Evaluation of heavy metal levels in effluents from Mosul water treatment plants and their environmental and agricultural safety

Hajir A. Alzubair*, Ayman Albanna and Mazin N. Fadhel

Department of Environmental Science, College of Environmental Sciences, University, of, Mosul, Iraq.
***Corresponding author e-mail: hajir.24evp5@student.uomosul.edu.iq**
https://doi.org/10.59658/jkas.v12i4.5178

Received: July 02, 2025

Accepted: Aug. 18, 2025

Published: Dec. 25, 2025

Abstract

The aim of this study was determining its suitability for reuse, especially in agricultural irrigation. Water samples were collected from multiple sites including hospitals, treatment plants, industrial zones, universities, and slaughterhouses, and analyzed using atomic absorption technology after standard calibration curves were prepared to ensure measurement accuracy. The analysis focused on five common metal elements known for their environmental and health impact, namely: lead (Pb), cadmium (Cd), zinc (Zn), iron (Fe), and copper (Cu). The results were showed that the iron concentration ranged from 0.000077 to 0.01603 mg/L, which is less than the maximum allowable for drinking water according to the World Health Organization (0.3 mg / l). For lead, the concentrations ranged from 0.000721 to 0.007151 mg/L, and are also within the safe drinking limits (0.01 mg / l), although they vary between sample sources. In contrast, cadmium concentrations have been shown exceeding the permissible limit (0.003 mg / L) in several locations, especially in industrial areas and some university discharges, raising environmental and health concerns that warrant intervention. Zinc recorded low levels ranging from 0.000074 to 0.00848 mg/L, which are below the recommended limits for irrigation (2.0 mg/L) and drinking (3.0 mg/L), indicating no immediate environmental risk. The highest copper concentrations were recorded at the Tel Rumman drainage site (0.204 mg/L), which is close to the irrigation guideline limit (0.2 mg/l), but still within the Safe Drinking range. Spatial and functional analysis of the distribution were showed that industrial and university sources significantly contributed to raising cadmium and copper levels, while residential and medical sources showed relatively low levels. Geographically, the southern and western areas of the city tend to record the highest concentrations, attributed to the intensity of industrial activities and increased population pressure.

Keywords: Heavy Metal, wastewater, Agricultural, Treated Wastewater.

Introduction

Water resources are essential for achieving food security and environmental stability, but with the continuous increase in industrial activity and unregulated urbanization, the pressure on fresh water sources has increased, especially in arid and semi-arid regions such as Iraq [1]. As a result, the reuse of treated wastewater has become a strategic option for Water Resources Management and evaluating the efficiency of local treatment plants, not only in terms of removing organic pollutants, but also in terms of the ability of these plants to get rid of toxic inorganic elements, mainly heavy metals, especially in agricultural sectors that consume the bulk of available water [2].

While the reuse of treated water provides economic and environmental advantages, the success of this approach depends mainly on the quality of the reused water and its freedom from dangerous pollutants, mainly heavy metals [3]. Heavy metals such as lead (Pb), cadmium (Cd), zinc (Zn), iron (Fe), and copper (Cu) are some of the most dangerous inorganic pollutants that may remain in water even after treatment, due to their non-biodegradable nature and high susceptibility to accumulate in soil and plants, and then move up the food chain, leading to serious health and environmental impacts [4].

The danger of these metals stems from their physical and chemical properties that make them stable and stable in the environment, gradually accumulating over time [5]. Some of them are highly toxic even at low concentrations, and may adversely affect soil microorganisms, cause disturbances in plant growth, in addition to their potential risks to human health through the consumption of contaminated agricultural products or direct contact with soil [6].

In Mosul city, wastewater treatment is a prominent environmental challenge, especially after the water infrastructure has been severely damaged over the past years [7]. With the increasing dependence on treated water in some agricultural activities, there is an urgent need to accurately assess the quality of this water by analyzing heavy metal concentrations and comparing them with local and global environmental determinants [8,9]

This assessment is necessary to lay the necessary scientific foundations to ensure the safe reuse of treated water, avoiding long-term damage to the environment and public health [2]. Based on this, the current study aims to analyze the concentrations of a number of heavy metals in treated wastewater at several sites within the city of Mosul, and assess their compliance with the environmental standards adopted for agricultural reuse. It also seeks to determine the spatial distribution of these elements, and monitor sites that record high concentrations, in order to provide scientific recommendations that can be adopted in improving the efficiency of processing and reducing the potential risks associated with reuse.

Materials and Methods

This study was conducted to assess the concentrations of some heavy metals in treated wastewater within the city limits of Mosul, Iraq, to determine its suitability for reuse in the agricultural field. To achieve this goal, the design of an analytical observational study was adopted, which included the collection and analysis of samples from various sites representing various drainage sources in the city.

32 samples of wastewater were collected from selected locations within the city of Mosul, as shown in Table (1). The coordinates of the locations of the treatment plants from which samples were taken, including hospitals, industrial facilities, treatment plants, and municipal drainage sites. These sites have been carefully selected to ensure the representation of functional and spatial diversity within the urban fabric, allowing to obtain a comprehensive picture of the concentrations of heavy metals in various types of treated water. The samples were collected in sterile, pre-washed polyethylene containers using 10% diluted nitric acid to ensure the removal of any metal impurities that may affect the results of the analysis. After collection, the samples were immediately kept at a temperature of 4 degrees Celsius to maintain the stability of chemical properties and prevent changes affecting the results. Before analysis, the samples underwent a filtration process using fine membrane filters with a pore diameter of 0.45 micrometers to remove suspended solids. The PH (pH) of each sample was also adjusted to a value below 2.0 by adding concentrated nitric acid (HNO3), in order to stabilize the metals in their dissolved state and prevent their deposition or adhesion to the walls of the containers.

Quantitative analysis of the target heavy elements, namely lead (Pb), cadmium (Cd), zinc (Zn), iron (Fe), and copper (Cu), was carried out using the flame atomic Absorption Spectrophotometer - AAS, in accordance with the protocols approved in the manual of the American Public Health Association [10].

An air-acetylene flame (Air-Acetylene Flame) was used to ionize the atoms inside the device, which made it possible to accurately detect the concentration of each element at a specially selected wavelength for each metal. The device has also been calibrated using standard solutions with known concentrations to ensure the accuracy and reliability of measurements. As shown in Table (2).

Table (2): Coordinates of the locations of the treatment plants from which the samples were taken

Location No.	Location Name	longitude	latitude
1	Thalassemia Hematology hospital	43.08293	36.36722
2	Ibn Sina hospital	43.17535	36.3439004
3	Green Apartments treatment plant	43.2019658	36.34062
4	Sahron station	43.15632	36.33908
5	Yarmouk apartments treatment plant	43.11374	36.33805

6	Women's health hospital	43.11501	36.38112
7	Intravenous solution factory	43.16636	36.32258
8	Al-Madinah Al-Ahli Hospital	43.12308	36.3093
9	Bab Sinjar apartment processing plant 1	43.11354	36.5688
10	Bab Sinjar apartment processing plant 2	43.11474	36.35658
11	Al-Rabeeah Al-Ahli Hospital	43.11626	36.35659
12	Military hospital (General)	43.11509	36.35852
13	German hospital	43.11118	36.356888
14	Al-Batol hospital	43.108922	36.3771
15	Al-Gemhory hospital	43.1486	36.3519
16	Burn hospital	43.1253	36.3584
17	Al-Ataba hospital	43.1297	36.3602
18	Blood Bank hospital	43.1322	36.3749
19	Wastewater treatment plant-Left site	43.1781	36.4032
20	Wastewater treatment plant-Right site	43.1105	36.3865
21	Al-Kendy hospital wastewater	43.1508	36.36722
22	Nineveh massacre	43.08293	36.3439004
23	Wadi Al Ain drainage outlet	43.17535	36.34062
24	Drainage of the industrial area (east)	43.2019658	36.33908
25	Discharge of the University of Mosul	43.15632	36.33805
26	Northern drainage towards the Tigris River	43.2027	36.475
27	Discharge of the Mosul Sugar Factory	43.128	36.4007
28	Drainage of the Rashidiya area	43.2027	36.475
29	Al-Samah district drainage	43.1854	36.3828
30	Drainage of waste water-Tel Rumman	43.1043	36.3215
31	Cement plant drainage (Western)	43.2889	35.8031
32	Drainage of Mosul General Hospital	43.1428	36.342

Table (2): The elements for which the tests were carried out

Item code	Lamp (Am) current	Wavelength (nm)	flame	Slit width (nm)
Lead (Pb)	5.0	283.3	Air-acetylene	0.5
Iron (Fe)	5.5	248.3	Air-acetylene	1.4
Copper (Cu)	6.0	324.8	Air-acetylene	0.5
Zinc (Zn)	5.0	213.9	Air-acetylene	0.5

Results and Discussion

This study was conducted with the aim of evaluating the analytical results of heavy metal concentrations in treated wastewater samples taken from different areas within the city of Mosul, and discussing them in the light of environmental standards adopted locally and internationally. These results are of particular importance due to their role in assessing the suitability of treated water for reuse, especially in the agricultural irrigation sector, which is one of the sectors most affected by the accumulation of inorganic pollutants such as heavy metals. The analysis focused on five main elements, namely lead (Pb), cadmium (Cd), iron (Fe), copper (Cu), and zinc (Zn), due to their serious environmental and health effects even at low concentrations [4]. The samples were subjected to analysis using an atomic absorber, and the results were compared with the standard determinants issued by the World Health Organization [8], the food and Agriculture Organization (FAO), in addition to the Iraqi standards for irrigation and drinking water.

The discussion in this section includes the observed variations in heavy metal concentrations between different sites, with an explanation of the possible causes that may be attributed to the different type of source (industrial, medical, residential), geographical location, and the efficiency of the processing units at each site [11,12]. A comparison was also made with the results of previous local and international studies to enhance the environmental understanding of the city of Mosul, and to clarify the extent of the challenges facing the safe reuse of treated water.

Iron concentration (Fe)

The iron concentrations in the water samples ranged from 0.000077 mg/l (Yarmouk apartments plant) to 0.01603 mg / l (Western Cement Plant drainage) [11]. Samples taken from hospitals and apartment treatment plants showed a concentration of less than 0.001 mg/l, while industrial discharges—including the eastern industrial zone (0.01565 mg/l), Rashidiya (0.01488 mg/L), and the discharge of the University of Mosul (0.01406 mg/l)—recorded relatively higher concentrations [11,13] despite this disparity, all samples remained below the WHO acceptable maximum limit for drinking water (0.3 mg/l).[14] Therefore, iron levels at all studied sites are within safe limits for human health and agricultural uses [15,16]. However, the accumulation of iron in pipes and soil over time, especially from industrial discharges, may affect the infrastructure and soil texture [17,18]. As shown in Figure (1).

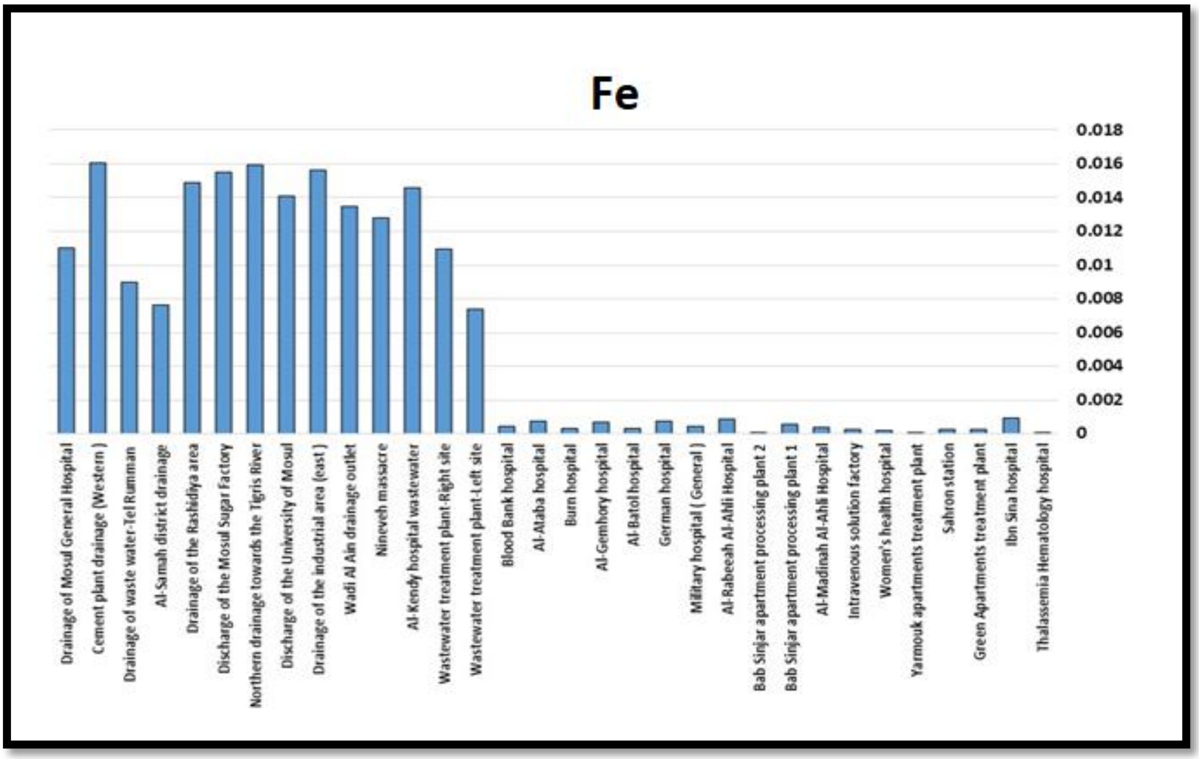

Figure (1): shows the Iron values in the water of the sites covered in this study.

Lead (Pb)

The lead concentrations in the analyzed samples ranged from 0.000721 mg/L at the Yarmouk apartments treatment plant to 0.007151 mg/L at the Burn Hospital [11]. The majority of samples from medical facilities such as Avicenna hospital (0.002105 mg/l), Women's care hospital (0.002683 mg/L), and Republican hospital (0.006207 mg/l) showed moderate levels of lead, while some private hospitals and apartment treatment plants recorded lower values. Industrial wastes such as Mosul Sugar Factory (0.005259 mg/L) and Mosul University discharge (0.005264 mg/l) approached the upper limit of the range, but remained below the WHO guideline limit for drinking water (0.01 mg / l) [14] and these results indicate that lead levels are generally acceptable for agricultural reuse and for non-potable domestic uses [13,15]. However, continued exposure at elevated levels may require long-term monitoring due to lead accumulation and its toxic effects on health and the environment [17,18]. Figure (2) shows the lead concentrations.

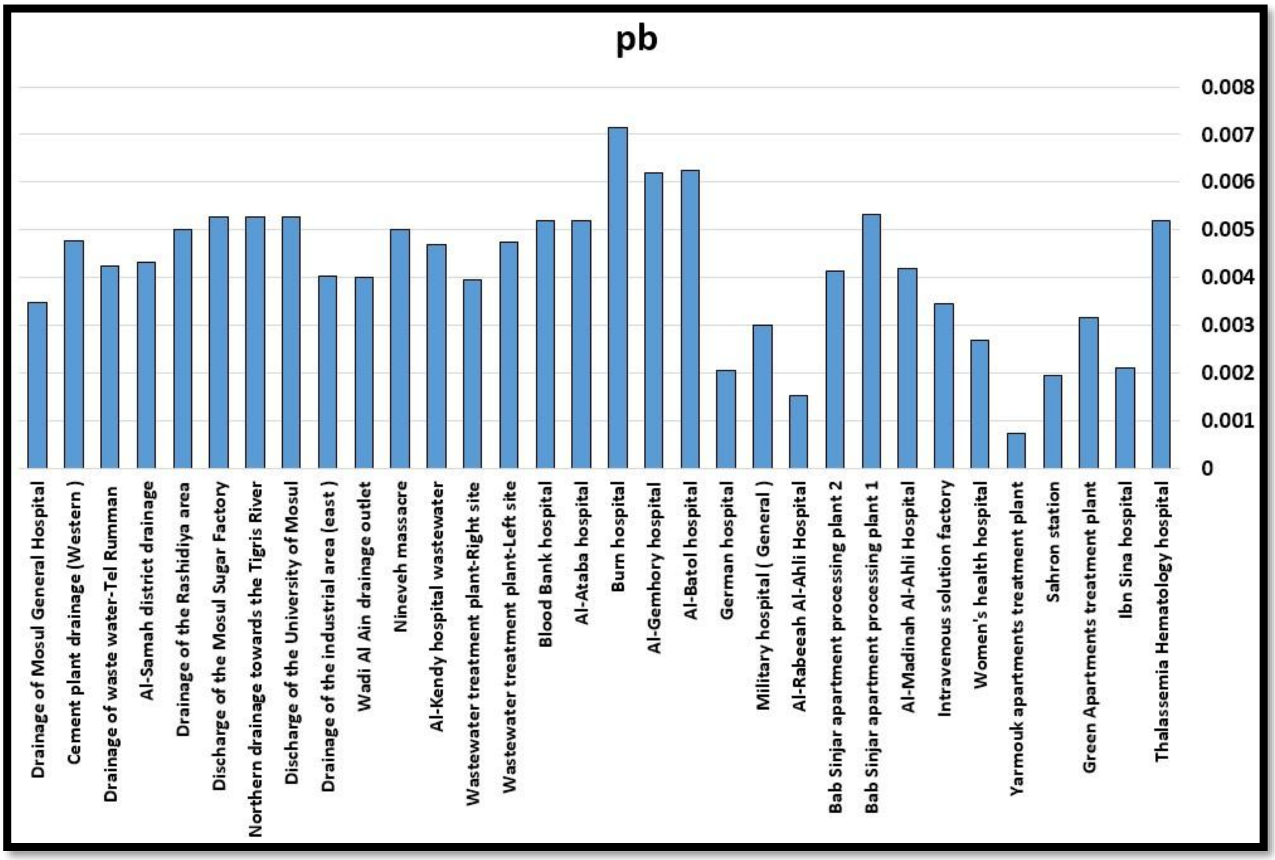

Figure (2): shows the lead values in the water of the sites covered in this study.

Cadmium (CD)

Cadmium levels showed significant variability between the sampled sites. The lowest concentration was recorded at the Yarmouk apartments treatment plant (0.000216 mg/l), while the highest concentration was found in the discharge of the University of Mosul (0.094 mg/l) [11] and this value has significantly exceeded the WHO guideline limit for drinking water (0.003 mg/l) [14]. Similarly, several other sites—including the Al—Kindi hospital wastewater (0.054 mg/l), Nineveh massacre (0.055 mg/l), Wadi Al-Ain outlet (0.056 mg/L), the eastern industrial zone drainage (0.061 mg/L), and the northern Tigris River drainage (0.074 mg/l) - showed elevated levels of cadmium that exceeded the limits of drinking water and agricultural reuse [13,15] These results indicate widespread and potentially dangerous cadmium contamination in several parts of Mosul's sewage structure, especially those associated with industrial areas and major treatment exits. These high levels pose a serious risk to soil health and food safety if reused for irrigation without adequate treatment [17,18]. Figure (3) shows cadmium concentrations.

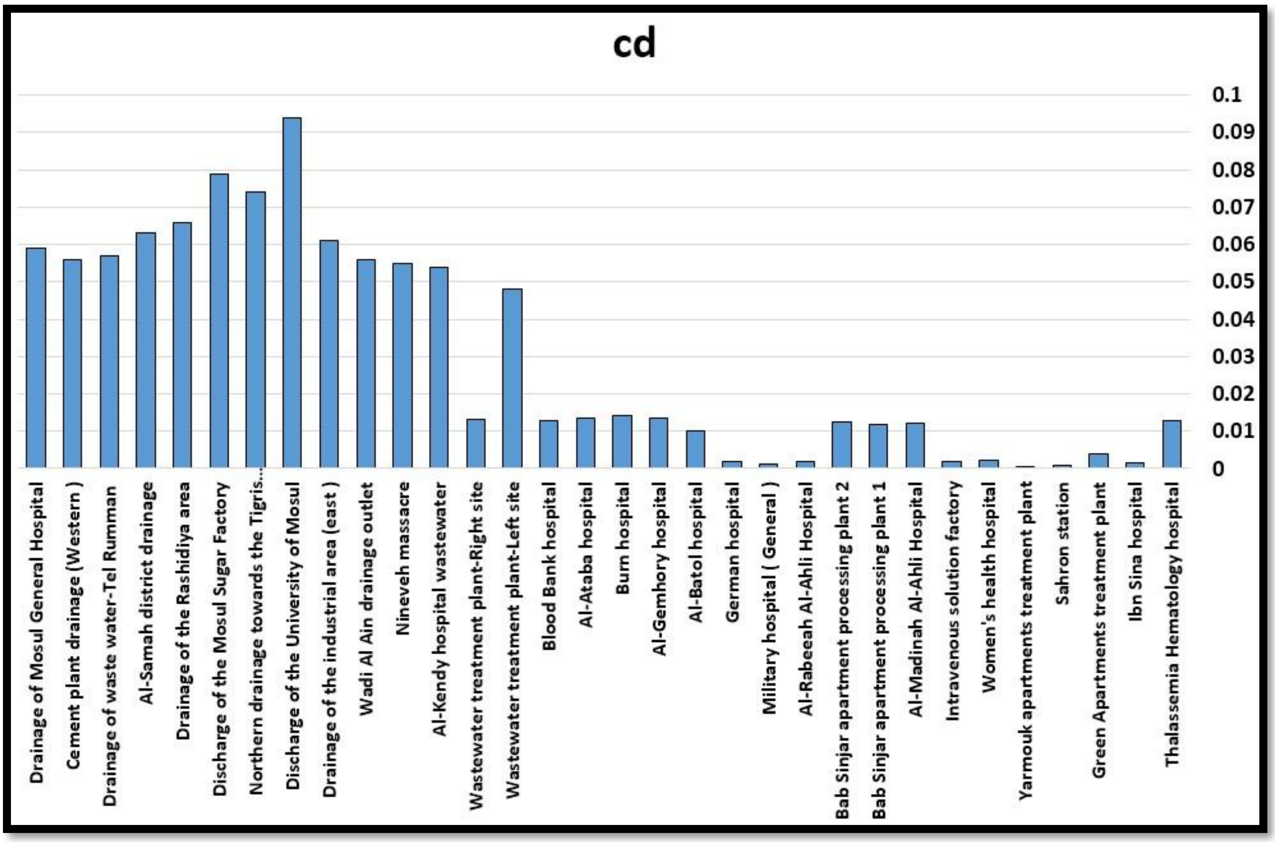

Figure (3): shows the cadmium values in the water of the sites covered in this study.

The results of the analysis indicate the presence of elevated cadmium levels in most of the study samples, which requires a comprehensive assessment of the efficiency of medical and industrial treatment plants, as well as the development of more stringent strategies for monitoring effluent discharge. The study recommends the need to introduce advanced treatment techniques to reduce the accumulation of cadmium, and ensure that it does not affect public health and the environment.

Zinc concentration (Zn)

Zinc concentrations ranged from 0.000074 mg/L in the wastewater of Al–Kindi hospital to 0.00848 mg / L in the wastewater treatment plant-Left Bank [11]. Most samples showed zinc levels below 0.005 mg / l, including hospital discharges and residential apartment treatment plants [15]. While industrial wastes recorded slightly higher concentrations, they remained well below the WHO guideline limit for drinking water (3.0 mg/L) and the FAO limit for irrigation (2.0 mg/l) [19,20]. These results indicate that zinc, although present, does not pose an acute environmental or health hazard in the studied wastewater [13]. However, very low zinc concentrations at some hospital sites may reflect dilution effects or reduced drug and metal residues [17] based on this, figure (4) shows zinc concentrations.

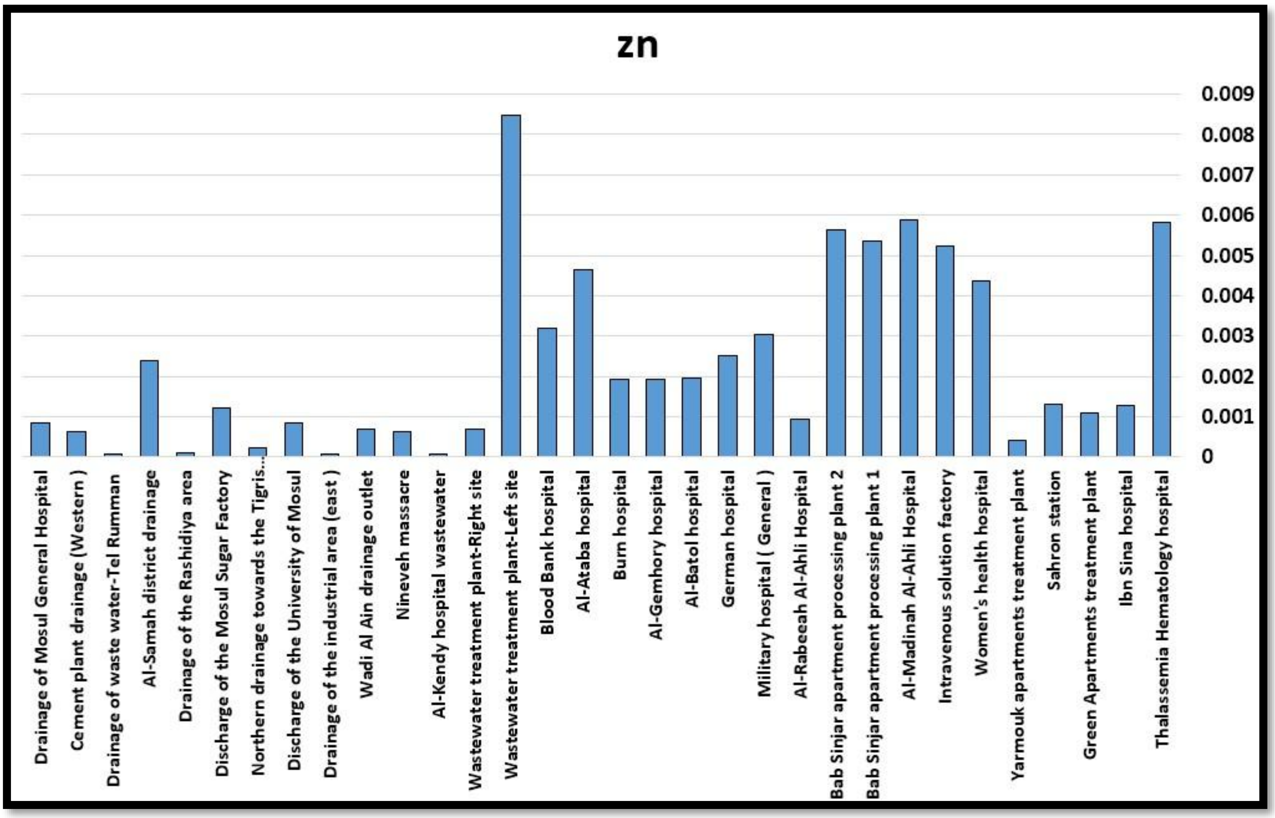

Figure (4): shows the zinc values in the water of the sites covered in this study.

The results of zinc analysis show that all concentrations recorded in wastewater samples in Mosul are within the safe limits allowed for human and agricultural uses, according to Iraqi and international standards [19-21] due to the acceptable efficiency shown by treatment plants, especially in service sites such as hospitals and apartment stations, which recorded.

Copper concentration (Cu)

Copper concentrations showed marked variability, with the lowest concentration recorded at the Green Apartments treatment plant (0.001116 mg/L) and the highest concentration in the Tel Rumman wastewater discharge (0.204 mg/l) [11]. Other sites with high concentrations included Al-Samah district (0.183 mg/l), Mosul Sugar Factory (0.176 mg/L), and Mosul University discharge (0.175 mg/l) [11,21]. These values have approached or slightly exceeded the FAO guideline limit for irrigation (0.2 mg/l) [20], but are still within the WHO maximum allowable limit for drinking water (2.0 mg/l) [19]. In contrast, the majority of hospital and residential sources showed relatively low concentrations of copper, usually less than 0.004 mg/l [11]. These results highlight a clear discrepancy between hospital discharges and industrial or mixed discharges, as the latter pose a greater risk in relation to the accumulation of copper in agricultural soils and crops [22,23]. Figure shows (5) copper concentrations.

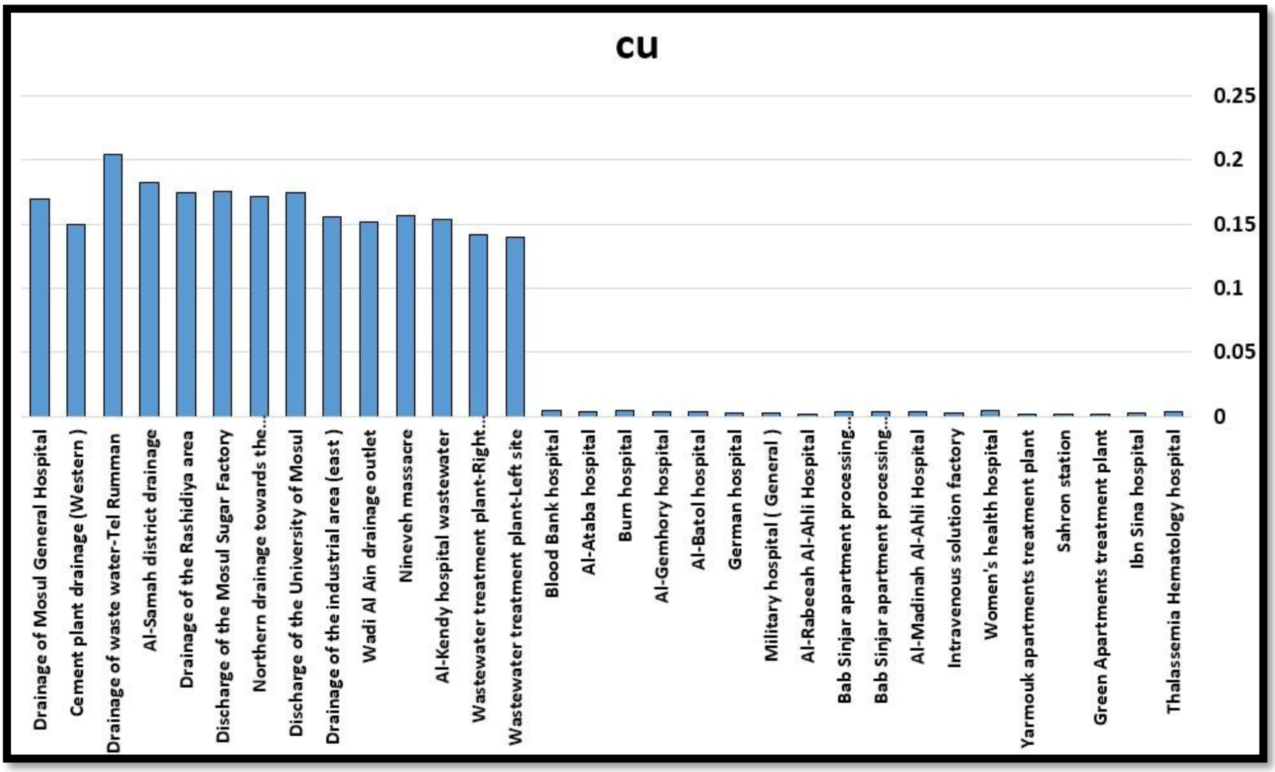

Figure (5): shows the copper values in the water of the sites covered in this study.

The results of the study show that copper concentrations in the wastewater of Mosul are within the permissible limits for drinking and irrigation water, which indicates its suitability for civil and agricultural uses in general. However, some drainage sites, such as Tel Rumman and Al-Samah, recorded concentrations approaching the maximum allowable limit for irrigation according to the FAO classification, which requires periodic environmental monitoring. High concentrations are due to industrial and medical waste, while low values at service stations reflect acceptable processing efficiency.

Comparative Distribution by Source Type and conformity with international standards

The results of the analysis of heavy metal concentrations in treated wastewater, as shown in Table (3), showed distinctive patterns when classifying samples by source type, where clear differences in concentrations emerged depending on the origin of the water. With regard to medical facilities, such as hospitals, generally low to moderate concentrations of most of the five metals were recorded, with some notable exceptions, especially in the burn hospital and the Republican hospital, where high levels of lead and cadmium were recorded. As for the industrial sources, such as the Western Cement plant, the eastern industrial zone and the Tel Rumman site, the highest concentrations of cadmium, copper and iron were detected, indicating direct contributions from untreated industrial waste [11,15]. On the other hand, the wastewater coming out of the public treatment plants showed a clear contrast between the Right-Bank and Left-Bank plants. The Left Bank station recorded high levels of cadmium and zinc, while the Right Bank station was more contaminated with iron and copper elements. Discharges from universities and slaughterhouses also showed relatively high levels of cadmium and copper, reflecting the possibility of laboratory waste or biomedical waste leaking into the drainage [13].

In terms of geographical distribution, it was noted that the highest concentrations of heavy metals, especially cadmium and copper, were concentrated in the drainage areas located south and southwest of the city of Mosul, areas close to large industrial clusters and high-density residential areas. This spatial distribution indicates the need to adopt ad hoc local treatment strategies, applying control protocols designed based on the level of environmental hazards associated with each region [20].

When comparing the results with the international determinants issued by the World Health Organization (WHO) and the food and Agriculture Organization (FAO), the data showed the following: lead concentrations were within the permissible limits for all sites, indicating that there was no immediate danger related to the use of this water for drinking or irrigation. For zinc and iron, all sites have recorded concentrations that fully comply with international standards. As for copper, concentrations at most sites were within the permissible limits, with some cases approaching the upper permissible limit for irrigation. In contrast, cadmium has been a major environmental concern, with concentrations exceeding permissible limits in several locations, an indication of potential risks when reusing this water without additional treatment [8,20]. The presence of these varying concentrations of heavy metals in treated wastewater underscores the environmental and health challenges facing urban and industrial cities such as Mosul. The results of this study highlight the need to develop integrated management plans that include effective treatment, continuous monitoring and reduction of polluting sources, especially in areas with high industrial pollution, to ensure that treated water can be safely used in agriculture without endangering human health or the environment [18].

Table (3): shows the results of the analysis of heavy metal concentrations in treated wastewater

ID	Location Name	Pb	Cd	Zn	Fe	Cu
1	Thalassemia Hematology hospital	0.005204	0.01264	0.005826	0.000086	0.003806
2	Ibn Sina hospital	0.002105	0.001523	0.001268	0.000916	0.002061
3	Green Apartments treatment plant	0.003166	0.004026	0.001081	0.000283	0.001116
4	Sahron station	0.00194	0.000781	0.001311	0.000254	0.001453
5	Yarmouk apartments	0.000721	0.000216	0.000415	0.000077	0.001336

	treatment plant					
6	Women's health hospital	0.002683	0.002088	0.004375	0.000186	0.00423
7	Intravenous solution factory	0.003457	0.002003	0.005225	0.000243	0.002426
8	Al-Madinah Al-Ahli Hospital	0.004183	0.01219	0.005879	0.000357	0.003098
9	Bab Sinjar apartment processing plant 1	0.005323	0.01185	0.005367	0.000546	0.003379
10	Bab Sinjar apartment processing plant 2	0.004145	0.01237	0.005631	0.000078	0.003823
11	Al-Rabeeah Al-Ahli Hospital	0.001527	0.001773	0.000953	0.000861	0.001426
12	Military hospital (General)	0.003009	0.001318	0.003052	0.000419	0.00231
13	German hospital	0.002036	0.001744	0.002503	0.000741	0.002051
14	Al-Batol hospital	0.006248	0.01013	0.001961	0.000342	0.003498
15	Al-Gemhory hospital	0.006207	0.01352	0.001923	0.000713	0.003796
16	Burn hospital	0.007151	0.01409	0.001916	0.000339	0.004761
17	Al-Ataba hospital	0.005196	0.01332	0.004647	0.000724	0.003997
18	Blood Bank hospital	0.005193	0.0127	0.003206	0.000451	0.004255
19	Wastewater treatment plant-Left site	0.004733	0.048	0.00848	0.007404	0.14
20	Wastewater treatment plant-Right site	0.003955	0.013	0.000703	0.01098	0.142
21	Al-Kendy hospital wastewater	0.004687	0.054	0.000074	0.01459	0.154
22	Nineveh massacre	0.004995	0.055	0.000635	0.01277	0.157
23	Wadi Al Ain drainage outlet	0.00401	0.056	0.000691	0.01346	0.152
24	Drainage of the industrial area (east	0.004024	0.061	0.000081	0.01565	0.156

25	Discharge of the University of Mosul	0.005264	0.094	0.000852	0.01406	0.175
27	Northern drainage towards the Tigris River	0.005259	0.074	0.000225	0.01593	0.172
28	Discharge of the Mosul Sugar Factory	0.005259	0.079	0.001203	0.01552	0.176
29	Drainage of the Rashidiya area	0.005004	0.066	0.000116	0.01488	0.175
30	Al-Samah district drainage	0.004308	0.063	0.00239	0.007606	0.183
32	Drainage of waste water-Tel Rumman	0.004238	0.057	0.00008	0.009015	0.204
33	Cement plant drainage (Western)	0.004776	0.056	0.000644	0.01603	0.15
34	Drainage of Mosul General Hospital	0.00347	0.059	0.000843	0.01102	0.17

The results of this research indicate that wastewater in Mosul contains varying concentrations of heavy metals, where the concentrations of some elements, such as lead (Pb), copper (Cu) and iron (Fe), exceeded the permissible limits according to Iraqi environmental standards (specification 417 of 2009) and who standards, especially in samples from industrial and medical sources. While cadmium (Cd) concentrations remained within the acceptable range at most sites, their approach to the upper limit in some samples foreshadows a possible cumulative Hazard. As for zinc (Zn), its results showed regularity within the permissible limits, without indications of immediate environmental or health effects [24,25]. These results reflect the uneven efficiency of treatment plants in removing heavy metals, especially at sites that do not adopt advanced treatment technologies or lack separation of domestic and industrial drainage. Its reflects the limited suitability of treated water for residential or environmentally sensitive applications, while it can be considered relatively suitable for some limited agricultural uses, provided that it is not used to irrigate food crops directly. The results also confirm the need to modernize the processing units at existing plants, adopt more sophisticated treatment systems, such as membrane filtration or adsorption on nanomaterials, as well as establish strict and regular environmental control programs [8,20].

These results are consistent with the findings of previous local studies [24,25], which highlighted the poor efficiency of conventional treatment in removing heavy elements, and showed the possible environmental and health impacts caused by the discharge of insufficiently treated water to the surrounding environment.

References

1) UN-Water. (2021). *World water development report 2021: Valuing water*. UNESCO.
2) Qadir, M., Wichelns, D., Raschid-Sally, L., et al. (2010). The challenges of wastewater irrigation in developing countries. *Agricultural Water Management, 97*(4), 561–568. https://doi.org/10.1016/j.agwat.2009.09.008
3) World Health Organization. (2017). *Guidelines for drinking-water quality* (4th ed.). WHO.
4) Jaishankar, M., Tseten, T., Anbalagan, N., Mathew, B. B., & Beeregowda, K. N. (2014). Toxicity, mechanism and health effects of some heavy metals. *Interdisciplinary Toxicology, 7*(2), 60–72. https://doi.org/10.2478/intox-2014-0009
5) Alloway, B. J. (2013). *Heavy metals in soils: Trace metals and metalloids in soils and their bioavailability*. Springer.
6) Tchounwou, P. B., Yedjou, C. G., Patlolla, A. K., & Sutton, D. J. (2012). Heavy metal toxicity and the environment. *EXS, 101*, 133–164. https://doi.org/10.1007/978-3-7643-8340-4_6
7) Al-Mosuli, M., Al-Jassim, N., & Khalaf, H. (2020). Assessment of wastewater treatment challenges in Mosul city, Iraq. *Environmental Monitoring and Assessment, 192*(5), 301. https://doi.org/10.1007/s10661-020-8220-4
8) World Health Organization. (2023). *Guidelines for drinking-water quality, 4th edition with updates*. WHO.
9) Food and Agriculture Organization. (2021). *Water quality for agriculture: FAO irrigation and drainage paper 29, Rev. 1*. FAO.
10) American Public Health Association. (2017). *Standard methods for the examination of water and wastewater* (23rd ed.). APHA.
11) Al-Jassim, N., Al-Mosuli, M., & Khalaf, H. (2020). Heavy metals in wastewater of Mosul city. *Journal of Water Pollution and Purification Research, 7*(2), 45–56.
12) Ali, Z. S., Mahmood, A. A., & Ahmed, R. (2019). Assessment of heavy metals pollution in wastewater from different districts of Mosul. *Iraqi Journal of Science, 60*(6), 1241–1253. https://doi.org/10.24996/ijs.2019.60.6.12
13) Zhang, X., Wang, L., & Li, J. (2021). Spatial distribution and risk assessment of heavy metals in industrial wastewater. *Environmental Science and Pollution Research, 28*(15), 18520–18531. https://doi.org/10.1007/s11356-020-12089-3
14) World Health Organization. (2017). *Guidelines for drinking-water quality* (4th ed.). Geneva, Switzerland: WHO.
15) Saeedi, M., Mousavi, S. F., & Ghasemi, S. (2019). Assessment of heavy metals contamination in agricultural soils irrigated with treated wastewater. *Environmental Monitoring and Assessment, 191*(4), 238. https://doi.org/10.1007/s10661-019-7386-6
16) United States Environmental Protection Agency. (2022). *National primary drinking water regulations*. Washington, DC: EPA.

17) Wu, F., Zhang, S., & Liu, Y. (2020). Impact of heavy metal accumulation on soil properties and infrastructure. *Journal of Environmental Management, 256*, 109984. https://doi.org/10.1016/j.jenvman.2019.109984

18) Jaishankar, M., Tseten, T., Anbalagan, N., Mathew, B. B., & Beeregowda, K. N. (2019). Toxicity, mechanism and health effects of some heavy metals. *Interdisciplinary Toxicology, 12*(1), 60–72. https://doi.org/10.2478/intox-2019-0009

19) World Health Organization. (2017). *Zinc in drinking-water: Background document for development of WHO guidelines for drinking-water quality*. WHO.

20) Food and Agriculture Organization. (2018). *Water quality for agriculture: FAO irrigation and drainage paper 29, Rev. 1*. Rome, Italy: FAO.

21) Mahmoud, S. A., Hassan, H. A., & Ibrahim, M. A. (2021). Assessment of heavy metals contamination in wastewater and its environmental impact. *Environmental Science and Pollution Research, 28*(12), 14725–14734. https://doi.org/10.1007/s11356-020-12159-2

22) Chen, Y., Wu, F., & Wang, L. (2019). Effects of heavy metals accumulation on soil and crop safety: A review. *Environmental Pollution, 254*, 112976. https://doi.org/10.1016/j.envpol.2019.112976

23) Ali, Z. S., Mahmood, A. A., & Ahmed, R. (2023). Heavy metals pollution in agricultural soils irrigated with treated wastewater in Mosul. *Iraqi Journal of Science, 64*(3), 845–856. https://doi.org/10.24996/ijs.2023.64.3.19

24) Al-Jubouri, A. A., Al-Khateeb, S. A., & Al-Jumaili, A. S. (2017). Assessment of heavy metals in wastewater and their impacts on environment in Mosul city. *Iraqi Journal of Environmental Science, 27*(4), 45–54.

25) Hussein, M. H. (2020). Evaluation of wastewater treatment efficiency and heavy metals contamination in Mosul. *Mosul Journal of Engineering, 28*(1), 72–81.