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Original Article

Assessing Health Risk Mitigation Efficiency of the Halabja Water Treatment Plant in Drinking Water Purification

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ABSTRACT

Water quality management represents a paramount public health issue, especially within areas where surface water resources are particularly susceptible to contamination. This investigation evaluates the efficacy of health risk mitigation provided by the Halabja Water Treatment Plant (HWTP) located in the Kurdistan Region of Iraq. The facility processes water sourced from Sirwan river, employing methodologies such as sedimentation, filtration, and disinfection. The primary aim was to ascertain the removal efficiency of trace elements (such as., As, Pb, Cd, and cr) throughout various treatment phases, also the health hazards of tap water consumption have been assessed. Water samples were systematically collected every month two years (2022–2023) at three distinct phases: raw water, treated water, and tap water. Analytical techniques encompassed trace element quantification alongside health risk evaluation utilizing hazard quotient indices (HQ). The results indicated a significant reduction in turbidity (from 59 NTU; in raw water to between 0.1 and 5 NTU in treated water) as well as in heavy metal concentrations, such as Cd levels diminished from 0.48 µg/L in raw water to 0.018 µg/L in treated water, In contrast, arsenic concentrations were reduced from 2.951 µg/L to 2.503 µg/L. Nonetheless, occasional exceedances of WHO standards were detected in tap water, with lead concentrations peaking at 9.4 µg/L in November, suggesting potential recontamination during the distribution process. Hazard indices remained below the critical threshold of 1 for most metals, signifying manageable health risks. The highest hazard index for Pre-treated water was recorded at 0.61 (in September), which subsequently declined to 0.15 following treatment. These findings underscore the success of HWTP in diminishing contaminants, while simultaneously highlighting the necessity for improved distribution infrastructure and the implementation of advanced treatment technologies. This study contributes to the optimization of water treatment methodologies and emphasizes the critical importance of ongoing monitoring to ensure safe drinking water.

Keywords: Water Treatment plant, Purification, Drinking water, Health Risk Assessment, Halabja.

1 Introduction

Water is essential for human existence and socio-economic development. The quality and accessibility of water resources employ a direct effect on public health outcomes, industrial activities, agricultural production. However, the imperative to guarantee access to safe drinking water has risen as a critical global challenge, attributable to the intensifying issues of water contamination, rapid demographic expansion, and industrial development. Trace element contaminants, such as As, Pb, Cd, and Ni, present considerable risk due to their persistency and bioaccumulative characteristics, toxicity, and environmental resilience. Extended exposure to these metals is correlated with a variety of health complications, including neurological impairments, organ dysfunction, and carcinogenic consequences [1,2]. Consequently, it is imperative to enhance water treatment methodologies to proficiently eradicate these pollutants, thereby protecting public health and facilitating sustainable water resource management.

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Independently of its form, in regions with low or middle income, such as Iraq's Kurdistan Region, the water quality governance presents significant challenges. This includes the current effects of environmental deterioration, limited resources and poor infrastructure that make surface water supplies vulnerable to contamination. However, relevant studies on this region are rare, and specifically on the Duhok governorate, with studies showing poor performance of water treatment plants in disinfection. Investigation indicated that in some of the plants tested, the water exceeded the standards set by the World Health Organization, despite the treatment process [3,4]. This is a serious problem for consumers, such findings underline the critical need for comprehensive evaluations of water treatment plants to detect operational shortcomings and recommend targeted improvements.

The Halabja Water Treatment Plant is a critical project in the Kurdistan Region which supplies drinking water to the people of the Saidsadeq, Sirwan, and Halabja areas. Conventional technologies such as sedimentation, filtration, and disinfection are employed in this facility, which draws raw water from Sirwan river, a primary surface water reservoir in the area. To the best of our knowledge, research on the potential efficacy of tea waste for heavy metal remediation to meet international water quality standards has been scarce. Because of the Considering the mounting dependency on surface water resources, which are susceptible to pollution from mineralogical processes, agricultural discharge, and industrial waste in the region, it is crucial to evaluate the plant's performance [2,5,6]. The research tries to expand the existing knowledge gap by analyzing the functional performance of the Halabja Water Treatment Plant in detail. This study aims to understand the trace elements concentration in water samples taken in different treatment stages and compliance with WHO criteria for drinking water quality. The investigation looks at the potential health risks residents face due to trace elements in their drinking water supply. Overall, our study provides evidence-based recommendations for addressing the challenges related to direct potable reuse and public perception, particularly in improving water treatment technologies in the Kurdistan Region and beyond.

Trace elements' characteristic of being harmful to soil and water makes the contamination of drinking water by them a complicated issue of considerable environmental preservation and public health concern. This chronic toxicity is due to the bioaccumulation of trace elements in human tissues for more extended periods as trace elements are non-biodegradable [7]. The Pb exposure harms neurodevelopment in children it is associated with hypertension in adults, while As exposure is associated with skin lesions, cardiovascular diseases, and in some cases, it is considered as carcinogenic [1,2]. While Ni exposure is linked to respiratory disorders, Cd induced disorder is kidney in nature [8]. Surface water body such as Sirwan river are more susceptible to pollution with trace elements due to anthropogenic activities (industrial discharge, agricultural runoff containing pesticides and fertilizers, and urban wastewater disposal) [5]. Hence, the implementation of suitable water treatment technologies, tailored to the unique regional environmental and socio-economic context, is vital to address these pressing issues.

This is relevant to broader questions about water treatment technology and regulation in comparable conditions. The results will inform more advanced treatment approaches like membrane filtration, ion exchange, and adsorption, as well as working to increase existing treatment systems' treatment efficiency. This highlights the crucial role of incorporating health risk assessment in water quality management systems and encourages progressive monitoring programs. Adopting international best practices as laid out in the Sustainable Development Goal (SDG) of the United Nations would enable the Kurdistan Region to strengthen its capacity to tackle water quality issues while contributing to the global efforts to ensure universal access to safe drinking water.

The main objectives of the present study are as follows:

1. To evaluate the levels of selected trace elements in pre- and post-treated Halabja Water Treatment Plant water.
2. To assess the efficiency of the treatment processes in purifying and disinfecting water.
3. To evaluate the potential health risks of tap water treatment in Halabja, city

2 Materials and Methods

2. 1 Study Area and Sampling Sites

The study was conducted in Halabja Province, located in the eastern part of the Kurdistan Region of Iraq. Sampling sites were selected within the Halabja Water Purification Project area, the primary source of drinking water for the majority of Halabja’s population. Water samples were collected at three stages: before treatment, post-treatment, and from household taps to evaluate water quality throughout the purification and distribution process.

2. 2 Water treatment plants

Figure 1 illustrates a detailed schematic of the Halabja Water Treatment Plant, designed to supply clean and safe drinking water to the city of Halabja in the Kurdistan Region. The facility integrates several essential units for water purification, ensuring efficient raw water treatment from natural reservoirs. The key components of the plant include the primary intake and sedimentation units, marked as "NDR-1," "NDR-2," and "NDR-3," which channel water into the treatment system. the schematic highlights water flow rates and levels essential for monitoring operational efficiency.

The treatment process involves chemical dosing units (e.g., for alum and polymer), filtration tanks (ER GF1 and GF2), and backwash systems for filter cleaning. Circular clarifiers and sedimentation basins handle particle settling and removal. Advanced flow measurement and monitoring systems are installed, ensuring water quality and plant performance. Including storage reservoirs, pipelines, and backwash mechanisms reflects the plant's capacity to deliver a consistent water supply while maintaining operational sustainability.

Figure 1: A detailed schematic of the Halabja Water Treatment Plant.

2. 3 Water Sampling Procedure:

Water samples were collected monthly over two years, from January 2022 to December 2023, covering all four seasons. Each sampling session followed stringent protocols to prevent metal contamination. Three replicate samples were taken at five-minute intervals for each sampling site to ensure representativeness.

Samples were collected in 500 mL of pre-conditioned polyethene bottles by soaking them in a 2% nitric acid solution and rinsing thoroughly with deionised water. Immediately after collection, samples were transported to the Halabja Technical Institute laboratory, where they were acidified with 2% nitric acid to prevent precipitation and adsorption of metals onto container walls. Samples were then stored in refrigeration until analysis.

2. 4 Quality Control and Sample Analysis Preparation:

All laboratory equipment used for analysis was rigorously cleaned by immersion in 2% nitric acid and was rinsed several times with deionised distilled water before use. This ensured minimal contamination and high accuracy during the subsequent trace element determinations.

2.5Hazard Quotient (HQ)

The HQ for non-carcinogenic risk can be calculated by the following equation

: $HQ = CDI / RfD$

$CDI = C*DI / BW$

Where: C, DI and BW represent the concentration of PTE in water (µg/L), average daily intake rate (2 L/day) and body weight (72 kg), respectively [16]. According to USEPA database the oral toxicity reference dose values (RfD) are 3.0E−04, 5.0E−04, 1.5, 3.7E−02, 2.0E−02,3.6E−02, 3.0E−01 mg/kg-day for Cd, Cr, Cu, Ni, Pb, Zn, respectively. The exposed population is assumed to be safe when HQ>1

3. Results and Discussion

3. 1 Physico-chemical properties of water

Table 1 and Fig. 1 showed that the assessment of the Halabja treatment plant revealed variations in water quality parameters across raw water, treated water, and tap water samples. The pH levels of raw water were slightly basic, ranging from 7.3 to 7.74, which decreased to 7.0–7.59 in treated water, indicating effective neutralisation. However, tap water occasionally showed higher pH levels (up to 7.8), likely due to interactions with distribution pipelines, such as material leaching, a common phenomenon in municipal water systems [9]. Maintaining consistent pH is critical, as deviations can affect consumer health and plumbing infrastructure [2].

Table 1: The assessment of the Halabja treatment plant in water quality parameters across raw water, treated water, and tap water samples.

Parameters	Sample type	Aug.	Sep.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.
pH	Raw water	7.3	7.6	7.56	7.48	7.74	7.67	7.7	7.52
	Treated water	7	7.5	7.47	7.35	7.28	7.37	7.59	7.44
	Tap water	7.8	7.67	7.7	7.58	7.33	7.56	7.65	7.42
Turbidity (NTU)	Raw water	9	59	33	50	21	10	16	13
	Treated water	0.1	0.3	4.6	5	3	0.7	0.9	0.7
	Tap water	0.2	0.5	5.1	5.4	3.7	1.1	1.8	1.2
T.D.S (mg/L)	Raw water	268	246	230	242	231	282	238	247
	Treated water	270	250	220	223	245	324	244	238
	Tap water	286	267	246	239	271	343	256	241
As µg/L	Raw water	1.41	1.3	1.500	1.500	1.146	0.85	2.951	2.892
	Treated water	1.129	1.500	1.200	1.300	1.029	0.275	2.503	1.847
	Tap water	1.13	1.500	1.200	1.300	1.329	0.415	2.824	1.851
Ba µg/L	Raw water	157	148	296	349	104.9	86.29	96.05	66.92
	Treated water	152	181	256	240	101.9	114.3	67.98	93.87
	Tap water	176	364	207	257	99.04	173.2	64.31	94.61
Ca mg/L	Raw water	80.3	72.8	86.2	81.2	59.61	59.66	74.11	48.71
	Treated water	78.1	97.7	64.2	70.3	56.97	62	54.34	74.28
	Tap water	71.7	102	67.6	64.9	65.43	97.04	48.04	73.64
Cd µg/L	Raw water	0.48	0.42	0.40	0.5	0.043	0.045	0.022	0.024
	Treated water	0.33	0.31	0.30	0.4	0.079	0.038	0.018	0.02
	Tap water	0.33	0.29	0.30	0.4	0.038	0.024	0.017	0.024
Co µg/L	Raw water	1.3	0.30	2.0	3.0	0.613	0.249	2.156	1.399
	Treated water	0.30	0.50	0.40	0.5	0.528	0.044	1.198	0.376
	Tap water	0.60	0.0	0.00	0.2	0.818	0.09	1.29	0.394
Cr µg/L	Raw water	3.4	2.3	8	9.6	1.715	2.354	1.411	2.214
	Treated water	1	1.3	0.4	1.8	2.798	1.993	3.85	2.302
	Tap water	0.5	1.8	0.5	1.3	5.139	3.109	1.736	0.875
Cu µg/L	Raw water	11.2	4.20	17.0	16.9	2.279	1.274	1.915	1.003
	Treated water	0.80	3.80	6.8	9.3000	2.59	0.63	1.162	0.698

	Tap water	17.6	11.0	14.4	22.300	1.915	0.464	0.927	0.601
	Raw water	10.6	10.1	10.6	15.000	9.881	1.563	8.619	4.891
K mg/L	Treated water	10.4	10.4	9.05	13.400	9.064	0.57	4.656	2.164
	Tap water	10.4	10.4	9.13	14.100	10.48	0.542	4.94	2.151
	Raw water	21.4	20.5	23.3	33.500	6.851	10.13	9.34	8.163
Mg mg/L	Treated water	20.9	21.1	19.3	28.800	6.483	10.95	7.215	12.58
	Tap water	22.3	21.4	19.6	28.600	9.329	12.48	8.152	12.61
	Raw water	2.5	0.40	2.5	6.5000	5.272	14.83	2.933	2.563
Mo µg/L	Treated water	2.9	6.2	3.4	5.6000	8.035	13.75	3.14	2.798
	Tap water	3.6	3.20	2.3	5.6	10.35	3.939	2.287	2.09
	Raw water	44.400	41.7	38.	58.9	61.32	2.463	29.47	23.56
Na mg/L	Treated water	41.6	42.5	35.3	52.8	58.87	2.213	17.19	12.49
	Tap water	43.4	43.7	35.3	52.2	74.04	6.826	23.83	12.79
	Raw water	1.20	0.9	2.40	2.7	4.362	4.157	13.28	9.294
Ni µg/L	Treated water	0.60	0.4	0.30	0.5	9.787	1.463	8.833	4.826
	Tap water	0.40	0.5	0.50	0.7	5.069	2.124	8.613	3.392
	Raw water	0.0	4.7	3.0	10.8	0.63	0.242	0.164	0.167
Pb µg/L	Treated water	1.3	0.2	0.0	3.0	0.895	0.366	0.144	0.093
	Tap water	6.7	1.7	2.8	9.4	0.395	0.089	0.131	0.091
	Raw water	2.7	0.0	0.8	0.0	0.625	1.081	0.424	0.371
Se µg/L	Treated water	0.0	0.0	0.0	0.70	0.674	1.285	0.334	0.563
	Tap water	0.0	0.90	2.8	0.0	0.943	0.358	0.35	0.55
	Raw water	4.9	3.80	7.6	9.1	2.964	5.861	7.76	8.104
V µg/L	Treated water	3.1	2.70	2.4	2.8	2.317	1.929	7.48	5.433
	Tap water	2.8	2.90	2.9	3.0	3.456	3.424	7.952	5.687
	Raw water	72.2	52.7	256.	78.5	44.76	37.05	21.77	18.88
Zn µg/L	Treated water	120.	174	106.	85.7	93.24	138.7	25.43	21.43
	Tap water	108	62.7	85.3	125	37.13	19.14	17.05	13.35

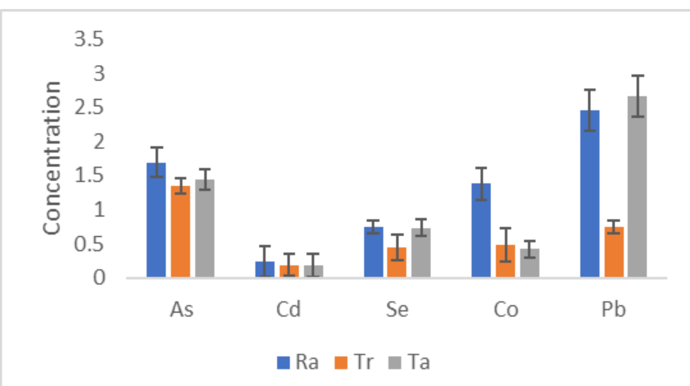
Turbidity, which reflects the presence of suspended particles, showed significant variations in raw water, peaking at 59 NTU; in September. The treatment process effectively reduced turbidity to 0.1–5 NTU; meeting WHO guidelines for drinking water. However, slight increases in tap water turbidity (up to 5.4 NTU;) suggested possible recontamination during distribution, a challenge often linked to ageing or poorly maintained systems [10,9].

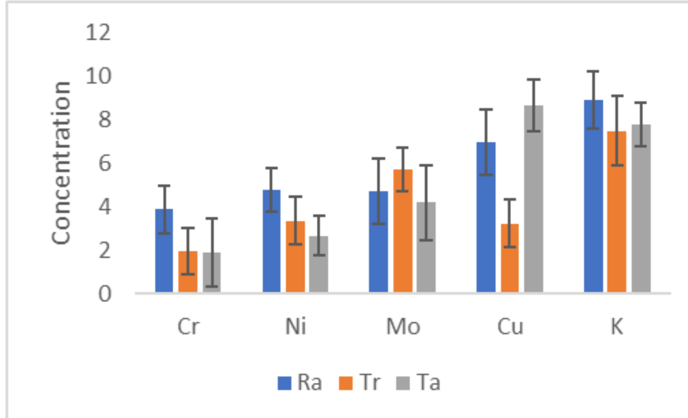
Total Dissolved Solids (TDS) in raw water were within acceptable limits (230–282 mg/L). The treatment process maintained stable TDS levels, but occasional spikes (e.g., 324 mg/L in January) may indicate variations in raw water characteristics or treatment inconsistencies. In some cases, tap water TDS exceeded treated water levels, likely due to leaching from distribution system materials, as observed in similar municipal water networks [11].

Tace elements analysis showed mixed results. Arsenic levels decreased post-treatment (e.g., 2.951 µg/L in February raw water vs. 2.503 µg/L in treated water) but occasionally remained close to WHO limits, highlighting the need for enhanced removal efficiency [2]. Cadmium levels were effectively reduced, with raw water concentrations dropping from 0.022 µg/L to 0.018 µg/L post-treatment. Chromium, which spiked at 9.6 µg/L in raw water during November, was significantly lowered by treatment. However, while reduced from raw water levels as high as 10.8 µg/L, lead concentrations remained concerning in tap water during certain months (e.g., 9.4 µg/L in November)2023. This points to potential contamination in the distribution network, a known issue in water systems with corroded or inadequate pipelines [9,11].

Zinc concentrations demonstrated inconsistent behaviour, with treated water occasionally exhibiting higher levels than raw water. This anomaly could be due to leaching from zinc-containing materials in treatment equipment or pipes, as documented in similar studies [10]. Such fluctuations underscore the need for regular monitoring and preventive measures to ensure compliance with drinking water standards.

The Halabja treatment plant efficiently reduced turbidity and trace elements such as Cd and Cr. However, the relative increases in elements such as As, Pb, and Zn highlight the importance of optimising treatment processes and improving the maintenance of pipe distribution. Enhancing water quality monitoring and adopting advanced treatment technologies could improve compliance with international standards and protect public health [12, 2].





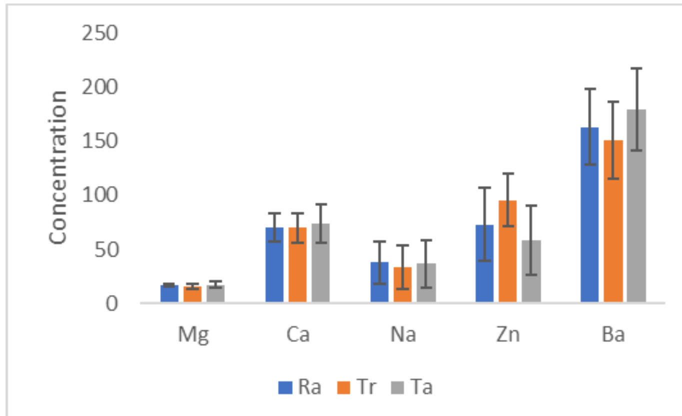


Figure 2: The concentration of selected trace elements in raw water, treated water, and tap water in the Halabja water treatment plant.

Figure 2 shows the concentrations of selected trace elements, As, Pb, Cd, and N, in water samples collected at three stages: raw water from Sirwan River, treated water from the Halabja Water Treatment Plant, and tap water distributed to Halabja city.

The figure showed the concentrations of specific trace elements As, Pb, Cd, and Ni in water samples obtained at three phases: raw water from Sirwan Lake, treated water from the Halabja Water Treatment Plant, and tap water supplied to Halabja, Sirwan, and Saidsadeq. This analysis offers critical insights into the efficiency of existing water treatment methods and identifies areas necessitating enhancement.

The study of Pre-treated water indicated significant contamination with trace elements, which may lead to agriculture and industrial activities and urban wastewater, under regional studies [8,5]. Increased levels of Cd and Pb may indicate the use of pesticides and the presence of industrial contaminants. Despite treatment processes mitigating these contaminants, As and Ni concentrations in treated water occasionally exceed WHO guidelines, indicating deficiencies in treatment technologies, including the absence of advanced methods such as reverse osmosis or ion exchange [13 2]. Moreover, post-treatment contamination seems to influence trace element concentrations in tap water, likely resulting from leaching from deteriorating pipes and storage tanks [3].

These findings underscore the need for a comprehensive approach to improve water quality. Chronic exposure to these metals is linked to severe health risks, including cancer, neurological damage, and kidney dysfunction [8,14]. Therefore, recommendations include upgrading treatment technologies with advanced methods, maintaining pipeline infrastructure to prevent recontamination, and implementing robust monitoring programs to address emerging threats.

By addressing these challenges, the safety and sustainability of Halabja's water resources can be significantly improved.

3. 2 Correlation analysis:

Relationships between trace elements can provide information on their sources and pathways [15]. Pearson correlation coefficients (r) were calculated to interpret and confirm relationships between trace elements and related water properties (pH and EC) for the sampled areas (Table 2). Overall, hostile relationships between pH and Ca, Mn, Cu, As, and Cd were observed and positive but very weak correlations were observed between pH and Cr, Ni, Zn and Pb. This suggests that the narrow range of pH (7.9-8.3) of these waters limits the interpretation of this relationship [16]. In contrast, significant positive correlations were found between organic matter (EC) and elements including Cr, Mn, Co, Cu, Zn, As, and Cd, which may reflect the strong adsorption of these elements by organic matter.

When the entire dataset was considered, strong positive correlations ($p > 0.01$) were observed between Cr and Mn, Fe, Co, Ni, and Cu. Cu, Zn, Cd, and Pb were also highly correlated with each other :Cu-Zn ($r=0.80$; $p>0.01$), Cu-Cd ($r=0.97$; $p>0.01$), Cu-Pb ($r=0.68$; $p>0.01$), Zn-Cd ($r=0.82$; $p>0.01$), Zn-Pb ($r=0.72$; $p>0.01$), and Cd-Pb ($r=0.70$; $p>0.01$), suggesting familiar sources. [17].

Correlations between elements are more variable when comparison is made site-by-site. For example, in pre-treated (n=32) and treated (n=32) significant correlations were found between pH, EC, and trace elements (Al, V, Cr, Mn, Fe, Co, Ni, and As), but in other areas, these correlations were weak. Strong significant relationships between essential elements (Na, Mg, K and Ca) and all trace elements except Pb and U were found in Pre-treated water (n=32), e.g. correlations with Cd were r= 0.99, 0.90, 0.98 and -0.97 at $p<0.01$, respectively. In contrast, for pre-treated water (n=32), essential elements (Na, Mg, K and Ca) were weakly correlated with several trace elements, e.g. V, Mn, As and Ba.

In these sampling sites, correlation coefficients indicated that Cu was significantly correlated with Mn (r^2=0.87, 0.55, 0.84), Zn (0.87, 0.90, 0.77), and Cd (r^2=0.56, 0.71, 0.44), respectively, suggesting probable adsorption of these metals on oxyhydroxides [18]. Copper and Zn correlations varied from $r = 0.91$ to $r = -0.14$. Cu and Cd correlations ranged from strongly positive ($r = 0.98$) to strongly negative ($r = -0.97$) at SUL and, respectively. Correlations between Cu and Pb were significant in all sites except for Pre-treated water, treated water and tap water, where very poor correlations were observed ($r=0.07$, $r=-0.12$ and 0.28 at $p<0.01$, respectively). Correlations of Zn with Cd and Pb also greatly varied between sampling areas. Strong positive correlations ($p<0.01$) of Zn-Cd and Zn-Pb were found in Pre-treated and treated samples, while weak correlations were observed in tap water.

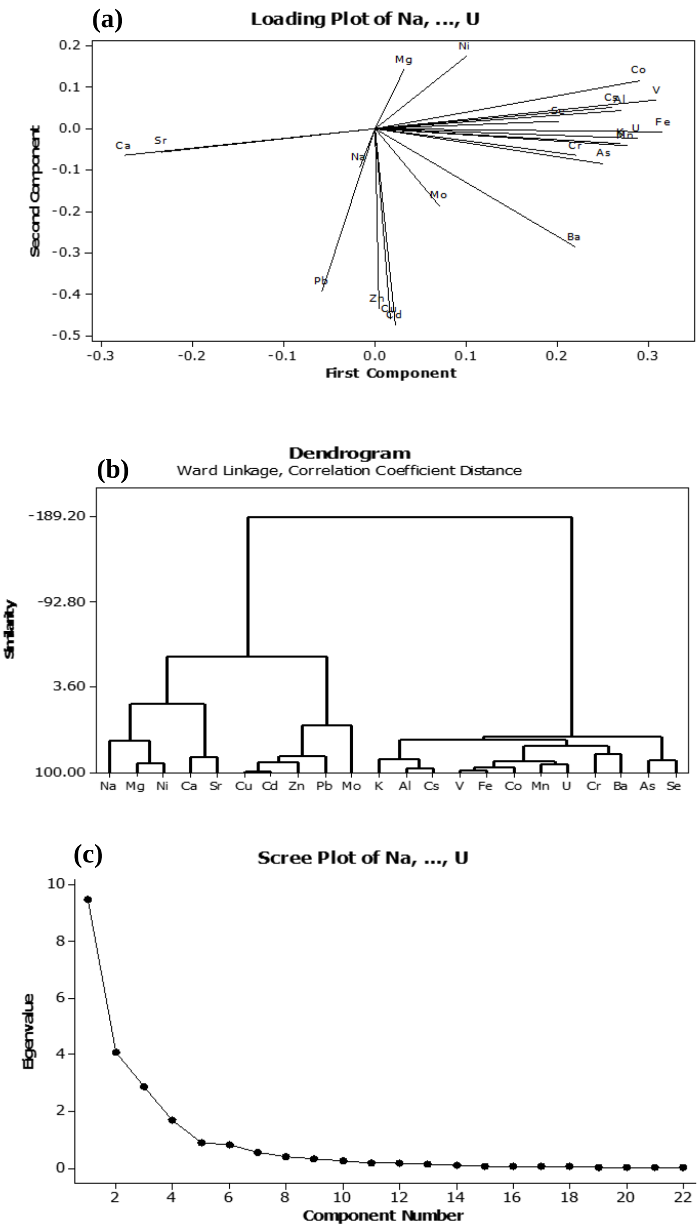


Figure 3: Principal component analysis of (PCA) mean trace elements in all sampling sites. (a) loading plots for all aspects (mg kg-1) of water (b) Dendrogram of elemental analysis on water from sample areas (c) scree plots for all trace elements at all sampling.

Table 2: Correlation coefficients between trace element concentrations and water properties in raw Pre-treated water, bold values denote significance at the level $p<0.01$.

	pH	**Ec**	**Na**	**Mg**	**K**	**Ca**	**Al**	**V**	**Cr**	**Mn**	**Fe**	**Co**	**Ni**	**Cu**	**Zn**	**As**	**Se**	**Sr**	**Mo**	**Cd**	**Cs**	**Ba**	**Pb**
pH																							
Ec	**-0.49**																						
Na	**-0.82**	**0.65**																					
Mg	**0.70**	-0.33	**-0.71**																				
K	**0.79**	**-0.50**	**-0.78**	**0.89**																			
Ca	**-0.66**	0.32	**0.53**	**-0.40**	**-0.51**																		
Al	**0.59**	-0.15	**-0.48**	**0.94**	**0.76**	**-0.37**																	
V	0.25	0.07	-0.21	**0.72**	**0.65**	-0.17	**0.76**																
Cr	**0.68**	**-0.36**	**-0.68**	**0.81**	**0.91**	**-0.44**	**0.69**	**0.75**															
Mn	0.00	0.05	0.33	-0.21	-0.08	0.31	-0.15	-0.19	-0.11														
Fe	**0.76**	**-0.35**	**-0.70**	**0.96**	**0.95**	**-0.54**	**0.90**	**0.75**	**0.90**	-0.13													
Co	**0.77**	**-0.49**	**-0.86**	**0.90**	**0.97**	**-0.51**	**0.72**	**0.65**	**0.92**	-0.22	**0.93**												
Ni	**0.48**	-0.32	**-0.52**	**0.62**	**0.62**	-0.27	**0.52**	**0.44**	**0.65**	-0.03	**0.63**	**0.65**											
Cu	**0.92**	**-0.63**	**-0.89**	**0.67**	**0.80**	**-0.70**	**0.51**	0.23	**0.74**	-0.11	**0.76**	**0.81**	**0.52**										
Zn	**0.87**	**-0.50**	**-0.66**	**0.48**	**0.61**	**-0.78**	**0.42**	0.07	**0.55**	0.08	**0.61**	**0.57**	**0.40**	**0.91**									
As	**-0.35**	0.20	0.32	-0.21	-0.08	**0.51**	-0.25	0.09	0.01	**0.56**	-0.17	-0.11	0.09	-0.28	**-0.35**								
Se	**0.64**	**-0.36**	**-0.51**	**0.52**	**0.57**	-0.17	**0.45**	0.25	**0.56**	0.30	**0.57**	**0.53**	**0.52**	**0.65**	**0.61**	0.02							
Sr	**-0.67**	0.12	**0.67**	**-0.56**	**-0.65**	**0.78**	**-0.44**	**-0.39**	**-0.65**	**0.40**	**-0.65**	**-0.72**	**-0.43**	**-0.71**	**-0.61**	0.19	-0.24						
Mo	0.14	-0.17	-0.05	-0.05	0.03	0.02	-0.09	-0.29	-0.11	**0.53**	-0.04	-0.01	-0.06	0.11	0.17	0.32	0.16	0.06					
Cd	**0.93**	**-0.57**	**-0.87**	**0.64**	**0.74**	**-0.72**	**0.49**	0.16	**0.65**	-0.11	**0.71**	**0.75**	**0.41**	**0.97**	**0.92**	**-0.39**	**0.63**	**-0.69**	0.10				
Cs	**0.82**	**-0.49**	**-0.85**	**0.97**	**0.92**	**-0.53**	**0.86**	**0.59**	**0.82**	-0.22	**0.95**	**0.94**	**0.64**	**0.81**	**0.62**	-0.27	**0.56**	**-0.64**	0.02	**0.78**			
Ba	**0.71**	**-0.44**	**-0.40**	**0.41**	**0.56**	**-0.53**	**0.43**	0.13	**0.50**	**0.42**	**0.56**	**0.44**	0.32	**0.74**	**0.87**	-0.07	**0.65**	-0.32	0.29	**0.72**	**0.49**		
Pb	**0.79**	**-0.39**	**-0.63**	**0.50**	**0.58**	**-0.66**	**0.44**	0.16	**0.60**	0.00	**0.61**	**0.57**	**0.71**	**0.84**	**0.89**	-0.24	**0.64**	**-0.63**	0.05	**0.80**	**0.61**	**0.73**	1

PCA is a multivariate analysis method widely used in water contamination research. It can be an effective method for estimating anthropogenic influence on a specific spatial scale [19]. PCA is performed to understand the interrelationships of trace elements in the water bodies [20]. Scree plots detect the number of factors influencing a data set, and correlations between trace elements can be identified using cluster analysis and dendrograms.

This investigation identifies three central components for the data set: a whole water sample. These components are determined using a loading plot (Fig.3a) and appear to be (i) the calcareous geology of the area illustrated by a grouping comprising Sr and Ca, (ii) elements associated with Fe and Mn oxides such as As, Cr, Mn, K, U Fe, Se, Al, Cs, V and Co, and (iii) anthropogenic activities indicated by the grouping of Pb, Zn, Cu and Cd. The Cluster Analysis (CA) results in Fig. 3b also indicate three distinct groupings. Cluster I includes Na-Mg-Ni-Ca-Sr, cluster II Cu-Cd-Zn-Pb-Mo, and cluster III contains K-Al-Cs-V-Fe-Co-Mn-U-Cr-Ba-As-Se. Elements in cluster I seem to be strongly associated with (alumino –silicate phases) indicating a natural origin for these elements [12]. Elements in cluster III may also be controlled by natural factors, particularly erosion and weathering [15]. In contrast elements in cluster II appear to be influenced by anthropogenic activities such as fertiliser and pesticide application, vehicle exhaust emissions, sewage irrigation and waste disposal [15, 21]. Figure 3c shows the scree plot in which values >2 indicate significant factors. Three important values >2 are again noted, in agreement with the other parts of the PCA analysis.

3. 3 Risk assessment analyses

The table displays the hazard quotient (HQ) indices for several trace elements, namely arsenic (As), cadmium (Cd), chromium (Cr), lead (Pb), and nickel (Ni), in the drinking water of a treatment facility in Halabja Province across various months. Specific indices evaluate the health risks associated with certain constituents, where a Hazard Quotient (HQ) below 1 signifies that the water is safe for consumption. In contrast, values beyond 1 suggest potential health hazards.

Table 3: Hazard quotient indices (HQI) of trace elements in drinking water.

	As		**Cd**		**Cr**		**Pb**		**Ni**		**Hazard indices**	
	pre	**post**	**Pre**	**Post**	**Pre**	**Post**	**pre**	**post**	**pre**	**post**	**pre**	**post**
August	0.45	0.25	0.77	0.33	2.39E-03	2.67E-03	0.04	0.02	0.05	0.05	0.31	0.11
September	0.88	0.62	0.54	0.36	2.24E-02	1.79E-02	0.04	0.03	0.05	0.04	0.61	0.15
October	0.07	0.07	0.23	0.16	1.10E-03	1.32E-03	0.05	0.05	0.05	0.04	0.41	0.33
November	0.41	0.32	0.57	0.40	2.58E-05	2.63E-05	0.07	0.04	0.04	0.04	0.38	0.11
December	0.20	0.19	0.31	0.32	1.13E-06	1.15E-06	0.04	0.05	0.02	0.04	0.60	0.21
January	0.16	0.21	0.23	0.15	1.02E-02	1.21E-02	0.05	0.06	0.03	0.03	0.58	0.36
February	0.74	0.73	0.26	0.16	2.60E-04	2.47E-04	0.06	0.06	0.04	0.04	0.49	0.24
March	0.31	0.22	0.47	0.30	2.38E-05	2.13E-05	0.05	0.03	0.03	0.02	0.28	0.01

A comparison of Pre-treated and post-treated water indicates that HQ values for all trace elements are consistently elevated in Pre-treated water, illustrating the efficacy of the treatment process in reducing hazards [22]. The maximum HQ for cadmium (Cd) in Pre-treated water was 0.88 in September, which dramatically decreasing to 0.62 post-treatment. The maximum hazard index (HI) reached 0.61 in raw water in September, while reducing to 0.15 after the treatment process. In contrast, Cr had the lowest HQ values, recording a minimum of 2.38E-05 in March; was slightly reducing to 2.13E-05 in post-treated water. The HI in March; demonstrated the lowest values for Pre-treated water (0.28) and post-treated water (0.01).

Over the months showed that HQ of all trace elements in both Pre-treated and post-treated water remains less than 1, indicating no appreciable risk to health [23]. The monthly concentrations of certain trace elements Cd, Pb, and others) were affected by seasonal variation where elevated HQ values were observed in certain months (such as. Cd in September). The findings demonstrate the relevance of the treatment process in reducing trace elements and preventing the degradation of conservation water quality. Although the treated water frequently meets safety standards, continuous monitoring and treatment remain crucial, particularly during wet seasons. This study highlights the importance of effective water treatment systems in maintaining public health [24].

4 Conclusion

In conclusion, results showed that the efficiency of the treatment process in eliminating turbidity, trace elements, and other contaminants was within a range that greatly adhered with World Health Organization (WHO) guidelines. Turbidity of treated water (0.1 NTU) was significantly reduced (from a maximum turbidity of 59 NTU; in untreated water). Besides that, trace elements like Cd, As and, Cr had a massive reduction in treated water with Cd decrease from 0.48 µg/L to 0.018 µg/L, while As decreased from 2.951 µg/L to 2.503 µg/L

However, the study identified recurrent problems regarding contamination of treated water, especially regarding Pb that would occasionally surpass the threshold limit (e.g. 9.4 µg/L in tap water in Novembers). The investigation established such findings show that it can lead to possible exposures in the distribution network, due to piping distribution deprivation and leaking of the material.

According to health risk assessments, the hazard quotient (HQ) of trace elements in processed water has been found to be always less than 1, suggesting the health hazards are well-controlled. The seasonal fluctuations in the levels of pollutants, particularly Cd and Pb, indicate a necessity for continuous monitoring and adaptable control mechanisms.

According to the study, it has been noted that unlike previous studies which focused on the design of proper piping for the plant, in addition, the study recommends highly advanced treatment techniques such as membrane filtration and ion exchange to maintain the safety of the water supply, as the filtration system displayed inconsistencies over time (disruption, insufficient recovery of treated water, clogging), which affected the operational efficiency of the plant. The improvements will safeguard public health and must also harmonies water quality management systems in What are, Report ∗ 1, 3, 7 of Halabja with international best practice.

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