572	0,000	-0,109	0,001	-0,165	0,001
				River water				
RV9	-0,037	0,0168	1,225	0,0009	-0,098	0,0005	-0,21	-0,0016
RV10	-0,035	0,017	1,297	0,0009	-0,099	0,0005	-0,19	-0,0013
RV11	-0,036	0,0169	1,261	0,0009	-0,099	0,0005	-0,18	-0,0009
RV12	-0,034	0,0173	1,25	0,0009	-0,093	0,001	-0,11	0,0006
RV13	-0,034	0,0174	1,354	0,001	-0,096	0,0007	-0,16	-0,0005
RV14	-0,034	0,0174	1,428	0,001	-0,098	0,0005	-0,24	-0,0023
Average concentration	-0,035	0,017	1,303	0,001	-0,097	0,001	-0,182	-0,001
				Lake Tanganyika surface water				
TAN1	-0,04	0,0159	1,391	0,001	-0,103	0,0002	-0,24	-0,0024
TAN2	-0,031	0,018	1,287	0,0009	-0,103	0,0002	-0,25	-0,0027
TAN3	-0,03	0,0182	1,401	0,001	-0,102	0,0003	-0,25	-0,0025
TAN4	-0,03	0,0184	1,45	0,001	-0,104	0,0001	-0,23	-0,0021
TAN5	-0,027	0,019	1,538	0,0011	-0,102	0,0003	-0,23	-0,0022
TAN8	-0,029	0,0185	1,502	0,0011	-0,102	0,0003	4,19	0,1013
Average concentration	-0,031	0,018	1,428	0,001	-0,103	0,000	0,498	0,015

TABLE 6: Results of Samples Collected from Bubanza

Code	Cd		Cr		Cu		Pb	
	Conc. mg/L	Abs.	Conc. mg/L	Abs.	Conc. mg/L	Abs.	Conc. mg/L	Abs.
				Tape water				
RB1	-0,033	0,0175	0,53	0,0003	-0,089	0,0012	-0,11	0,0006
Average concentration	-0,033	0,018	0,530	0,000	-0,089	0,001	-0,110	0,001
				River water				
RV1	-0,031	0,018	0,887	0,0006	-0,099	0,0005	-0,17	-0,0007
RV2	-0,005	0,0241	0,883	0,0006	-0,098	0,0005	-0,2	-0,0013
Average concentration	-0,018	0,021	0,885	0,001	-0,099	0,001	-0,185	-0,001

TABLE 7: Results of Samples Collected from Gitega

	Cd		Cr		Cu		Pb	
	Conc. mg/L	Abs.	Conc. mg/L	Abs.	Conc. mg/L	Abs.	Conc. mg/L	Abs.
				Tape water				
RB13	-0,037	0,0167	0,808	0,0005	-0,112	-0,0004	-0,2	-0,0013
RB14	-0,033	0,0175	0,705	0,0004	-0,11	-0,0003	-0,2	-0,0015
RB15	-0,033	0,0176	0,77	0,0005	-0,109	-0,0003	-0,16	-0,0011
Average concentration	-0,034	0,017	0,761	0,000	-0,110	0,000	-0,187	-0,001

TABLE 8: Results of Samples Collected from Ngozi

	Cd		Cr		Cu		Pb	
	Conc. mg/L	Abs.	Conc. mg/L	Abs.	Conc. mg/L	Abs.	Conc. mg/L	Abs.
				Tape water				
RB10	-0,037	0,0166	0,671	0,0004	-0,112	-0,0005	-0,2	-0,0015
Average concentration	-0,037	0,017	0,671	0,000	-0,112	-0,001	-0,200	-0,002
				Bottled drinking water				
MI2	-0,055	0,0125	1,509	0,0011	-0,103	0,0002	-0,27	-0,003
Average concentration	-0,055	0,0125	1,509	0,0011	-0,103	0,0002	-0,27	-0,003

TABLE 9: Results of Samples Collected from Kirundo and Kayanza

	Cd		Cr		Cu		Pb	
	Conc. mg/L	Abs.	Conc. mg/L	Abs.	Conc. mg/L	Abs.	Conc. mg/L	Abs.
				Tape water				
RB9	-0,039	0,0162	0,626	0,0004	-0,113	-0,0005	-0,19	-0,0012
RB12	-0,038	0,0165	0,752	0,0005	-0,1	0,0004	-0,16	-0,0005
Average concentration	-0,039	0,016	0,689	0,000	-0,107	0,000	-0,175	-0,001

TABLE 10: Water Samples Analysis Results

Samples	Cd Conc. mg/L	Cr	Cu Conc. mg/L	Pb Conc. mg/L	Conc. mg/L
Tap water[a]					
Min	-0.042		0.447	-0.114	-0.200
Max	-0.026		0.808	-0.089	-0.110
Mean	-0.03387		0.62967	-0.10840	-0.16800
SD	0.004764		0.112563	0.007395	0.026241
River water[b]					
Min	-0.10		0.67	-0.10	-0.24
Max	-0.004		1.43	-0.09	-0.11
Mean	-0.0334		1.1108	-0.0971	-0.1836
SD	0.02981		0.22272	0.00262	0.03079
Lake Tanganyika water[c]					
Min	-0.04		1.29	-0.10	-0.26
Max	-0.03		2.24	-0.10	4.19
Mean	-0.0301		1.5505	-0.1026	0.3113
SD	0.00432		0.29453	0.00074	1.56729
Bottled water[d]					
Min	-0.12		1.33	-0.10	-0.29
Max	-0.06		1.54	-0.10	-0.25
Mean	-0.077		1.46	-0.10	-0.27
SD	0.039		0.12	0.0006	0.02
Dialysis water[e]					
Min	-0.06		1.61	-0.10	-0.31
Max	-0.06		1.66	-0.10	-0.28
Mean	-0.06		1.64	-0.10	-0.30
SD	0.001		0.03	0.001	0.02

DISCUSSION

The analysis of water samples from various sources (tap water, river water, Lake Tanganyika water, bottled water, and dialysis water) revealed significant concentrations of chromium (Cr) across all sample types with values consistently exceeding established safety standards. While other metals, such as cadmium (Cd), copper (Cu), and lead (Pb), were also measured, chromium emerged as the primary concern based on the results; in fact, lead has been found in concentrations exceeding the required range in one sample.

Statistical analysis reported no significant difference between the concentrations' results and the type of water, with p=0.76. On the other hand, it has been shown that there is a statistical difference among heavy metals' concentration in water, with $p < 0$. The results of these analyses provided insights into the variability and potential contamination levels of trace metals in the sampled water types.

Tap Water Samples

The presence of chromium at these levels is concerning, as the WHO recommends a maximum concentration of 0.05 mg/L for drinking water. Prolonged exposure to high levels of chromium can lead to serious health risks, including respiratory problems, skin irritation, and increased cancer risk, particularly for hexavalent chromium (Cr(VI)), which is known for its toxicity.[7,41,42]

In contrast, a study conducted in Mali reported that concentrations of toxic metals, including chromium, were below the maximum permissible limits, suggesting that their water sources were free from contamination.[43] Similarly, a study conducted in Ethiopia where the Chromium level varied from 0.004 to 0.006 mg/L, which are above the WHO maximum admissible limit of Cr in drinking water (0.002 mg/L) and, 71.43% of samples analyzed contain chromium level above WHO maximum admissible limit. In the same study, the result of heavy metals like cadmium, lead and copper assay showed low detection limit, except chromium which present value above the recommended value of potable drinking water [44]. A study from Uganda also reported that the average of copper and chromium content of the tap water samples from the municipal supply system were 0.155 ± 0.0384 mg/L and 0.056 ± 0.02073 mg/L, respectively. These values were within the maximum permissible limits of 0.3 mg/L, 0.5 mg/L and 0.05 mg/L for copper and chromium in drinking water as recommended by the WHO. Conversely, this study reported chromium levels within permissible limits, although some sites still recorded concentrations above the recommended threshold.[45]

River Water Samples

Such elevated levels of chromium can be attributed to runoff from industrial activities, improper waste disposal, and agricultural runoff containing fertilizers and pesticides. The elevated chromium levels pose similar health risks as observed in tap water, making the river water unsafe for both human consumption and aquatic life.

Contrarily, a study conducted in South Africa reported that the concentration range of heavy metals were: 1.6–9.3, 2.0–3.0, 10.5–20.1 and 2.1–2.5 µg per littre for Cd, Cu, Pb and Zn, respectively; in this study, the concentration levels of all measured metals were found to be within the international guidelines and acceptable limits for drinking water, except for (Cd) and (Pb), which exceeded these standards.[20] Similarly, contamination (in mg/l) of Pb (0.496 ± 0.159), Cd (0.01 ± 0.002) and Cr (1.935 ± 0.258) has been recorded in water on the Kenyan coast[46]; in Zambia, Kafue river, Cr has been reported to a mean concentration of 0.7+-0.4 mg/kg[46]; additionally, the Kafue River exhibits notable water and sediment pollution, primarily from heavy metals such as copper (Cu), cobalt (Co), chromium (Cr), lead (Pb), and cadmium (Cd). Pollution levels significantly rise downstream, following an alternate sink-source-sink pattern. [47] These dynamics highlight the complexity of pollution processes in the river system, underscoring the need for targeted monitoring and remediation efforts to address environmental and health risks associated with heavy metal contamination.

Tanganyika Water Samples

The high levels of chromium and lead in Lake Tanganyika are particularly concerning, as this water body serves as a vital resource for drinking water, fishing, and tourism for surrounding communities. Lead exposure can result in neurological damage, especially in children, and chronic exposure can lead to severe health issues.

Some studies reported the mean concentration of chromium of 3.125 mg/kg at Shinko site in Nigeria[48] and from 23.9–138.1µg g^{-1} in Tanzania[49]; these findings were higher than the concentration of our results. In the Democratic Republic of the Congo, high concentrations of lead (Pb) have been reported in the surface water of the Lake Tanganyika, measuring 1.42 µg/L. In the same study, the toxicity assessments of effluent from the collector revealed significantly elevated levels of several heavy metals including lead (Pb) at 8.25 µg/L, chromium (Cr) at 7.25 µg/L and copper (Cu) at 1.95 µg/L, among other.[50] These findings indicate a concerning level of contamination, highlighting the potential ecological and health risks associated with the effluent and the need for further monitoring and control efforts.[50,51]

Chromium and lead are not only hazardous for soil and aquatic biota but may also contaminate the food chain through uptake and accumulation by plants and fishes; furthermore, they may become soluble and thus enter the groundwater, the only source of drinking water in the area. Variations in concentrations can be attributed to different human activities and the sampling process. Lake's water heavy metals, has the potential to pose health and environmental risks by contaminating aquatic environments.

Bottled Water Samples

These levels are alarming, given that bottled water is often perceived as a safer alternative to tap water. The presence of high chromium levels in bottled water suggests potential contamination during the bottling process or inadequately treated source water.

A study in Nigeria reported the maximum concentrations of some metal including aluminum (Al), iron (Fe), magnesium (Mg), calcium (Ca), potassium (K), and manganese (Mn) in certain samples exceeded the permissible limits for drinking water quality set by the WHO; whereas, concentrations of other analyzed elements remained within acceptable limits.[52] Several other studies reported the health risks associated with toxic chromium exposure, linking it to various conditions, including cancers of the stomach, lungs, kidneys, and urinary system, as well as dermatological and hematological disorders. Additional concerns include immune system issues, genitourinary and gastrointestinal disorders, gallbladder diseases, chronic renal failure, COPD, arterial hypertension, and motor neuron disease (MND).[7,52,53]

Dialysis Water Sample

This high level of Cr is particularly alarming, as patients undergoing dialysis are already vulnerable and rely on clean water for their treatment. High chromium levels in dialysis water could lead to serious complications and adversely affect patient health.

A study in Nigeria reported a poor quality of haemodialysis water[54]; whereas, another systematic study showed evidence for exposure to arsenic, cadmium, lead and chromium through drinking water and incidence of kidney problems.[1]

Study Limitations

This study provides important baseline data on heavy

metal contamination across diverse water sources in Burundi using standardized laboratory analysis methods. However, it had several limitations, including a relatively small sample size, limited geographical coverage, and analysis restricted to only four heavy metals. Sampling was conducted during a short period, preventing assessment of seasonal variations in contamination. In addition, chromium speciation was not performed, and the exact sources of contamination were not identified. Future studies should include nationwide longitudinal monitoring, larger sample sizes, and expanded analysis of additional contaminants such as mercury and arsenic. Research should also investigate contamination sources, assess health effects through biomonitoring and epidemiological studies, evaluate food-chain contamination, and develop affordable and effective water treatment strategies for Burundi.

CONCLUSION

The analysis of water samples from various sources revealed alarmingly high concentrations of chromium (Cr), consistently exceeding safety standards. Tap water, river water, Lake Tanganyika water, bottled water, and dialysis water all showed Cr levels significantly above the WHO's recommended limit of 0.05 mg/L. This poses serious health risks, underscoring the urgent need for monitoring and follow-up efforts to ensure safe drinking water and protect public health.

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