



Science Forum (Journal of Pure and Applied Sciences)

Journal Homepage: <https://atbuscienceforum.com.ng/index.php/jpas>



Evaluation of the Efficiency of Drinking Water Treatment Plants Using the Heavy Metal Pollution Index in Hawija District, Kirkuk, Iraq

Mariam Wassmi Al-Dulaimi

Department of Basic Science, College of Nursing, University of Kirkuk, Kirkuk, Iraq.

Abstract

This study assessed the concentrations of selected heavy metals (Pb, Cr, Cd, and Ni) in drinking water from three water treatment plants in Hawija District, Kirkuk Governorate, Iraq, during November 2025. Heavy-metal concentrations were determined using atomic absorption spectrometry (AAS). Treatment performance was assessed by calculating metal removal efficiencies, while overall water quality was evaluated using the Heavy Metal Pollution Index (HPI). The results showed that, following treatment, lead and cadmium concentrations remained above the permissible limits established by the World Health Organization (WHO) at all three stations, whereas nickel and chromium concentrations were within permissible limits. Removal efficiencies ranged from 68.47-73.76% for Pb, 64.03-69.20% for Cr, 54.92-62.20% for Cd, and 60.29-60.86% for Ni. Despite these reductions, metal concentrations increased again within the distribution network relative to treated water, indicating secondary contamination during water distribution. Following treatment, HPI values ranged from 104.3 to 116.9 and remained above the critical threshold of 100, indicating persistent heavy-metal pollution. Moreover, HPI values increased further to 142.7-162.5 within the distribution network, confirming deterioration in water quality after treatment. Overall, the findings demonstrate that the treatment plants were effective in substantially reducing the concentrations of the investigated heavy metals; however, treatment was insufficient to achieve safe water quality based on the HPI criterion. The study therefore emphasizes the need to upgrade treatment systems, particularly for Pb and Cd removal, and implement periodic inspection and maintenance of distribution networks to minimize secondary contamination and improve drinking-water safety.

Keywords

Drinking water,
Pollution,
Heavy metals,
Water Treatment Plant,
Heavy Metal Pollution Index (HPI).



Introduction

Water is one of the most important natural resources on Earth, as it is essential for sustaining life, achieving sustainable development, and maintaining ecological balance [1]. Despite the importance of water resources, they are under increasing environmental pressure as a result of pollution caused by industrial, agricultural, and human activities, as well as the disposal of toxic waste containing chemicals and heavy metals [2]. Water pollution is one of the most important environmental problems global, it arises from human, natural, or geological sources, and its danger depends on the type of pollutant, its concentration, and the duration of exposure to it [3]. It contributes to the spread of many diseases and is one of the leading causes of death worldwide [4].

Drinking water is defined as water that is safe for human consumption and free of biological and chemical contaminants, or in which the concentrations of such contaminants fall within the permissible limits set by approved water quality standards [5]. However, this water may be contaminated by various sources, including heavy metal pollution, which is considered one of the most dangerous forms of environmental pollution due to its high toxicity and its ability to bioaccumulate and persist in the environment [6]. These metals include hexavalent Cr(VI), Cd(II), Pb(II), As(III,V), Hg(II), Ni(II), and Cu(II), which pose a significant threat to human health and ecosystems because these metals tend to accumulate in the food chain and drinking water sources [7].

The dissolution of these metals in water may degrade its quality and render it unfit for human consumption, thereby increasing health risks to humans and animals, as they affect the nervous and respiratory systems, as well as the liver and kidneys, and may cause behavioral and cognitive disorders and chronic diseases, including an increased risk of diabetes [8], [9]. To mitigate these risks, various techniques have been developed to detect heavy metals in water, the most important of which are atomic absorption

spectroscopy (AAS) and inductively coupled plasma mass spectrometry (ICP-MS). Determining the concentrations of these elements is a fundamental step in assessing water quality (P. Zhang et al., 2023). As a result of the expansion of energy production, the intensification of agricultural and industrial activities, urban expansion, and improved living standards, water consumption has increased significantly, leading to a growing need to provide water that is safe and suitable for human consumption [11].

Water treatment plants have been established for drinking water to improve the quality of water, and their efficiency depends on the effectiveness of the treatment processes in removing the different such as heavy metals, and making the water suitable for human consumption in according to the approved health standards [12]. Although the treatment processes may be efficient, water quality may deteriorate within the distribution network due to corrosion, poor pipe maintenance, and infiltration of pollutants and microorganisms [13]. Many countries in the world including Iraq, suffer from the contamination of drinking water sources and the decline of surface water quality as a result of the environmental and economic conditions by the country in recent years [14].

Kirkuk Governorate is a region of high industrial and agricultural activity that increases the chances of water sources being contaminated with heavy metals. The people of Hawija district depend on treated water for their daily needs; therefore, it is important to evaluate the quality of drinking water and conformity with national and international standards. The study of concentrations of some heavy metals such as lead, nickel, chromium, and cadmium is of particular importance because of their potential health and environmental impacts [15].

This study evaluated the quality of drinking water at water treatment plants in selected areas of the Hawija District specifically, the Hawija Water Project in Kirkuk Governorate by determining the

concentrations of certain heavy metals, namely lead (Pb), nickel (Ni), chromium (Cr), and cadmium (Cd), at three different stages: raw water before treatment, treated water, and water in the distribution network. The study aimed to evaluate the efficiency of the treatment plants in removing these elements and to identify any potential sources of contamination within the distribution network, as well as to compare the results with permissible limits according to international drinking water standards to determine the suitability of the water for human consumption. In addition, the study calculated the Heavy Metal Pollution Index (HPI) and estimated the heavy metal content in the water using appropriate statistical methods to analyze the data and interpret the results.

Materials and Procedure

1- Sample collection

Was conducted this study in the Hawija District, Kirkuk Governorate, Iraq, during November 2025 with the aim of determining the concentrations levels of certain heavy metals in drinking water. The study covered three water treatment plants: the Al-Mahouz (Plant 1), the Al-Abbasi (Plant 2), and the Riyadh (Plant 3). Three sampling sites were selected at each station: raw water prior to treatment, water immediately after treatment, and water from the distribution network in residential areas. samples were collected in sterile, one-liter polyethylene containers previously cleaned with dilute nitric acid and rinsed with distilled water, then transported to the laboratory and stored at 4°C until laboratory analyses were performed [16].

2- Heavy Metal Analysis

Acid digestion of the samples was performed using concentrated nitric acid (supplied by Al-Duraish) prior to measurements. This involved adding 10 mL of the acid to 50 mL of each sample, followed by heating to reduce the volume without allowing the samples to dry completely. After cooling, the samples were filtered, and the volume was adjusted to 50 mL with

deionized water in accordance with analysis requirements.

Concentrations of lead (Pb), cadmium (Cd), chromium (Cr), and nickel (Ni) were measured using a Shimadzu AA-6200 atomic absorption spectrometer. For calibration purposes, standard solutions of varying concentration were used to prepare calibration curves for each element, with the instrument operated under optimal conditions regarding wavelength and flame type (air-acetylene), a blank solution was used to ensure the absence of any interferences during measurement. Each sample was measured three times, and the arithmetic mean were calculated to ensure the accuracy of the results. Additionally, the instrument underwent periodic calibration and the glassware was meticulously cleaned to prevent interference during measurement, the result was then compared against international drinking water standards.

3- Calculation of Heavy Metal Concentrations

After measuring the absorbance values of the samples, heavy metals concentrations were calculated based on the calibration curves for each element, taking into account the dilution factor resulting from digestion and preparation processes. The results were expressed in units of per (mg/L), while Figures (1-4) show the calibration curves used to determine the concentrations of lead, cadmium, chromium, and nickel.

4- Statistical Calculations and Indices

4.1 - Calculation of the Heavy Metal Pollution Index (HPI)

A Heavy Metal Pollution Index (HPI) was used to measure the level of heavy metal contamination in the water, as it relates the measured elemental concentrations to the standard values and respective weighting factors for each element. The index was calculated using the concentrations of lead, cadmium, chromium, and nickel according to the following equations: [17].

$$HPI = [\sum_{i=0}^n W_i Q_i] / [\sum_{i=0}^n W_i] \dots \dots \dots (1)$$

$$Q_i = [M_i - I_i] / [S_i - I_i] \times 100 \dots \dots \dots (2)$$

Where (W_i) is represents the unit weight, (Q_i) is sub-index, (M_i) is measured concentration of the metal (mg/L), (S_i) is permissible standard limit, (I_i) is ideal value of the metal, which was considered equal to zero for all heavy metals, (n) is total number of metals included in the assessment.

4.2- Calculation of Removal Efficiency

To evaluate the efficiency of treatment plants in removing heavy metals, the following removal efficiency equation was used:

$$\text{Removal Efficiency (\%)} = [(C_{\text{before}} - C_{\text{after}}) / C_{\text{before}}] \times 100 \dots \dots \dots (3)$$

Where C_{before} Concentration of the element before treatment, and C_{after} Concentration of the element after treatment.

This equation was used to compare metal concentrations before and after treatment and to determine the efficiency of each plant in reducing pollution levels.

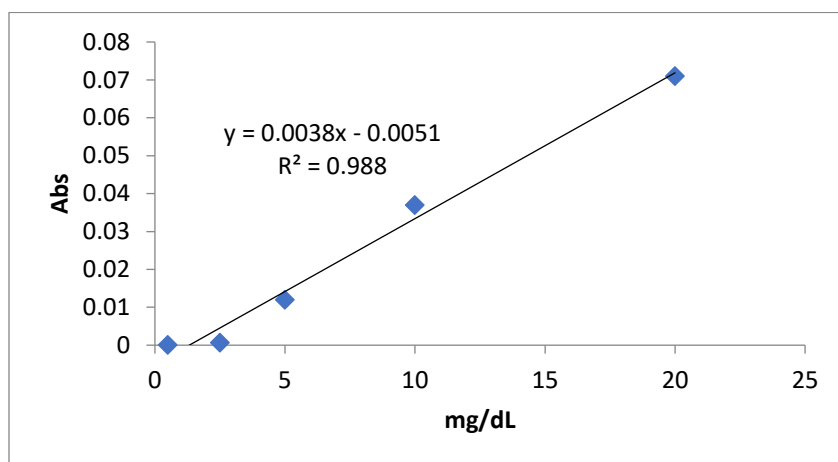


Figure 1. calibration curve of Lead

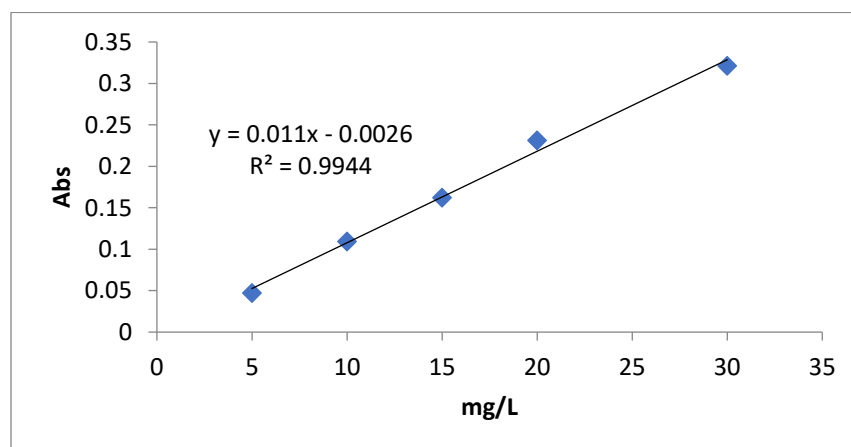


Figure 2. calibration curve of Chromium

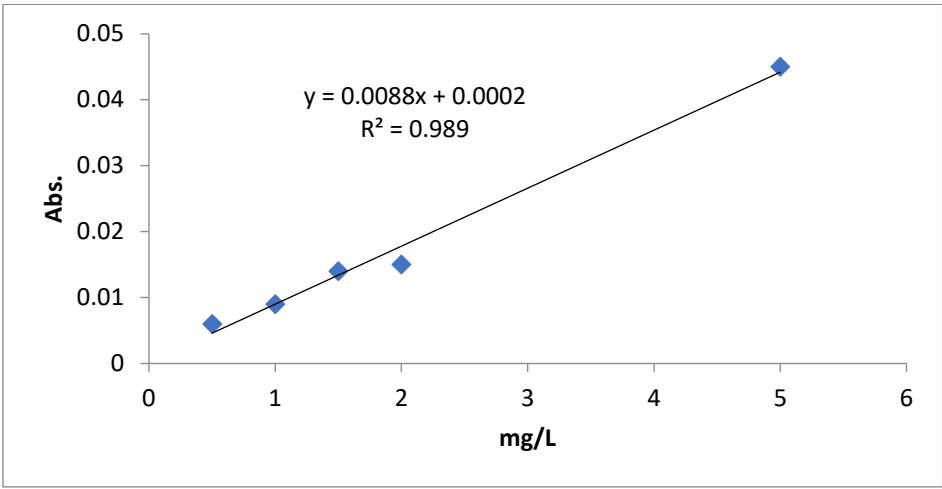


Figure 3. calibration curve of Cadmium

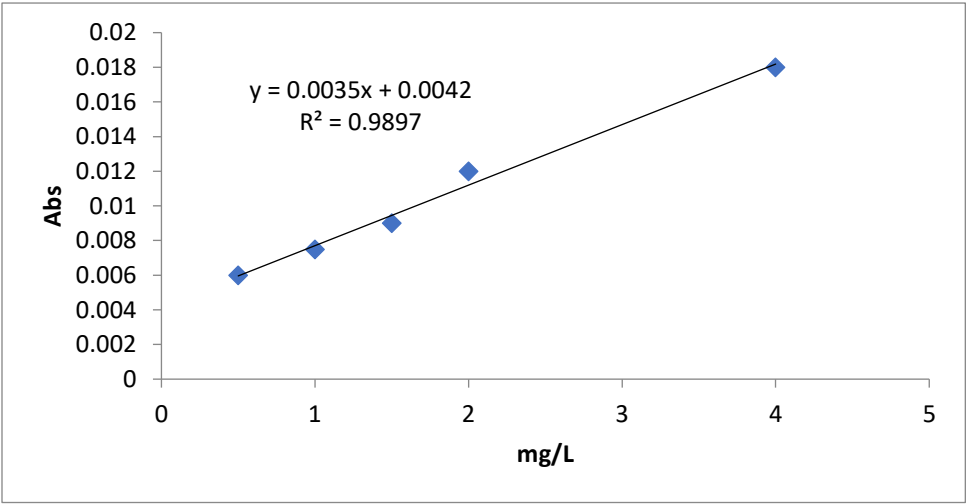


Figure 4. calibration curve of Nickel

Results and Discussion

Concentrations of heavy metals (lead, chromium, cadmium, and nickel) varied significantly across the different treatment stages (pre-treatment, post-treatment, and in the distribution network),

according to the results of the current study presented in **Table (1)**. This variation indicates the impact of filtration processes, alongside the potential for secondary contamination within the distribution network.

Table (1): Concentration of Heavy Metals in Drinking Water Samples

Station	Sampling Point	Pb mg/L	Cr mg/L	Cd mg/L	Ni mg/L
		Mean	Mean	Mean	Mean
St1	Before Treatment	0.0459	0.0591	0.0087	0.0441
	After Treatment	0.0144	0.0182	0.0033	0.0173
	Distribution Network	0.0198	0.0231	0.0045	0.0212
St2	Before Treatment	0.0465	0.0535	0.0071	0.0414
	After Treatment	0.0122	0.0172	0.0032	0.0162
	Distribution Network	0.0178	0.0235	0.0043	0.0213
St3	Before Treatment	0.0593	0.0631	0.0082	0.0481
	After Treatment	0.0187	0.0227	0.0031	0.0191
	Distribution Network	0.0233	0.0274	0.0046	0.0244
Safe Limit mg/L		0.01	0.05	0.003	0.07

Lead (Pb)

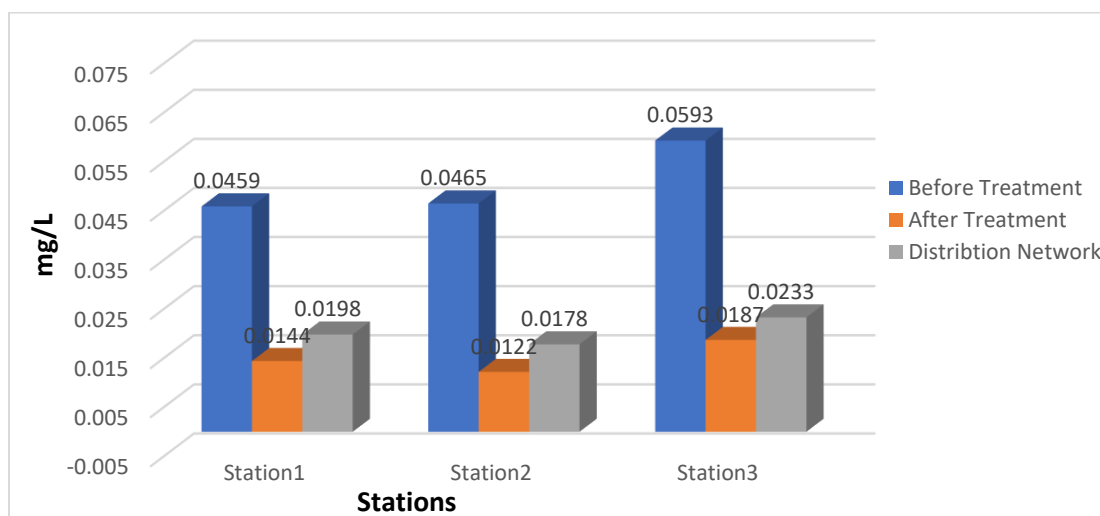


Figure 5. Lead (Pb) Levels

The results presented in **Table (1)** and **Figure. 5**, indicated elevated lead concentrations in the raw water prior to treatment, ranging from (0.0459-0.0539) mg/L, these levels exceed the World Health Organization's (WHO) permissible limit of (0.01) mg/L [18]. demonstrating lead contamination in the water source. This is due to several factors, including industrial activities the discharge of agricultural and human waste, and surface runoff, as well as the decomposition of sediments and lead-rich soil [19]. A recent study has also shown that aging water infrastructure and industrial pollution are among the primary sources of lead contamination in water, particularly in areas with weak environmental monitoring systems [20]. Following treatment, lead concentrations decreased to (0.0187-0.0122) mg/L, demonstrating the efficiency of the filtration plants in reducing these levels. This is attributed to the effectiveness of filtration processes, in addition to coagulation and sedimentation, in removing lead bound to suspended and colloidal matter [21].

However, the levels remained above the globally recommended limits, which may be due to the presence of some lead in a dissolved form that is difficult to remove using conventional treatment techniques [22]. In the distribution network, lead concentrations rose to (0.0178-0.0233) mg/L

compared to treated water. This is attributed to the corrosion of metal pipes or the release of sediment accumulated within the network, particularly in older pipes or those containing lead. In addition, changes in the water's chemical properties such as a decrease in pH or an increase in the water's residence time within the network enhance the dissolution of lead and its transfer into the water supplied to consumers [23]. These findings are consistent with studies indicating that distribution networks are a major source of lead recontamination in water due to internal corrosion of pipes, welded joints, and aging infrastructure [24].

The results indicate that the treatment plants have helped reduce lead concentrations and improve the quality of drinking water; however, all concentrations recorded before and after treatment, as well as in the distribution network, exceeded internationally accepted limits, which calls for improving the efficiency of treatment processes and upgrading outdated distribution networks, to ensure that the water meets health standards [25]. Lead is considered a toxic element that easily accumulates in the human body, prolonged exposure to it can cause damage to the nervous system, kidneys, and brain, as well as behavioral disorders, particularly in children [20].

Chromium (Cr)

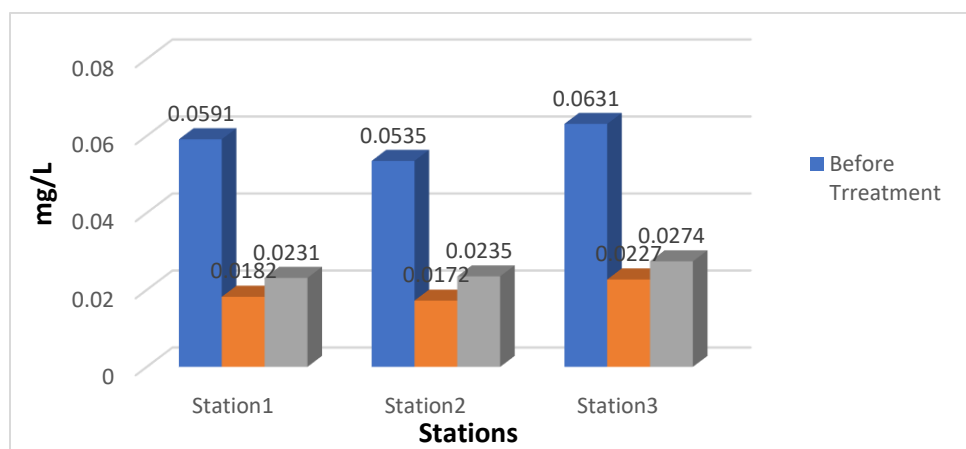


Figure 6. Chromium (Cr) Levels

The results presented in **Table (1)** and **Figure. 6** indicate elevated chromium concentrations in the water prior to treatment, ranging from (0.0535-0.0631) mg/L, this is slightly above the World Health Organization's (WHO) permissible limit of (0.05) mg/L [18]. This indicates contamination of water sources by various pollutants such as those resulting from human or agricultural activities, as well as the dissolution of chromium bearing rocks within the aquatic environment. Or it may result from industrial processes, such as leather tanning or fuel combustion, leading to increased concentrations in water sources [26].

Following treatment, chromium concentrations decreased to ranging (0.0172-0.0227) mg/L. levels that fall within internationally permissible limits, demonstrating the filtration plant's effectiveness in removing a significant portion of the chromium. As indicated in previous studies, certain chemical treatment processes may contribute to reduces hexavalent chromium (Cr^{+6}) to trivalent chromium (Cr^{+3}), which is less toxic and less water soluble, thereby enhancing its removal efficiency during the treatment stages. However, the chemical mechanism responsible for this reduction was not identified in the current study, as no analysis was conducted to determine the chromium species [27].

These results are consistent with a study by Jassim et al., who found that treatment leads to a significant reduction in chromium concentrations. however, the removal efficiency depends on the nature of the raw water and the efficiency of the filtration units used [28]. As for the distribution network, chromium concentrations showed a slight increase compared to the treated water, ranging from (0.0231-0.0274) mg/L; however, they remained within the limits permitted by the WHO **Figure. 6**. This is attributed to corrosion of metal pipes and old tanks, as well as chemical reactions occurring inside the pipes, such as chromium oxidation or the reaction of water with metals [19].

From a health perspective, continuous exposure to high concentrations of chromium, particularly hexavalent chromium (Cr^{+6}), poses health risks, including an increased likelihood of developing certain types of cancer and damage to the respiratory system, kidneys, and liver. However, concentrations whether after treatment or in the distribution network remained within the limits permitted by WHO standards, demonstrating the efficiency and success of the treatment plants in controlling this factor [29].

Cadmium (Cd)

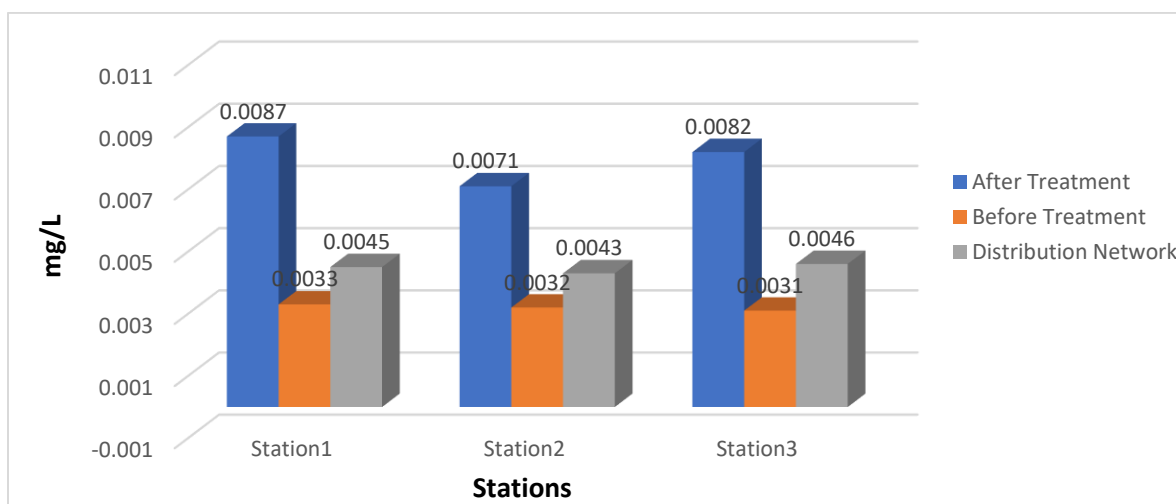


Figure 7. Cadmium (Cd) Levels

The results in Table (1) and **Figure. 7**, indicate the presence of contamination in the raw water source. Pre-treatment cadmium concentrations ranged from 0.0071 to 0.0087 mg/L. These values exceed the WHO permissible limit of (0.003) mg/L [18]. This is attributed to the impact of human agricultural and industrial activities, particularly the use of phosphate fertilizers containing cadmium impurities, as well as the discharge of untreated wastewater into water sources [30], [31]. Furthermore, the agricultural nature of the Hawija region may contribute to elevated cadmium concentrations in raw water, as confirmed by a recent study indicating that the intensive use of phosphate fertilizers and agricultural pesticides, along with the discharge of industrial waste, increases the accumulation of cadmium in the aquatic environment and drinking water [32].

After treatment, cadmium concentrations decreased to (0.0031-0.0033) mg/L. This indicates the effectiveness and efficiency of the treatment plants in removing a portion of the cadmium and reducing its concentration however, the levels remained slightly above or close to internationally permissible limits, necessitating improvements in treatment process efficiency to ensure safe levels are achieved [18]. This is consistent with what was concluded by Al-amarr and Hamood [33].

Within the distribution network, cadmium concentrations rose slightly, ranging from (0.0043-0.0046) mg/L. This indicates secondary contamination within the network, potentially caused by the redissolution of cadmium from pipe sediments resulting from cracks in the pipes or from the interaction between the water and the metals. While cadmium is present in low concentrations in natural water sources, its levels increase significantly in contaminated areas [34]. This aligns with the findings of Hatam et al., who noted that distribution networks can increase heavy metal concentrations in drinking water due to chemical reactions between the water and the pipes, particularly when periodic maintenance of the networks and pipes is inadequate or when changes occur in certain chemical properties of the water, such as a drop in pH levels [35]. The results indicated that cadmium concentrations at all stages exceeded the limits set by the WHO necessitating the upgrading of treatment systems and distribution networks to mitigate health risks. This is because cadmium is a heavy metal with a high potential for bioaccumulation in the body, continuous exposure to it can lead to kidney toxic, bone softening osteomalacia, and an increased risk of certain types of cancer [36].

Nickel (Ni)

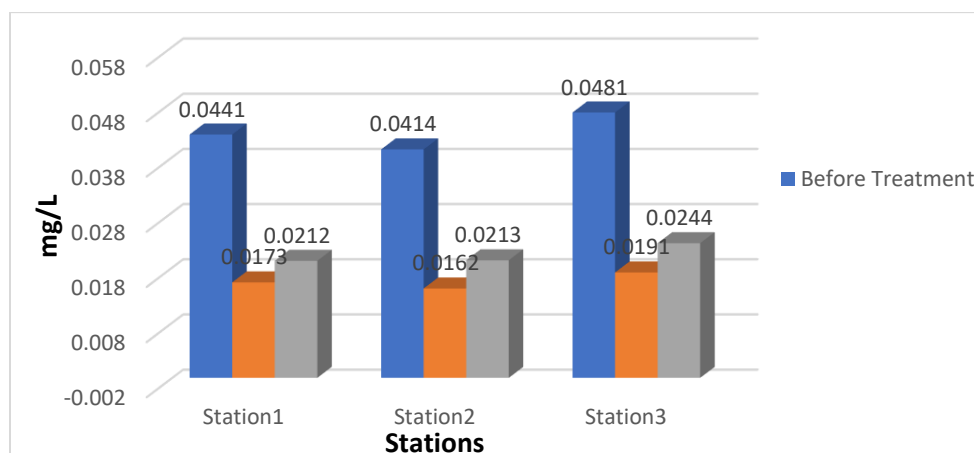


Figure 8. Nickel (Ni) Levels

The results shown in **Table (1)** and **Figure.8**, indicate that nickel concentrations prior to treatment ranged from (0.0414-0.0481) mg/L. These concentrations are slightly elevated but remain within the World Health Organization's (WHO) permissible limit of 0.07 mg/L [18]. However, it is considered relatively high compared to later stages, which indicates the presence of contamination in raw water sources, such as industrial activity or metal corrosion [37].

After filtration, nickel concentrations decreased, ranging from (0.0162-0.0191) mg/L. This demonstrates the effectiveness of filtration processes in removing a significant proportion of nickel bound to suspended solids and colloids. Furthermore, the adsorption of nickel ions onto fine sediments and organic matter during the treatment stages contributes to reducing its concentration in the treated water. A recent study has confirmed that treatment and filtration techniques, as well as adsorbents, clearly contribute to reducing nickel concentrations in water [38]. In the distribution network, the concentration rose slightly, ranging from (0.0212-0.0244) mg/L, but remained within

internationally accepted limits. This is due to several factors, including the interaction of water with components of the network particularly under specific chemical conditions or the corrosion of metal pipes [39]. This is consistent with research showing that nickel is typically found in small amounts in water, but its levels may rise due to geological or industrial pollution. According to the WHO, leaks from metal pipes and fittings are the main source of nickel in drinking water, in addition to natural sources [18], [40].

The results also showed that all recorded concentrations were within the limit permitted by the WHO, indicating that the drinking water was within acceptable health limits for nickel. However, continuous exposure to large amounts of nickel may cause illnesses such as skin allergies or respiratory problems, or it may cause heart disease or lung cancer [41]. Therefore, transmission and the infrastructure continuously maintained to ensure that water quality remains within internationally accepted health limits.

Heavy Metal Pollution Index (HPI)

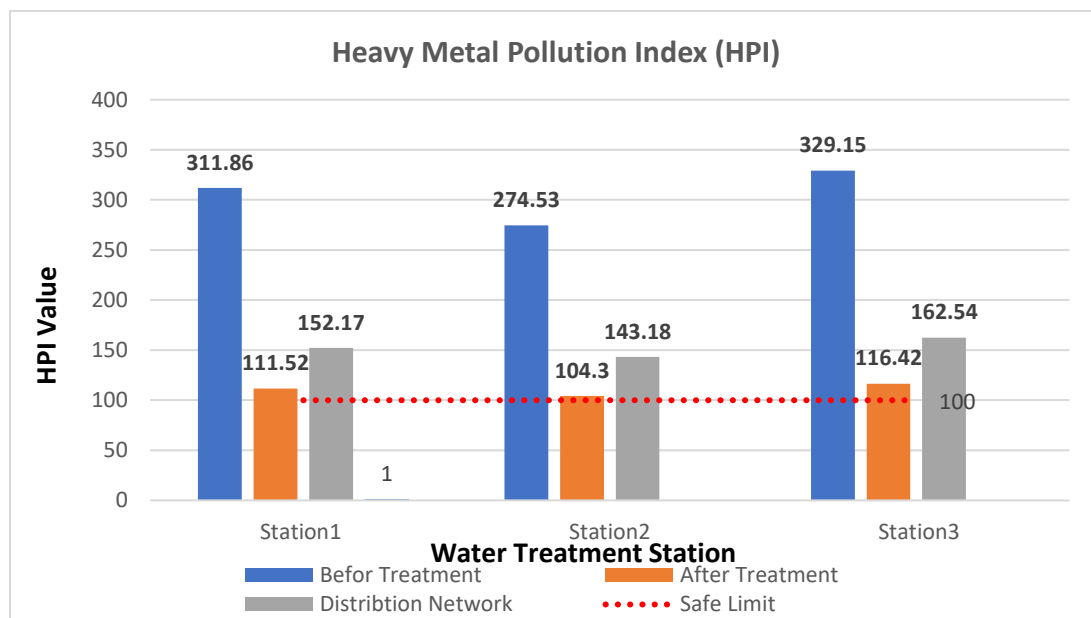
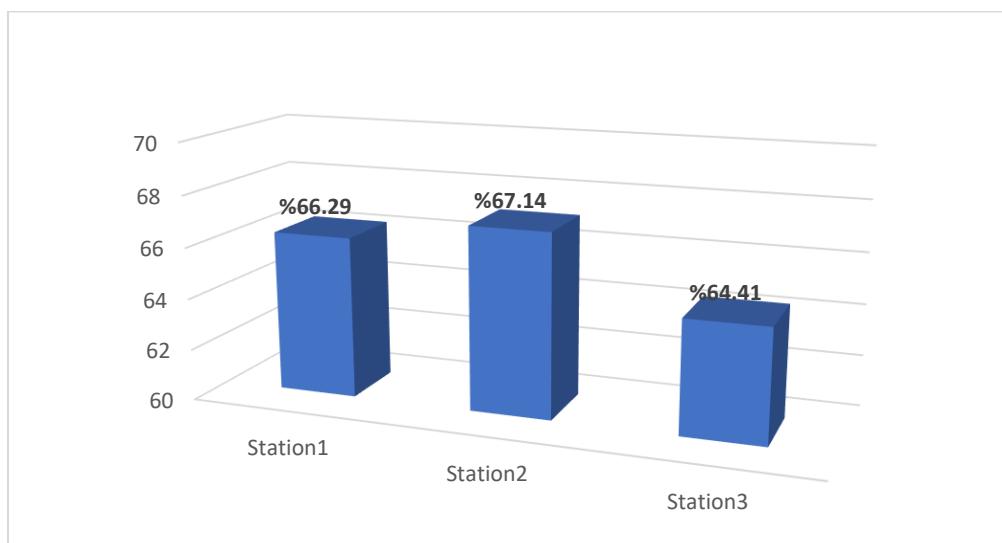


Figure 9. Heavy metal pollution index

Table (2): The efficiency of the stations in removing each element

Metal	Station1	Station2	Station3
Pb	%68.63	%73.76	%68.47
Cr	%69.20	%67.85	%64.03
Cd	%62.06	%54.92	%62.20
Ni	%60.77	%60.86	%60.29

**Figure 10. Efficiency of Station Removal**

The Heavy Metal Pollution Index (HPI) was calculated individually for each station. Based on globally recognized HPI classification standards, a value of 100 serves as the critical threshold representing the upper limit for drinking water suitability. The results indicated that HPI values across all stations and study phases exceeded this critical threshold of 100, a level classified as indicating severe pollution. This demonstrates the presence of heavy metal contamination in the water treatments plants of Hawija District [42].

The result indicates that Station 3 recorded the highest pre-treatment index value (329.15), followed by Station 1 (311.86) and then Station 2 (274.53), as shown in **Figure 9**. This is attributed to high heavy metals concentrations in the raw water, specifically, concentrations of lead, chromium, and nickel were highest at Station 3 compared to the other stations, as shown in **Table (1)**. This suggests that the water source supplying this station contains high levels of

pollutions, resulting from the impact of human and agricultural is subject to greater pollution pressures, which may be attributed to the impact of agricultural activities as well as the geological characteristics of the water intake area. These findings align with the study Al-Mayah et al., which showed that the pollution index (HPI) values exceeded the critical limit (100), with variations between the study sites based on differences in heavy metal concentrations and pollution sources [43]. treatment processes also contributed to reducing heavy metal concentrations and lowering HPI values at all stations, although they remained above the critical value (100).

Station 3 recorded highest HPI value of 116.42, while Station 2 recorded the lowest 104.3 after treatment, as shown in **Figure 9**. This indicates that although conventional treatment processes are successful in reducing metal concentrations, they are insufficient to eliminate the cumulative effect of these elements. This aligns with the findings of [6], who

demonstrated that the persistence of elevation HPI values above the critical limit (100) after treatment reflects the continued cumulative effect of heavy metals in drinking water.

The efficiency of lead removal ranged between (68.47-73.76) %, which is the highest among the elements studied, followed by chromium (64.03-69.20) %. Meanwhile, cadmium and nickel recorded relatively lower removal efficiencies ranging from (54.93-62.20) % and (60.27-60.87) %, respectively, as shown in **Tables (1) and (2)**. This is attributed to the different chemical properties of the elements, as Pb and Cr bound to suspended particles are easily and efficiently removed during coagulation, sedimentation, and filtration processes. Cd and Ni, however, remain in dissolved form, which reduces their removal efficiency using conventional treatments. Additional techniques, such as adsorption, membrane filtration, or ion exchange, may be required to achieve higher removal efficiency [44].

In the distribution network, the HPI values rose to (152.17), (143.18), and (162.54) at the first, second, and third stations, respectively, as shown in **Figure 9**. This indicates the possibility of secondary contamination within the distribution network, resulting from pipe corrosion, accumulated sediment, or changes in the chemical and physical properties of the water during transmission and distribution. It is also attributed to variations in the efficiency of purification processes and a lack of adherence to regular network maintenance, which was a major cause of contaminant concentration in drinking water [45].

A comparison of the treatment plants shows that the second plant achieved the highest efficiency in removing heavy metals, at (67.14) %, followed by the first plant (66.29) % and then the third (64.44) %, as shown in **Figure 10**. However, the differences between the plants were relatively small, indicating that the efficiency of the treatment systems used was comparable. Nevertheless, Plant 3 continued to

record the highest HPI values throughout all stages of the study. This suggests that the initial level of contamination in the raw water is a key factor in determining the final index value, even in the presence of effective treatment processes [46].

Conclusion

The study's findings indicate that raw water sources at water treatment plants in the Hawija district are clearly contaminated with lead, chromium, and cadmium at levels exceeding the limits set by the World Health Organization, while nickel concentrations remained within safe levels. Despite the treatment processes proving effective and efficient in reducing the concentrations of the studied heavy metals, lead and cadmium concentrations remained above the limits permitted by the WHO. The results also indicated secondary contamination in the distribution network due to several factors, including corrosion of old pipes, inadequate maintenance of transmission and distribution networks, and chemical changes in the water within the network. Furthermore, the metal contamination index value at all stations and stages exceeded the critical limit, indicated that the water reaching consumers does not fully comply with international health standards.

Overall, the study demonstrates that effective drinking-water management in Hawija District requires interventions at both the treatment and distribution stages. Priority should be given to upgrading treatment systems, particularly through technologies capable of improving Pb and Cd removal. In parallel, systematic inspection, rehabilitation, and periodic maintenance of transmission and distribution. Pipelines are required to minimize secondary contamination. Routine monitoring of heavy metals at the raw-water, post-treatment, and consumer-delivery stages should also be strengthened to identify contamination trends and evaluate treatment performance. Implementing these measures would improve the reliability of the water-

supply system, reduce heavy-metal exposure, and enhance the safety and quality of drinking water delivered to consumers in Hawija District.

Reference

- [1] A. Alitane et al., "Assessment of drinking water quality based on trace elements concentrations in the semi-arid region, Morocco," *E3S Web of Conferences*, vol. 489, p. 06001, Feb. 2024, doi: 10.1051/e3sconf/202448906001.
- [2] P. Saravanan et al., "RETRACTED: Comprehensive review on toxic heavy metals in the aquatic system: sources, identification, treatment strategies, and health risk assessment," *Environ. Res.*, vol. 258, p. 119440, Oct. 2024, doi: 10.1016/j.envres.2024.119440.
- [3] W. A. Khan and S. Jan, "Drinking Water Contamination and Treatment Techniques," *Journal of International Cooperation and Development*, vol. 6, no. 2, p. 57, Jul. 2023, doi: 10.36941/jicd-2023-0012.
- [4] Q. Liu et al., "Burden and trends of infectious disease mortality attributed to air pollution, unsafe water, sanitation, and hygiene, and non-optimal temperature globally and in different socio-demographic index regions," *Glob. Health Res. Policy*, vol. 9, no. 1, p. 23, Jun. 2024, doi: 10.1186/s41256-024-00366-x.
- [5] A. Shah, A. Arjunan, A. Baroutaji, and J. Zakharova, "A review of physicochemical and biological contaminants in drinking water and their impacts on human health," *Water Science and Engineering*, vol. 16, no. 4, pp. 333-344, Dec. 2023, doi: 10.1016/j.wse.2023.04.003.
- [6] M. Latif et al., "Human health risk assessment of drinking water using heavy metal pollution index: a GIS-based investigation in mega city," *Appl. Water Sci.*, vol. 15, no. 1, p. 12, Jan. 2025, doi: 10.1007/s13201-024-02341-w.
- [7] V. Singh et al., "Hexavalent-Chromium-Induced Oxidative Stress and the Protective Role of Antioxidants against Cellular Toxicity," *Antioxidants*, vol. 11, no. 12, p. 2375, Nov. 2022, doi: 10.3390/antiox11122375.
- [8] O. P. Aghamelu, M. E. Omeka, and C. O. Unigwe, "Modeling the vulnerability of groundwater to pollution in a fractured shale aquifer in SE Nigeria using information entropy theory, geospatial, and statistical modeling approaches," *Model. Earth Syst. Environ.*, vol. 9, no. 2, pp. 2385-2406, 2023.
- [9] A. L. Ezugwu et al., "Mechanism, formation and transport of polycyclic aromatic hydrocarbons (PAHs) in fruits, vegetables and fresh fish species in Africa: a systematic review of its health risk," *Chemistry Africa*, vol. 7, no. 5, pp. 2321-2344, 2024.
- [10] P. Zhang et al., "Water quality degradation due to heavy metal contamination: health impacts and eco-friendly approaches for heavy metal remediation," *Toxics*, vol. 11, no. 10, p. 828, 2023.
- [11] H. M. Farhan Shalal, K. S. Mohammed, M. H. Al-Kubaisi, I. Yusoff, M. T. Anees, and A. F. Bin Abu Bakar, "Analysis and assessment of surface water quality in Al-Habbaniyah, Iraq," *Journal of University of Anbar for Pure Science*, vol. 20, no. 1, pp. 345-357, 2026.
- [12] H. Mohammed Raheem and M. Rashid Al-Juhaishi, "Assessment of raw and produced water quality at Al-Doura water treatment plant," in *IOP Conference Series: Earth and Environmental Science*, IOP Publishing, 2024, p. 012070.

- [13] E. E. Atojunere and G. E. Amiegbe, "Automated Leak and Water Quality Detection System for Piped water Supply," *Malaysian Journal of Science*, pp. 98-108, 2024.
- [14] Q. A. Ali and O. A. Ghareeb, "Proposed solutions to improve deterioration of drinking water quality," *Global Scientific Review*, vol. 23, pp. 34-46, 2024.
- [15] S. L. Weston, A. Scheili, S. Behmel, and M. J. Rodriguez, "Water quality in drinking water distribution systems: research trends through the 21st century," *Environ. Sci. (Camb.)*, vol. 8, no. 12, pp. 3054-3064, 2022, doi: 10.1039/D2EW00491G.
- [16] W. C. Lipps, E. B. Braun-Howland, and T. E. Baxter, *Standard methods for the examination of water and wastewater*. 2023.
- [17] S. V. Mohan, P. Nithila, and S. J. Reddy, "Estimation of heavy metals in drinking water and development of heavy metal pollution index," *Journal of Environmental Science & Health Part A*, vol. 31, no. 2, pp. 283-289, 1996.
- [18] W. H. Organization, "Lead in drinking-water: health risks, monitoring and corrective actions: technical brief," 2022.
- [19] A. Generalova, S. Davidova, and G. Satchanska, "The mechanisms of lead toxicity in living organisms," *J. Xenobiot.*, vol. 15, no. 5, p. 146, 2025.
- [20] H. Shakoor, F. Alshehri, M. Shahab, F. A. Abanumay, and L. Ali, "Vulnerability and risk assessment of lead (Pb) concentrations in drinking water via statistical and geostatistical analyses," *Frontiers in Water*, vol. 7, p. 1548110, 2025.
- [21] J. A. Locsin, K. M. Hood, E. Doré, B. F. Trueman, and G. A. Gagnon, "Colloidal lead in drinking water: Formation, occurrence, and characterization," *Crit. Rev. Environ. Sci. Technol.*, vol. 53, no. 1, pp. 110-136, 2023.
- [22] S. Singh, "Water pollution in rural areas: Primary sources and associated health issues," in *Water Resources Management for Rural Development*, Elsevier, 2024, pp. 29-44.
- [23] M. M. Dehkordi, Z. P. Nodeh, K. S. Dehkordi, R. R. Khorjestan, and M. Ghaffarzadeh, "Soil, air, and water pollution from mining and industrial activities: Sources of pollution, environmental impacts, and prevention and control methods," *Results in Engineering*, vol. 23, p. 102729, 2024.
- [24] H. E. H. Ahmed, A. M. A. Mohammed, and M. Soylak, "A magnetic solid phase extraction procedure for Pb (II) at trace levels on magnetic Luffa@ TiO₂ in food and water samples," *Food Chem.*, vol. 428, p. 136794, 2023.
- [25] A. H. Sani, A. Musa, and M. D. Achimugu, "Assessment of heavy metal pollution of drinking water sources and staple food cultivars around artisanal mining site in Igade-Mashegu, Niger State, Nigeria," *World J. Biol. Pharm. Health Sci*, vol. 14, pp. 306-319, 2023.
- [26] S. Collin et al., "Bioaccumulation of lead (Pb) and its effects in plants: A review," *Journal of Hazardous Materials Letters*, vol. 3, p. 100064, 2022.
- [27] M. Langer, M. U. Jamal, A. Conklin, and M. Ernst, "Chromium removal in the presence of NOM during Fe (II) reductive precipitation for drinking water treatment," *Water (Basel)*, vol. 14, no. 18, p. 2903, 2022.

- [28] H. K. Jasim, H. K. Tayyeh, and A. M. Hussein, "Studying the Effects of Heavy Metals Concentrations on selected Water Treatment Plants in Babylon Governorate," *Journal of Water Resources and Geosciences*, vol. 4, no. 1, pp. 28-44, 2025.
- [29] R. Chakraborty et al., "Mechanism of chromium-induced toxicity in lungs, liver, and kidney and their ameliorative agents," *Biomedicine & Pharmacotherapy*, vol. 151, p. 113119, 2022.
- [30] A. Rashid et al., "Heavy metal contamination in agricultural soil: environmental pollutants affecting crop health," *Agronomy*, vol. 13, no. 6, p. 1521, 2023.
- [31] A. Daripa, L. C. Malav, D. K. Yadav, and S. Chattaraj, "Metal contamination in water resources due to various anthropogenic activities," in *Metals in water*, Elsevier, 2023, pp. 111-127.
- [32] G. Gunes, "The change of metal pollution in the water and sediment of the Bartın River in rainy and dry seasons," *Environmental Engineering Research*, vol. 27, no. 2, 2022.
- [33] Z. Saad, "Detection of lead and cadmium pollution in Tigris River, water stations, and tap water in Baghdad Governorate," *Experimental and Applied Veterinary Research Journal*, vol. 1, no. 1, pp. 38-46, 2025.
- [34] L. Bouida et al., "A review on cadmium and lead contamination: Sources, fate, mechanism, health effects and remediation methods," *Water (Basel)*, vol. 14, no. 21, p. 3432, 2022.
- [35] F. Hatam, M. Blokker, E. Doré, and M. Prévost, "Reduction in water consumption in premise plumbing systems: Impacts on lead concentration under different water qualities," *Science of The Total Environment*, vol. 879, p. 162975, 2023.
- [36] G. Kuna, S. Gullipalli, and V. Chintada, "Health risks associated with cadmium toxicity," in *Cadmium Toxicity in Water: Challenges and Solutions*, Springer, 2024, pp. 47-60.
- [37] W. Begum et al., "A comprehensive review on the sources, essentiality and toxicological profile of nickel," *RSC Adv.*, vol. 12, no. 15, pp. 9139-9153, 2022.
- [38] H. G. Faisal and Y. F. Al Fatlawy, "Using Different Kinds of Activated Carbon for Removing Some Pollutants from Tap Water and Well Water," *Iraqi Journal of Science*, pp. 96-110, 2026.
- [39] H. M. Hussein Farh, M. E. A. Ben Seghier, R. Taiwo, and T. Zayed, "Analysis and ranking of corrosion causes for water pipelines: a critical review," *NPJ Clean Water*, vol. 6, no. 1, p. 65, 2023.
- [40] S. Adhikari, E. Yanuar, and D.-Q. Ng, "Widespread nickel contamination in drinking water supplies of elementary schools in Taichung, Taiwan," *Environmental Science and Pollution Research*, vol. 29, no. 9, pp. 12531-12539, 2022.
- [41] G. Genchi, A. Carocci, G. Lauria, M. S. Sinicropi, and A. Catalano, "Nickel: Human health and environmental toxicology," *Int. J. Environ. Res. Public Health*, vol. 17, no. 3, p. 679, 2020.
- [42] B. H. Anitha, S. N. Maya Naik, C. Nanjundaswamy, and M. S. Divyanand, "Application of heavy metal pollution index and metal index for the assessment of groundwater quality in Peenya Industrial Area," in *IOP Conference Series: Earth and Environmental Science*, IOP Publishing, 2021, p. 012033.

- [43] W. T. Al-Mayah, A. R. Yasin, and T. Alyasiri, "A new approach for indexing potentially toxic elements pollution to assess drinking water quality," in *AIP Conference Proceedings*, AIP Publishing LLC, 2026, p. 110005.
- [44] J. O. Olowoyo, O. O. Olaiya, O.-O. L. Oharisi, J. A. Olusola, U. A. Tshoni, and O. M. Oladeji, "Heavy Metals Burden in Drinking Water: Global Patterns, Sources, and Public Health Implications," *Water (Basel)*, vol. 18, no. 8, p. 886, 2026.
- [45] H. Zhang *et al.*, "Effects of chloride on corrosion scale compositions and heavy metal release in drinking water distribution systems," *J. Hazard. Mater.*, vol. 465, p. 133452, 2024.
- [46] S. H. Jazza, S. Najim, and M. A. Adnan, "Using heavy metals pollution index (HPI) for assessment quality of drinking water in Maysan Province in Southern East in Iraq," *Egypt. J. Chem.*, vol. 65, no. 2, pp. 703-709, 2022.