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Trace Metals in *Unio tigris* Mussels at Tigris River in Maysan Governorate, Southern Iraq

Zahraa S. Al-Shamse[1], Maha K. Al-Mishrey[2], Altaf R. Shnaishe[4], Fadhal J. Farhan[3], Salah M. Saleh[3], Hamid T. Al-Saad[3]*

[1]College of Science, Department of Geology, University of Basrah, Iraq
[2]College of Science, Department of Biology, University of Basrah, Iraq
[3]College of Marine Science, University of Basrah, Iraq
[4]Ministry of Education General, Directorate for Education in the province of Maysan, Iraq

*** Corresponding Author: htalsaad@yahoo.com**

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BSTRACT

This study evaluated the concentrations of several heavy metals – lead (Pb), nickel (Ni), copper (Cu), zinc (Zn), cobalt (Co), cadmium (Cd), and iron (Fe) – in the tissues of the freshwater mussel *Unio tigris* collected from seven locations along the Tigris River in Maysan Governorate, southern Iraq. The analysis was performed using Inductively Coupled Plasma (ICP) spectroscopy. The results revealed significant variation in metal concentrations across the study area. Overall, high accumulations of the measured metals were observed in the mussels. The average concentrations in the mussel tissues decreased in the order: Fe > Co > Ni > Zn > Cu > Pb > Cd. Lower mean concentrations at certain sites appeared to correspond with fewer pollution sources in those regions, whereas higher mean concentrations at other sites (such as the Al-Eimarah stations) were associated with numerous pollution sources. The pollution levels in *Unio tigris* were further examined using the contamination factor (CF), enrichment factor (EF), geo-accumulation index (I-geo), and pollution load index (PLI). The findings from this research provide valuable baseline data on trace metal accumulation in mussel tissues, which can inform efforts to control potential poisoning from trace metal exposure and serve as reference information for assessing heavy metal pollution in aquatic ecosystems.

INTRODUCTION

The Tigris River is an important water resource that supplies major cities in Turkey and Iraq. Today, the Tigris is a seasonal river due to numerous upstream water resource projects. In winter and spring, the upper reaches of the river carry large amounts of runoff from surrounding landscapes, leading to an influx of sediments and associated materials. As waters flow downstream, evaporation causes further concentration of dissolved substances.

To regulate these fluctuations, large dams have been constructed; however, the impounded waters can significantly affect water quality and human health. Aquatic bivalves such as mussels tend to accumulate trace elements from their environment, especially once they reach maturity, resulting in high levels of these elements in their tissues **(Gao *et al.*, 2021; Jeong *et al.*, 2021)**. Therefore, examining the concentrations of trace elements in mussels over a broad area can provide insight into the spatial distribution of pollution in the river. Trace metals are natural components of the Earth's crust that can be mobilized by both natural processes and human activities. The term "trace metal" usually refers to heavy metals, which are high-density metallic elements that can be toxic, even at low concentrations.

Studies have identified up to 70 elements in various mussel samples, encompassing essential elements, non-essential elements, and metalloids. These categories are based on the biological role of the elements: Essential elements are required for physiological and enzymatic functions, whereas non-essential elements and certain metalloids may have no biological role and can be harmful at elevated levels. Toxic effects can occur when heavy metals exceed certain thresholds, and even at lower levels these metals may interfere with biological processes **(Pasinszki *et al.*, 2023)**.

Mussels are useful bioindicators for monitoring water pollution, as they are sessile and accumulate contaminants present in their environment **(Alvarez *et al.*, 2021; Farhan *et al*., 2025; Saleh *et al*., 2025)**. The degree of metal pollution in mussels reflects the pollution in the river because mussels occupy higher trophic levels and thus integrate contaminants from their food and water **(Xie *et al*., 2023)**. When mussels die, their shells (composed largely of calcium carbonate) are left on riverbanks and gradually decompose. Many studies have examined mussels using various preparation methods to determine metal concentrations **(Istanbullu *et al.*, 2023)**, highlighting the importance of consistent methodologies for comparing results. The clam species *Unio tigris* is a benthic, filter-feeding mollusk commonly found in the Tigris River. Its life cycle is closely tied to the river's ecological conditions. Research has shown that mollusks living in polluted waters are effective indicators of environmental health, particularly regarding inorganic pollutants **(Esmaili-Sari *et al.*, 2021)**. Numerous studies have demonstrated that bivalves serve as valuable biomonitors of heavy metal pollution. Recent investigations have noted the strong capacity of *Unio tigris* to accumulate trace metals in the Tigris River and other water bodies **(Mbadra *et al.*, 2021)**. By collecting mussels from specific locations and analyzing them with adequate sample replication, researchers can gauge the level of exposure to heavy metals. Chemical analyses of these mussels allow for the calculation of hazard indices, aiding in the interpretation of trace metal accumulation. However, when only a limited number of samples are analyzed, any increase in metal levels must be carefully evaluated against existing environmental benchmarks **(Moretzsohn, 2023)**. Studies of heavy metal concentrations aim to clarify the extent of metal contamination at highly industrialized and urbanized sites. Such information is critical for human health risk assessments and for understanding the condition of valuable natural river ecosystems. *Unio*

tigris is considered a suitable biomonitor for heavy metals due to its capacity to bioaccumulate these elements, its sedentary nature in the river, and its ecological and economic importance (through fisheries and ecosystem services). Large individuals of *Unio tigris* can be easily collected in shallow waters, facilitating both tissue analysis and histological studies. These mussels could potentially be used as a food source if contaminant levels are below safety thresholds for human consumption; thus, determining their heavy metal burden is also relevant for food safety.
The aim of the present study was to determine and compare the levels of selected trace metals in *Unio tigris* mussels collected from seven different locations along the Tigris River in Maysan Governorate, with particular attention to cadmium (Cd) and lead (Pb). In this work, concentrations of Fe, Cd, Pb, Cu, Ni, Zn, and Co in the soft tissues of *Unio tigris* were measured using ICP analysis. This study provides comparative data on trace metal contamination across multiple river sites, which can inform assessments of environmental pollution and potential health risks. The findings are intended to serve as baseline information for environmental monitoring and management, helping to evaluate the extent of heavy metal pollution in the Tigris River ecosystem and guiding efforts to mitigate anthropogenic impacts **(Oleiwi & Al-Dabbas, 2022; Varol *et al.*, 2022)**.

MATERIALS AND METHODS

This research was conducted along the Tigris River in Maysan Governorate, Iraq. Combustion processes (e.g. from industry and fossil fuel use) are a primary contributor to trace element pollution in this region's river water. The native population of *Unio tigris* in Maysan is largely confined to the muddy riverbanks and mudflats of the Tigris River (Fig. 1). During 2024, seven study locations (Fig. 2) were selected along the river. In each location, live mussels were placed or identified at approximately 20cm depth below the water surface. These seven sites spanned the upstream to downstream extents of the river within the governorate. The Tigris and Euphrates are the two major rivers of Iraq, both originating in Turkey; the Tigris in particular has been central to many civilizations (including ancient Mesopotamia) and continues to be critical for the region.

Sample preparation and analysis

Upon collection, the external shells of the mussels were scrubbed with a sponge under tap water to remove silt and debris. The mussels were then rinsed thoroughly with tap water. Soft tissues were carefully dissected out from each mussel and air-dried at room temperature. The dried tissue samples were homogenized using a stainless-steel grinder, and the powdered tissue from each individual was stored in labeled containers until analysis. Triplicate mussel samples were prepared from each site, and the results for each site were averaged.

Fig. 1. *Unio* Tigris

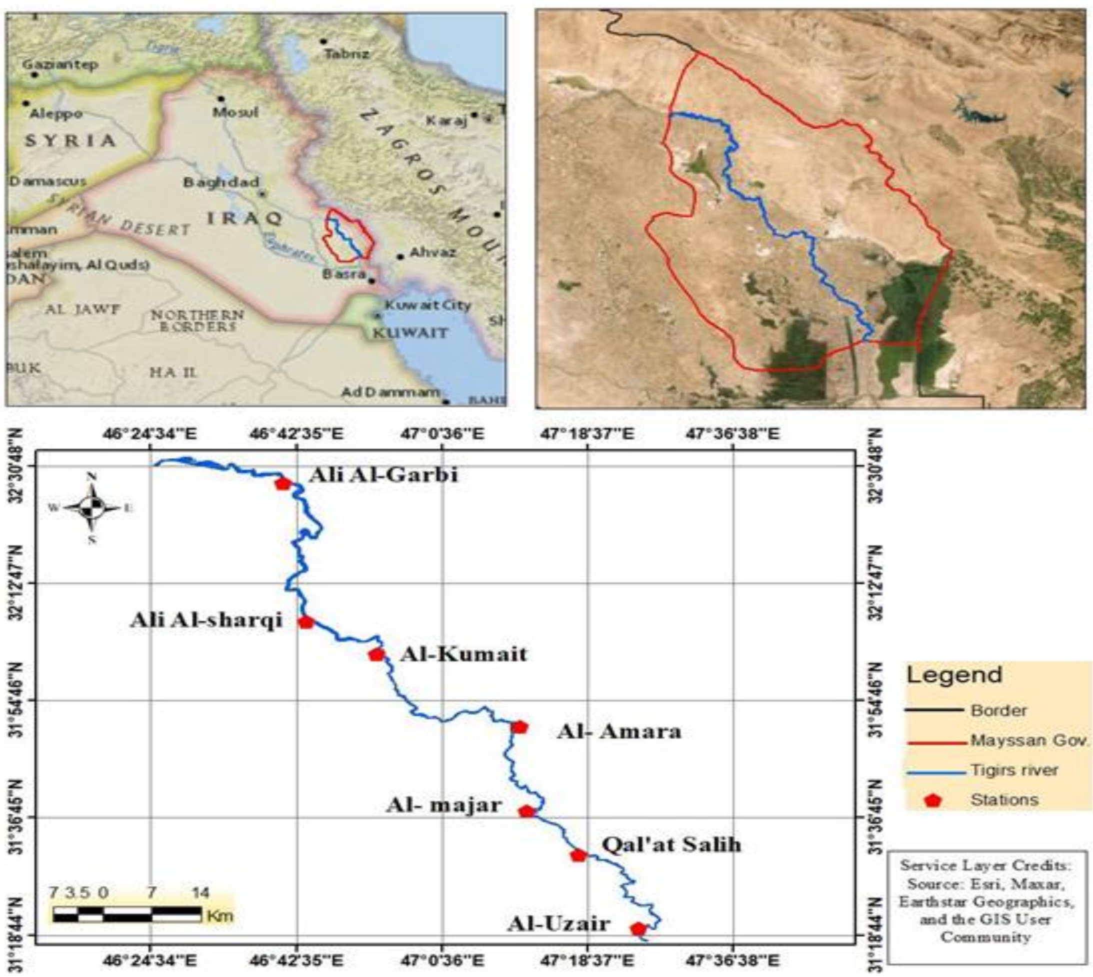

Fig. 2. The study area and stations

Each dried, homogenized tissue sample (approximately 2g) was digested using a mixture of concentrated nitric acid (HNO_3) and hydrogen peroxide (H_2O_2). The sample was placed in a Teflon digestion vessel with the acids, and the temperature was gradually increased from 70 to 170°C following a programmed schedule. After cooling, the digestate was transferred to a volumetric flask and was diluted with deionized water to a final volume of 25mL. All sample solutions were stored at 4°C until analysis. Blank samples and reference materials were subjected to the same digestion procedure to ensure accuracy and to account for any background contamination **(Bankaji *et al.*, 2023)**.

The concentrations of trace metals in the digested mussel samples were determined using inductively coupled plasma (ICP) spectroscopy following the methods of **Gomez-Delgado *et al.* (2023)**. An internal standard was added to all samples to monitor and correct for any instrumental sensitivity fluctuations **(Pasinszki *et al*., 2023)**.

Quality assurance and control measures were implemented to ensure the reliability of the analytical results. The accuracy of the metal concentration measurements was verified using standard reference materials and reagent blanks. Recovery tests were performed by spiking known quantities of metals into mussel tissue samples and checking that the ICP analysis could recover these known amounts within acceptable limits. These QA/QC procedures confirmed that the analytical method was producing accurate and reproducible results. All data were accepted only if the blank readings were negligible and the recovery of spiked samples was within the acceptable range.

Contamination factor (CF)

The contamination factor (CF) was used to evaluate the level of heavy metal pollution in the environment by comparing metal concentrations in mussel tissue to baseline levels. CF is defined by the equation:

$$CF = Mc / Bc$$

Where, Mc is the measured concentration of the metal in the mussel tissue, and Bc is the background concentration of the same metal (e.g., a reference value representing an unpolluted condition). A CF value around 1 indicates that the metal level is similar to background levels, whereas values greater than 1 indicate enrichment relative to the background. According to **Hakanson (1980)**, higher CF values can be classified to indicate moderate, considerable, or very high contamination (Table 1).

Table 1. CF value according to **Hakanson (1980)**

CF	Indicate of contamination factor
CF<1	low contamination
1≤CF≤ 3	moderate contamination
3≤CF<6	considerable contamination
CF>6	very high contamination

Enrichment factor (EF)

The enrichment factor (EF) was calculated to infer the likely source of the metals (natural or anthropogenic) by normalizing metal concentrations to a reference element. EF is given by the formula:

EF = (CM / CFe) sample / (CM / CFe) Earth's crust

Where, CM / CFe is the ratio of the concentration of a given metal M to that of iron (Fe) in the mussel sample, and is the ratio of the concentration of the metal to Fe in the Earth's crust (taken as a reference baseline). In this study, iron (with a crustal abundance of about 5.2%) was used as the reference element due to its stability and crustal dominance **(Huheey, 1983)**. An EF value close to 1 suggests a crustal (natural) origin for the metal, whereas significantly higher EF values (≫1) indicate enrichment from anthropogenic sources. The classification of EF values (e.g., minimal, moderate, significant, or extreme enrichment) follows the criteria of **Huheey (1983)**, as shown in Table (2).

Table 2. CF value according to **Huheey (1983)**

EF	Indicates of enrichment factor
< 1	no enrichment
1-3	minor enrichment
3-5	moderate enrichment
5-10	moderate to severe enrichment
10-25	severe enrichment
25-50	very severe enrichment
50	extremely severe enrichment

Geo-accumulation index (I-geo)

The geo-accumulation index (I-geo) was used to assess the pollution status of the sediments in which mussels live, by comparing current metal concentrations to pre-industrial levels. I-geo was calculated using **Muller's (1969)** equation:

I-geo = log2 (Cn / 1.5 Bn)

Where, Cn is the measured concentration of element n in the mussel tissue (as a proxy for local sediment contamination), and Bn is the geochemical background concentration of that element (often from shale or crustal average). The factor 1.5 is a constant that accounts for natural fluctuations in the background values (to minimize overestimation of contamination). The I-geo scale classifies pollution levels into categories from 0 (unpolluted) to 6 (extremely polluted) based on the resulting value (Table 3).

Table 3. Igeo classification pollution scale

Igeo	Soil pollution case
1>	practically unpolluted- Background sample
2-1	unpolluted to moderately polluted
3-2	moderately polluted to polluted
4-3	strongly polluted
5-4	strongly to extremely polluted
5<	extremely polluted

Pollution load index (PLI)

The pollution load index (PLI) provides an overall indication of the total heavy metal pollution at a site by combining contamination factors of multiple metals. The PLI is calculated as the nth root of the product of n contamination factor values **(Tomlinson *et al*., 1980)**:

$$PLI = n\sqrt{}(CF_1 \times CF_2 \times CF_3 \times ... \times CF_n)$$

Where, $CF_1 \times CF_2 \times CF_3 \times ... \times CF_n$ are the contamination factors for the n metals of interest. In this study, n = 7 (for Fe, Co, Ni, Zn, Cu, Pb, Cd). A PLI value of 1 indicates baseline levels of metals (no overall pollution), >1 indicates pollution, and <1 would indicate no pollution (or metal depletion) relative to the background. Table (4) shows the classification of PLI values according to **Tomlinson *et al.* (1980)**.

Table 4. The classification of PLI values according to **Tomlinson *et al.* (1980)**

PLI	The indicates
value1 <	Pollution
value1 >	no pollution

RESULTS

The heavy metal concentrations measured in *Unio tigris* mussels from the seven study locations are presented in Tables (5–11) (one table per site) and Figs. (3–9). Overall, the data show distinct spatial variations in metal accumulation among the sites. Below, we summarized the peak (maximum) and lowest (minimum) concentrations for each metal across all stations:

- **Iron (Fe):** The highest Fe concentration was 2315.3µg/ g (dry weight) in mussels from Al-Eimarah 2 station, while the lowest was 1058.3µg/ g in mussels from Ali Al-Gharbi 1 station. Fe was the most abundant metal in all samples, consistent with it being a major element in natural sediments and soils.
- **Cobalt (Co):** The maximum Co level observed was 55.36µg/ g at Al-Eimarah 1 station, and the minimum was 21.63µg/ g at Ali Al-Gharbi 3 station.
- **Lead (Pb):** The highest Pb concentration (20.83µg/ g) was recorded at Al-Eimarah 3 station, whereas the lowest (10.51µg/ g) was found at Ali Al-Gharbi 2 station.
- **Cadmium (Cd):** Cd levels were generally low compared to other metals. The peak Cd concentration was 20.83µg/ g at Al-Eimarah 3 station, and the minimum was 10.32µg/ g at Ali Al-Gharbi 1 station.
- **Copper (Cu):** The highest Cu concentration of 25.46µg/ g was measured at Al-Eimarah 1 station, and the lowest value of 12.24µg/ g was at Al-Uzair 2 station.
- **Nickel (Ni):** Ni showed a maximum of 82.64µg/ g at Al-Eimarah 2 station and a minimum of 13.25µg/ g at Ali Al-Gharbi 1 station.
- **Zinc (Zn):** The highest Zn concentration was 33.46µg/ g in Al-Eimarah 3 station mussels, while the lowest was 10.52µg/ g in Ali Al-Gharbi 1 station.

These results indicate that the Al-Eimarah stations (particularly stations 1, 2, and 3 in the Al-Eimarah area) had the highest concentrations for most of the studied metals. In contrast, the Ali Al-Gharbi stations (especially station 1) often had the lowest metal concentrations. This pattern suggests that the pollution sources contributing to heavy metal contamination are more intense around the Al-Eimarah region than in Ali Al-Gharbi or Al-Uzair.

The EF analysis helps identify the source of these metals. Using Fe as a normalization reference, EF values for Pb and Cd were significantly greater than 1 at most stations, which points to an anthropogenic origin (such as industrial discharges or agricultural chemicals) for these metals. For instance, high EF for Pb suggests that lead is entering the river system from human activities (like fuel combustion or paints) rather than natural weathering. Conversely, metals like Fe and Ni had EF values closer to 1 at some sites, implying a stronger influence of natural sources (erosion of soil and rock) in those cases.

Table 5. Concentration of trace metals (µg/g dry weight) at Al-Uzair station

	Fe	Co	Pb	Cd	Cu	Ni	Zn
Al-Uzair1	**1220.3**	25.68	11.42	10.42	12.33	18.24	14.53
Al-Uzair2	**1225.2**	23.79	11.63	11.04	12.24	19.23	15.32
Al-Uzair3	**1293.1**	24.03	12.08	11.31	12.54	19.54	15.38

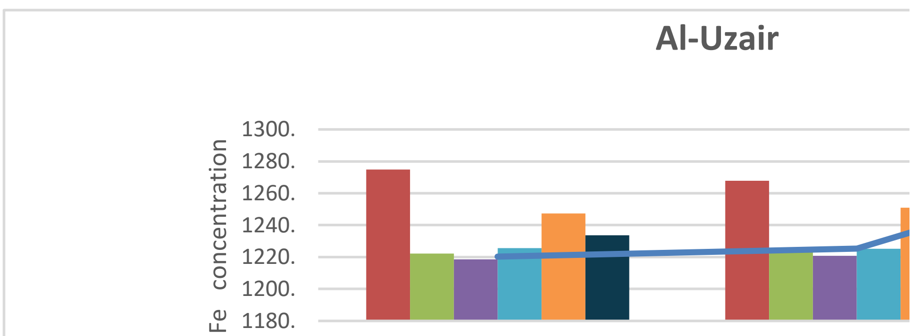

Fig. 3. Trace metals concentration in Al-Uzair station

Table 6. Concentration of trace metals (µg/g dry weight) in Qal'at Salih station

	Fe	Co	Pb	Cd	Cu	Ni	Zn
Qaleat **Salih1**	**1380.6**	28.52	15.23	12.22	16.45.	20.32	18.42
Qaleat **Salih2**	**1378.5**	29.31	14.78	12.63	16.54	20.42	18.54
Qaleat **Salih3**	**1385.4**	29.62	14.68	12.33	16.46	21.03	18.68

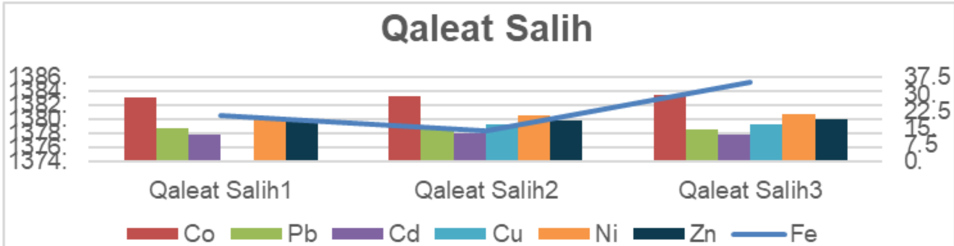

Fig. 4. Trace metals concentration in Qaleat Salih station

Table 7. Concentration of trace metals (µg/g dry weight) at Al-Eimarah station

	Fe	Co	Pb	Cd	Cu	Ni	Zn
Al-Eimarah1	**2122.6**	55.36	20.44	20.80	25.46	80.65	30.63
Al-Eimarah2	**2315.3**	53.72	20.54	20.79	24.74	82.64	32.54
Al-Eimarah3	**2250.8**	53.86	20.83	20.83	25.36	81.03	33.46

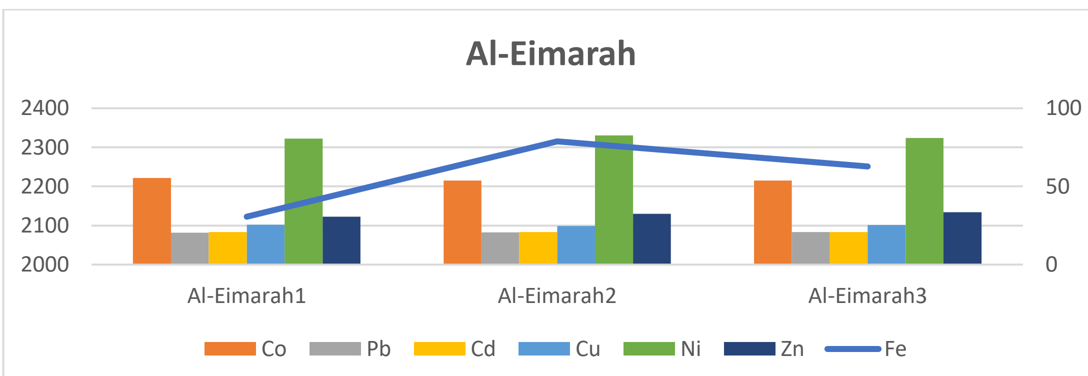

Fig. 5. Trace metals concentration in Al-Eimarah station

Table 8. Concentration of trace metals (µg/g dry weight) at Al-Majar station

	Fe	Co	Pb	Cd	Cu	Ni	Zn
Al-Majar1	**1420.3**	30.23	16.75	14.65	18.23	24.63	20.52
Al-Majar2	**1425.2**	30.64	16.82	14.67	18.42	25.28	21.32
Al-Majar3	**1423.3**	32.6	16.90	15.23	18.44	24.46	21.46

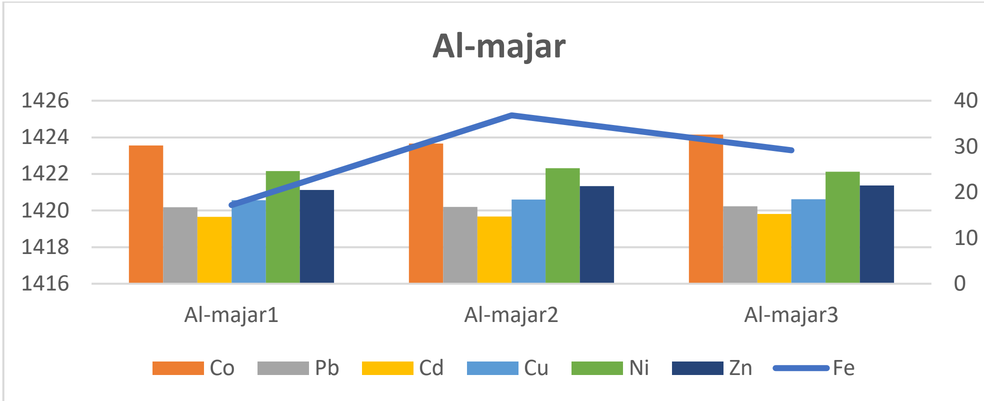

Fig. 6. Trace metals concentration at Al-Majar station

Table 9. Concentration of trace metals (µg/g dry weight) at Al-Kumait station

	Fe	Co	Pb	Cd	Cu	Ni	Zn
Al-Kumait1	**1870.6**	40.23	18.34	18.33	20.79	75.08	25.54
Al-Kumait2	**1850.8**	41.62	18.65	18.23	20.85	75.63	26.82
Al-Kumait3	**1880.7**	41.83	18.55	17.97	21.03	76.03	26.09

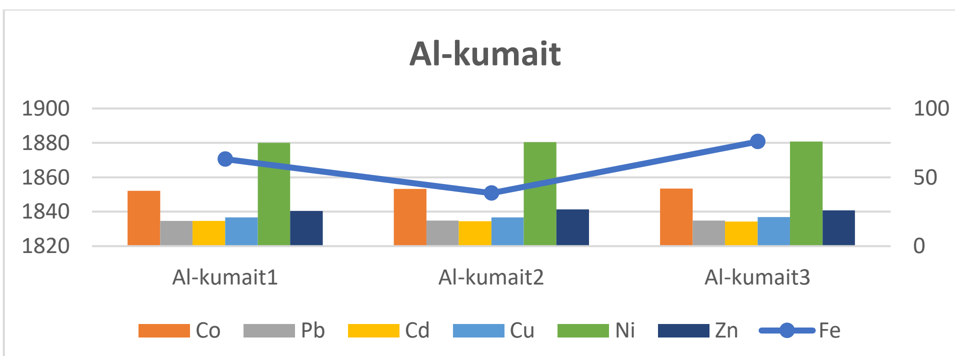

Fig. 7. Trace metals concentration at Al-Kumait station

Table 10. Concentration of trace metals (µg/g dry weight) at Ali Al-Sharqi station

	Fe	Co	Pb	Cd	Cu	Ni	Zn
Ali Al-Sharqi1	**1520.6**	30.52	15.35	16.25	19.23	17.65	12.54
Ali Al-Sharqi2	**1560.8**	31.63	15.26	16.23	19.83	17.45	12.30
Ali Al-Sharqi3	**1538.4**	31.84	15.43	16.42	20.65	18.35	12.58

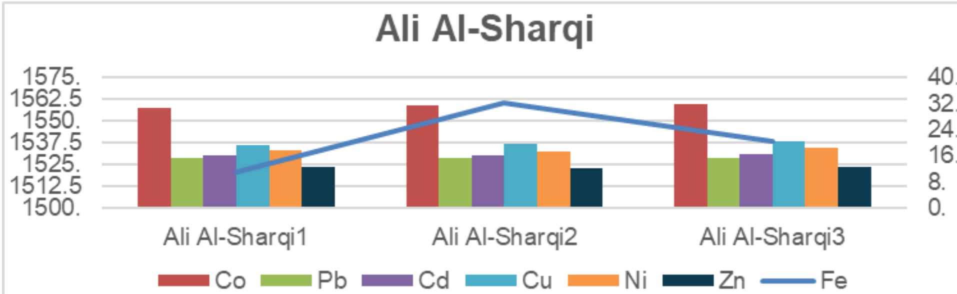

Fig. 8. Trace metals concentration at Ali Al-Sharqi station

Table 11. Concentration of trace metals (µg/g dry weight) at Ali Al-Gharbi station

	Fe	Co	Pb	Cd	Cu	Ni	Zn
Ali Al-Gharbi1	**1058.3**	22.62	10.92	10.32	13.98	13.25	10.52
Ali Al-Gharbi2	**1060.8**	21.85	10.51	10.43	12.87	14.63	10.55
Ali Al-Gharbi3	**1068.4**	21.63	10.62	10.40	12.89	14.84	10.58

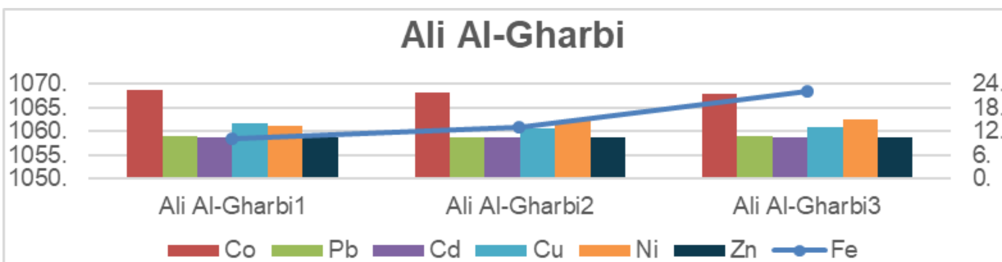

Fig. 9. Trace metals concentration at Ali Al-Gharbi station

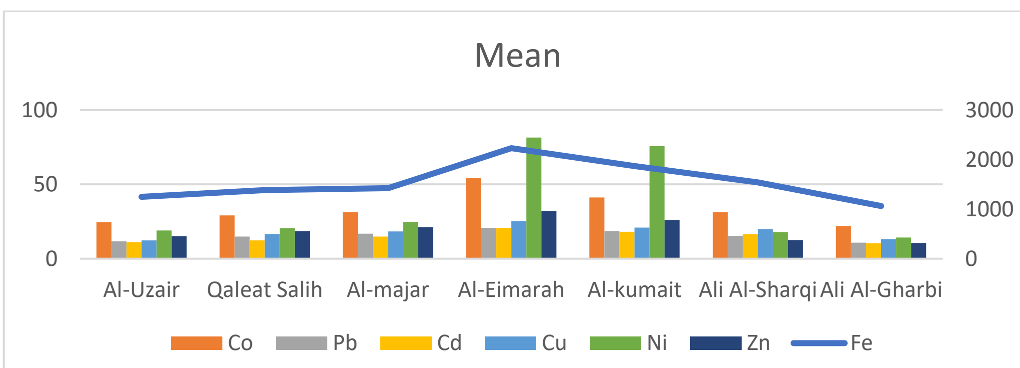

Fig. 10. Mean of trace metals at research site

Table 12. The contamination factor (CF) of minor elemental metals

Station	CF(FE)	CF(Co)	CF(Pb)	CF(Cd)	CF(Cu)	CF(Ni)	CF(Zn)
Al-Uzair	0.022	1.03	0.82	69.47	0.21	0.22	0.21
	0.022	0.95	0.83	73.60	0.20	0.23	0.22
	0.023	0.96	0.86	75.40	0.21	0.23	0.22
Qaleat Salih	0.025	1.14	1.09	81.47	0.27	0.24	0.26
	0.024	1.17	1.06	84.20	0.28	0.24	0.26
	0.025	1.18	1.05	82.20	0.27	0.25	0.27
Al-Majar	0.025	1.21	1.20	97.67	0.30	0.29	0.29
	0.025	1.23	1.20	97.80	0.31	0.30	0.30
	0.025	1.30	1.21	101.53	0.31	0.29	0.31
Al-Eimarah	0.038	2.21	1.46	138.67	0.42	0.96	0.44
	0.041	2.15	1.47	138.60	0.41	0.98	0.46
	0.040	2.15	1.49	138.87	0.42	0.96	0.48
Al-Kumait	0.033	1.61	1.31	122.20	0.35	0.89	0.36
	0.033	1.66	1.33	121.53	0.35	0.90	0.38
	0.033	1.67	1.33	119.80	0.35	0.91	0.37
Ali Al-Sharqi	0.027	1.22	1.10	108.33	0.32	0.21	0.18
	0.028	1.27	1.09	108.20	0.33	0.21	0.18
	0.027	1.27	1.10	109.47	0.34	0.22	0.18
Ali Al-Gharbi	0.019	0.90	0.78	68.80	0.23	0.16	0.15
	0.019	0.87	0.75	69.53	0.21	0.17	0.15
	0.019	0.87	0.76	69.33	0.21	0.18	0.15

The spatial differences in metal concentrations can be attributed to a combination of natural river processes and anthropogenic inputs. The Al-Eimarah area is more urbanized and industrialized, which likely introduces higher loads of contaminants such as Pb, Cd, and Ni through municipal wastewater, agricultural runoff, and industrial effluents. Upstream activities, including oil drilling and refining, can also contribute heavy metals that eventually settle in this area of the river. In contrast, Ali Al-Gharbi is less urbanized, resulting in comparatively lower anthropogenic input of these metals. Additionally, hydrological factors such as sediment deposition patterns could influence local metal concentrations; for example, slower-flowing sections near Al-Eimarah might promote the accumulation of metal-rich sediments.

Table 13. Pollution load index (PLI) of minor elemental metals for this study

Station	PLI		
Al-Uzair	**0.902**	**0.917**	**0.935**
Qaleat Salih	**1.099**	**1.108**	**1.110**
Al-Majar	**1.243**	**1.263**	**1.279**
Al-Eimarah	**2.075**	**2.086**	**2.104**
Al-Kumait	**1.754**	**1.785**	**1.776**
Ali Al-Sharqi	**1.098**	**1.103**	**1.129**
Ali Al-Gharbi	**0.803**	**0.797**	**0.799**

The calculated contamination factor values for each metal at each site provide insight into how polluted each location is relative to baseline levels. Many CF values were found to be greater than 1, confirming enrichment of metals in the mussels compared to expected background. In particular, Fe and Ni had especially high CF values at the Al-Eimarah stations, indicating those sites are considerably contaminated with respect to those metals. According to Hakanson's classification, some sites fell into the category of "very high contamination" for certain metals, notably Fe.

The enrichment factor analysis helps identify the source of these metals. Using Fe as a normalization reference, EF values for Pb and Cd were significantly greater than 1 at most stations, which points to an anthropogenic origin (such as industrial discharges or agricultural chemicals) for these metals. For instance, high EF for Pb suggests that lead is entering the river system from human activities (like fuel combustion or paints) rather than natural weathering. Conversely, metals like Fe and Ni had EF values closer to 1 at some sites, implying a stronger influence of natural sources (erosion of soil and rock) in those cases.

Table 14. Enrichment Factor (EF) of minor elemental metals

Station	EF (Fe)	EF(Co)	EF(Pb)	EF(Cd)	EF(Cu)	EF (Ni)	EF(Zn)
Al-Uzair	**1**	47.39	37.63	3204.93	9.48	10.02	7.98
	1	43.73	38.17	3382.04	9.37	10.52	8.38
	1	41.85	37.57	3282.82	9.10	10.13	7.97
Qaleat **Salih**	**1**	46.52	44.36	3322.16	11.18	9.86	8.94
	1	47.88	43.12	3438.85	11.26	9.93	9.01
	1	48.15	42.61	3340.45	11.15	10.17	9.04
Al-Majar	**1**	47.93	47.43	3871.46	12.04	11.62	9.68
	1	48.42	47.46	3863.42	12.13	11.89	10.03
	1	51.58	47.75	4016.25	12.16	11.52	10.11
Al-Eimarah	**1**	58.73	38.73	3678.00	11.26	25.47	9.67
	1	52.25	35.68	3370.27	10.03	23.92	9.42
	1	53.89	37.22	3473.52	10.57	24.13	9.96
Al-Kumait	**1**	48.43	39.43	3677.89	10.43	26.90	9.15
	1	50.64	40.52	3696.96	10.57	27.39	9.71
	1	50.09	39.66	3586.29	10.49	27.10	9.30

Ali Al-Sharqi	**1**	45.20	40.60	4011.03	11.87	7.78	5.53
	1	45.64	39.32	3902.91	11.92	7.49	5.28
	1	46.61	40.33	4006.09	12.60	7.99	5.48
Ali Al-Gharbi	**1**	48.13	41.49	3660.06	12.40	8.39	6.66
	1	46.39	39.85	3690.35	11.38	9.24	6.67
	1	45.59	39.97	3653.56	11.32	9.31	6.64

The geo-accumulation index was calculated to further evaluate the extent of pollution. The I-geo values for Cd and Pb in the Al-Eimarah stations were moderate to high, indicating that these sites range from unpolluted to moderately polluted with respect to those metals, according to Müller's scale. In contrast, the Ali Al-Gharbi stations yielded I-geo values in the unpolluted to lightly polluted range for most metals, reinforcing the observation that they are less impacted by heavy metal pollution.

The overall pollution load index (PLI) was computed for each site by combining the CFs of all seven metals. The Al-Eimarah stations had PLI values above 1, in some cases substantially so, which confirms an overall pollution load above natural background levels. Al-Uzair and Ali Al-Gharbi stations had PLI values closer to or slightly above 1, reflecting lower overall pollution. These PLI results align with the site-specific observations: Al-Eimarah area is the most polluted among the studied locations, while the upstream Al-Uzair and downstream Ali Al-Gharbi sites exhibit comparatively lower pollution levels.

It is noteworthy that even at sites with lower pollution, *Unio tigris* still accumulated measurable heavy metals in its tissues. This finding underscores mussels' effectiveness as bioindicators. Because *Unio tigris* is sedentary and filters large volumes of water for food, it integrates the contamination present in its immediate environment over time. Therefore, the presence of heavy metals in its tissues, even at "cleaner" sites, likely reflects diffuse sources of pollution such as atmospheric deposition and upstream activities.

Table 15. The geochemical accumulation coefficient (I-geo) of minor elemental metals concentration

Station	I-**Geo(Fe)**	Igeo**(Co)**	Igeo**(Pb)**	Igeo**(Cd)**	Igeo**(Cu)**	Igeo**(Ni)**	Igeo**(Zn)**
Al-Uzair	-6.113	-0.546	-0.879	5.533	-2.87	-2.79	-2.853
	-6.107	-0.657	-0.853	5.617	-2.88	-2.71	-2.777
	-6.029	-0.642	-0.798	5.652	-2.84	-2.69	-2.771
Qaleat **Salih**	-5.935	-0.395	-0.463	5.763	-2.45	-2.63	-2.511
	-5.937	-0.355	-0.507	5.811	-2.44	-2.63	-2.502
	-5.930	-0.340	-0.517	5.776	-2.45	-2.58	-2.491
Al-Majar	-5.894	-0.311	-0.326	6.025	-2.30	-2.35	-2.355
	-5.889	-0.291	-0.320	6.027	-2.29	-2.32	-2.3
	-5.891	-0.202	-0.313	6.081	-2.29	-2.36	-2.291
Al-Eimarah	-5.314	0.562	-0.039	6.531	-1.82	-0.64	-1.777
	-5.189	0.519	-0.032	6.530	-1.86	-0.61	-1.69
	-5.230	0.522	-0.012	6.533	-1.83	-0.64	-1.65
Al-Kumait	-5.497	0.101	-0.195	6.348	-2.11	-0.75	-2.04
	-5.512	0.150	-0.171	6.340	-2.11	-0.74	-1.969
	-5.489	0.158	-0.179	6.320	-2.10	-0.73	-2.009
Ali Al-Sharqi	-5.795	-0.297	-0.452	6.174	-2.23	-2.84	-3.066
	-5.758	-0.246	-0.461	6.173	-2.18	-2.85	-3.094
	-5.779	-0.236	-0.445	6.189	-2.12	-2.78	-3.061
Ali Al-Gharbi	-6.318	-0.729	-0.943	5.519	-2.69	-3.25	-3.319
	-6.315	-0.779	-0.998	5.535	-2.81	-3.11	-3.315
	-6.305	-0.794	-0.984	5.531	-2.80	-3.09	-3.311

Comparing these results with other studies, the concentrations of heavy metals in *Unio tigris* from the Tigris River are in the range of those reported for bivalves in other polluted freshwater systems. For example, the levels of Pb and Cd in mussels at the most contaminated sites here are similar to those found in mollusks from industrial regions reported by **Varol *et al.* (2022)**. However, Zn and Cu levels in our study were generally lower than values reported in some highly industrialized rivers, suggesting that certain heavy metal inputs (e.g., from mining or metal plating industries) might be less pronounced in this region.

In terms of ecological risk, the concentrations of Cd and Pb are of particular concern due to their toxicity and tendency to bioaccumulate. Both metals exceeded what is considered baseline in multiple stations. Chronic exposure to elevated Cd and Pb can pose risks to aquatic life, including the mussels themselves (affecting growth and reproduction) and their predators such as fish and birds. Additionally, if local communities harvest mussels or fish from the Tigris River for consumption, there could be implications for human health. The data from this study could be used to perform a more detailed risk assessment, including calculating hazard quotients for human consumers of aquatic organisms.

Overall, the patterns observed in this study highlight the impact of human activities on the Tigris River's water quality. The upstream sections near major urban and industrial centers show clear signs of heavy metal pollution, whereas downstream and less-developed areas are comparatively less contaminated. This gradient emphasizes the importance of pollution control measures in urban areas to protect the river system.

Research examining trace metals linked to *Unio tigris* in the Tigris River remains relatively scarce **(Abdoul *et al.*, 2024)**. Communities situated near rivers have relied on aquatic resources for consumption, making it essential to understand how metals accumulate in bivalve molluscs, specifically within the context of the Tigris River **(Vaessen *et al.*, 2024)**.

The trace metals entering the Tigris River primarily stem from industrial wastewater and domestic sewage located near urban areas, with the potential for contamination varying daily, weekly, or seasonally. Therefore, it is essential to analyze the concentration of certain metals in the tissues of freshwater mussels collected from the Tigris River, particularly at Iraq **(Rashid *et al.*, 2024)**.

The study examined trace metal levels in the freshwater bivalve *Unio tigris* collected from the Tigris River in Turkey. The findings highlight varying concentrations of metals activities. These findings underscore the necessity for developing comprehensive plans based on the existing data, which will enhance conservation strategies to effectively meet local biodiversity requirements **(Abdoul *et al.*, 2024)** within the bivalves, revealing distinct spatial variations. To analyze these variations, spatial distribution maps were employed. The results uncover two notable anomalies in metal concentrations, with elevated levels detected in locations associated with industrial activities.

A related study indicated that pollution levels in industrial, agricultural, and urban areas along the Tigris River have reached unacceptable thresholds for certain metal concentrations in *U. tigris*. This study aimed to quantify the concentrations of Ag, Cd, Co, chromium (Cr), Ni, Pb, Th, and Sr in *U. tigris* specimens from four different sampling locations along the river **(Al-Shawi *et al.*, 2022)**.

CONCLUSION

This study demonstrates that the freshwater mussel *Unio tigris* accumulates significant levels of heavy metals and can serve as a valuable indicator of environmental pollution in the Tigris River. We found that sites in the vicinity of Al-Eimarah, which are subject to intense human activity, had markedly higher concentrations of heavy metals in mussel tissues compared to less urbanized sites like Ali Al-Gharbi. The consistent patterns in contamination and enrichment factors suggest that anthropogenic inputs are a major source of metals such as Pb, Cd, and Ni in the river.

The decline of mussel populations in parts of the Tigris River is a warning sign of ecological stress. Understanding the causes of this decline requires pinpointing areas of high contamination and taking remedial actions. The information from this research, including identified hotspots of metal pollution and baseline contamination levels, can guide environmental agencies in implementing targeted pollution mitigation and habitat restoration efforts. By regularly monitoring *Unio tigris* populations and their metal burdens, it is possible to track improvements or deteriorations in water quality over time.

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