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Assessment of Heavy Metal Contamination and Pollution Indices in *Avicennia marina* of Nabq Mangrove Forest, the Red Sea, Egypt

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ABSTRACT

Mangrove forests are vital for the filtration of land-derived wastewater in industrialized tropical and sub-tropical coastal regions, contributing to the preservation of marine ecosystems. However, intertidal communities currently face significant challenges. One major concern is the potential threat posed by heavy metal contamination resulting from human activities associated with rapid urbanization and industrialization. Extensive research has been conducted to understand the biotic responses of mangrove plants to heavy metal exposure. Contaminants have significant implications for estuary management and coastal ecosystem preservation. This study focused on assessing the heavy metal in the tissue of the mangrove tree *Avicennia marina* collected from the Nabq protectorate area, the Red Sea. The enrichment factor (EF) values of seawater in the study area provide insights into the contamination levels. Notably, all sampled locations in the investigated region displayed EF values below 1, suggesting minimal contamination by these metals. The analysis of the Metal Pollution Index (MPI) of water in the Nabq area revealed that the examined sites within the Nabq protectorate experienced a minor degree of metal pollution. The sites examined are classified in class III. This classification is based on the MPI values falling within the range of 1- 2 levels for all sites within the protectorate. Metal concentrations in leaves, roots, stems, and surrounding seawater were investigated in twelve locations within the studied area. The analysis revealed that the concentrations of metals were ordered from high to low concentrations as follows: roots> leaves> stem. Manganese had the highest concentration of bioconcentration factor among the elements examined in the roots, leaves, and stem of *Avicennia marina*.

INTRODUCTION

Mangrove ecosystems play a critical role in providing vital ecological functions within coastal habitats **(Younis *et al.*, 2022)**. The studies of **Dahdouh-Guebas *et al*. (2000)**, **Younis (2020)**, **Taher *et al.* (2023)** and **Younis *et al.* (2023)** highlight their role as vital habitats within coastal communities and their protective nature against different threats. Mangroves contribute significantly to ecosystem management and preservation by storing sediments that contain organic matter and harmful contaminants. The objective is to enhance the presence of essential elements and compounds necessary for organisms' growth and development while mitigating the dispersion of harmful substances in coastal regions.

Additionally, it is noteworthy that, mangrove ecosystems play a vital role in protecting coastal areas from erosion and various weather-related extreme events, such as storm surges and cyclones **(Zhang *et al.,* 2020)**. These ecosystems are frequently employed for the preservation of coastal ecosystems, especially in estuaries that have undergone significant alterations due to human activity, particularly in regions characterized by rich growth and diverse species composition, such as the tropics and sub-tropics **(Harty, 1997)**.

Despite their unique characteristics and ecological significance, mangrove ecosystems face the threat of destruction from multiple factors. These include the increasing frequency of natural disasters and human activities, particularly urbanization **(Cuong *et al.,* 2005; Hanafy *et al.,* 2021; El-Naggar *et al.,* 2021; Hassan *et al.,* 2022)**. In recent years, many studies have specifically focused on the impact of heavy metal contamination on estuarine aquatic habitats. Activities, including urbanization, aquaculture, and agriculture are the primary sources of heavy metal contamination in coastal areas **(Younis *et al.,* 2019; Soliman *et al.,* 2020)**. Relevant studies conducted by **Elnaggar *et al.* (2022)**, **Förstner and Wittmann (2012)**, and **Harbison (1986)** provide valuable insights into this topic, further supporting the understanding of heavy metal contamination and its implications in mangrove ecosystems. According to **Polidoro *et al.* (2010)**, there has been a significant global decline of approximately 30 percent in mangrove vegetation cover since 1980. This decline can be attributed to extensive coastal development and industrial activities driven by population growth. As a result, numerous national and international agencies and local governments have implemented management and conservation strategies to mitigate these ecosystems' alarming levels of degradation **(Van Lavieren *et al.,* 2012; Younis *et al.,* 2023b)**.

The mangrove heights in Egypt, particularly those of *Avicennia marina*, are typically limited to a maximum of 5 meters due to prevailing environmental conditions, such as high salinity, limited rainfall, and harsh temperatures **(Elnaggar *et al.,* 2022; Younis *et al.,* 2023a)**. Notably, the Monqataa mangrove stand, located at coordinates 28.206397°N latitude and 34.420480°E longitude, represents the northernmost mangrove stand in the western Indo-Pacific region. Along the coastal region, these mangrove trees extend up to a maximum linear extent of 800 meters. A diverse assemblage of mangrove plants surrounds the primary mangrove lagoon.

Within the Nabq protectorate, the Rowaiseya mangrove stands out as the most expansive in the area, spanning approximately 4.8 kilometers along the shoreline. Its geographical coordinates are approximately 28.179887° N latitude and 34.445295° E longitude. The mangrove stands in this region exhibit a considerable breadth, extending along the beach for a distance of 480 meters toward the sea. The mangrove trees near Rowaiseya display significant growth and contribute to a dense vegetation cover.

This study centers on the Nabq protectorate in the Red Sea region of Egypt, specifically focusing on assessing heavy metals, namely iron, manganese, zinc, copper, lead, and cadmium, in seawater. Additionally, the study sought to compare the concentrations of these metals within mangrove trees of the species *Avicennia marina* tissue (roots, leaves, and stem). Metal bio-concentration and translocation factors were calculated to achieve this objective, providing insights into the plants' ability to accumulate heavy metals within this area.

MATERIALS AND METHODS

Study area

Nabq, situated in the southwestern region of the Gulf of Aqaba within the Egyptian Red Sea, is home to a prominent Protected Area (PA) established in 1992. This PA holds the distinction of being the largest in the region, spanning a total area of 736km², with 421km² of land and 315km² of sea. It includes the marine sector of Dahab City to the north of Nabq, contributing to its significance.

The Nabq Managed Resource Protected Area (NMRPA) is part of a larger network of five protected areas overseen by the South Sinai Protectorates and falls under the governance of the Egyptian Environmental Affairs Agency (EEAA). The NMRPA is renowned for its diverse range of habitats and ecosystems, particularly the three primary marine ecosystems: coral reefs, sea grass beds, and mangroves.

The study of NMRPA encompasses a variety of ecosystems and habitat types, with the majority of the protected area characterized by mountainous and Wadi desert ecosystems. Wadi Kid stands out as the largest wadi in the region, serving as a significant drainage system into the Gulf of Aqaba. This wadi gives rise to a broad delta featuring an alluvial fan, which is home to the largest concentration of the *Salvadora presica* species' Arak sand dunes. Additionally, the coastal region of the delta boasts an extensive expanse of *Avicennia marina* mangroves, commonly known as Al Shora.

The mangroves span a stretch of approximately 4.5 kilometers along the beachfront. In certain areas, these mangroves form dense and expansive groves, are characterized by the presence of large trees. The Nabq mangrove area has become a primary attraction for tourists within the protectorate, contributing significantly to its overall appeal. Its presence enhances the scenic landscape and preserves the integrity and stability of the attraction and the adjacent near-shore marine ecosystem.

The strategic placement of the mangrove stand, which covers as significant portion of the area's landscape, is crucial in preserving the overall appeal of the region. It forms a cohesive and integrated component of the scenic landscape, complemented by a lagoon with clear blue seas, seagrass meadows, and a shipwreck. The presence of the mangroves contributes to the overall tourist appeal and ensures the preservation of the ecosystem's integrity and stability.

Fig. 1. Geographical distribution of sampling location within the Nabq protectorate

Sampling and analysis

In this study, samples of seawater and mangroves were collected from the Nabq protectorates in South Sinai, the Red Sea, Egypt in 2018 (Fig. 1).

Seventeen surface seawater sampling sites were established in the Nabq protectorate based on the water system map of the study area and field observations of mangrove tree distribution. These sites were distributed across seven sectors, as depicted on the map, each comprising multiple research sites. In sector NA, a single sample was collected from the mangrove sediment, representing station 1. In sector NB, another sample was collected from the mangrove sediments, representing station 2. Sector NC consisted of three samples collected from the mangrove sediments, salt marsh, and intertidal areas, representing stations 3, 4, and 5, respectively. Similarly, sector ND, NE, NF, and NG each had three samples collected from the corresponding habitats, representing stations 6- 8, 9- 11, 12- 14, and 15- 17, respectively. Each sampling site was accurately positioned using a handheld Global Positioning System (GPS, Garmin 72, Lenexa, KS, USA) to ensure the representativeness of the collected samples.

A rapid survey of the mangrove environment was conducted to select twelve sub-stations within the Nabq protectorate that collectively represented the entire site. Samples of Avicennia marina mangrove tissue, including roots, leaves, and stems, were handpicked from various parts of the trees within the same sub-stations. These samples were then mixed to obtain a composite sample representing all mangrove trees in the site during the vegetation period in the protectorate's coastal area, which is predominantly dominated by Avicennia marina. However, there is a significant lack of studies focusing on heavy metal pollution in the Egyptian mangrove ecosystems. Hence, this study aimed to investigate the status of six heavy metals (Fe, Mn, Zn, Cu, Pb, and Cd) in water, sediments, and mangrove tissue (roots, leaves, and stems)in the study area. The distribution patterns of these selected heavy metals in water, sediments, and mangrove tissue were determined to better understand the roles of mangrove plants in their cycling.

According to **Eaton (1976)**, each filtered sample of 750ml was transferred to a separating funnel, and its pH was adjusted to a range of 4.8- 5.2 using concentrated nitric acid. To each sample, 15ml of 1% APDC and 30ml of MIBK were added. The funnels were shaken for 15 minutes on an automatic shaker. After phase separation, the aqueous layer was transferred to a clean separating funnel, and another 30ml of MIBK was added. The upper MIBK layer containing the extracted metals was retained in a corresponding small 100ml separating funnel. This procedure was repeated two more times for 15 minutes and then for 30 minutes. The MIBK extract in the 100ml separating funnel was treated with 15ml of 2N HNO3, shaken, and left for 48 hours for phase separation. The resulting 15ml aqueous layer of 2N HNO3 containing the chelated metal from the 750ml sample solution was stored in tightly stoppered scintillation vials until analysis using an atomic absorption spectrometer, Perkin Elmer AAF 100 USA.

All mangrove tissue samples were individually dried at room temperature until a constant weight was achieved. The determination of total metal content (Fe, Mn, Zn, Cu, Pb, and Cd) in mangrove tissue was performed following the method described by **Saeki *et al.* (1999)**. Approximately, 0.5g of wet sample was placed in 30ml Teflon containers with screw caps, and 5ml aliquots of concentrated nitric acid (69%) were added. The pre-digestion step was carried out at room temperature for 6 hours. After cooling, 0.5ml of nitric acid (69%) and 1ml of de-ionized distilled water were added to the sample container, which was then heated in a microwave oven for 40 seconds. Upon completion of digestion, the sample was transferred to a measuring flask (10ml) and diluted with de-ionized distilled water up to 10ml. The concentrations of heavy metals (zinc, iron, copper, cadmium, lead, and manganese) in the leaves, stems, roots of mangroves, and seawater were measured using an atomic absorption spectrophotometer (AAS Perkin Elmer analyst, Model100). The results were expressed in μg/ g dry weight for mangrove samples. Analytical grade reagents were used for blanks and calibration curves. Precision was checked against standard reference material, and the recovery for all metals studied ranged from 90 to 97%.

Ecological risk assessment

Enrichment factor (EF)

The enrichment factor (EF) was employed to assess the pollution degree of heavy metals in seawater influenced by anthropogenic activities. The EF for each metal was determined by comparing the observed dissolved metal concentration with the minimal risk concentration of metals reported for the water quality criteria (WQC).

Metal pollution index (MPI)

The MPI represents the sum of the ratio between the concentration of the analyzed metal and their corresponding maximum allowable concentrations (MAC). The MAC calculations for the determined metals were based on the WQC (1972).

$$MPI = \sum_{i=1}^{n} \frac{c_i}{(MAC)_i}$$

Where, the concentration of ith metal; MAC= Maximum allowable concentrations.

Bio-concentration (BCF) and translocation factors (TFs)

In this study, the bioconcentration factor was determined by dividing the concentration of the test substance in specified tissues (in mg/ kg) by the concentration of the chemical substance in the surrounding medium (in mg/ L or mg/ kg). The bioconcentration factors for the investigated heavy metals were calculated using the equation described by **Cui *et al.* (2007)** and **Yoon *et al.* (2006)**.

The bioconcentration factor (BCF) is calculated as follows:

$$BCF = \frac{\text{Concentration of metal in biota (mg/kg)}}{\text{Concentration of metal in water (mg/L)}}$$

The translocation factor (TF) was calculated using the following equation:

$$TF_{leave} = \frac{C_{leave}}{C_{root}}$$

Where, C_{leave} and C_{root} represent the concentrations of the heavy metal in the leaves and roots, respectively.

RESULTS AND DISCUSSION

1. Assessment of heavy metals in seawater

Anthropogenic activities, including industrial operations, the disposal of automobiles, batteries, and wastewater discharge, contribute to the elevated levels of heavy metals in the environment **(Younis *et al.*, 2022)**. **Defew *et al.* (2005)** conducted a study that revealed the potential threats posed by ongoing anthropogenic activity to the preservation of the remaining mangrove forest in Punta Mala Bay, Panama. The diverse physical and chemical characteristics of mangrove ecosystems within the intertidal zone determine whether they act as sinks or sources of heavy metals in coastal environments **(Pekey, 2006)**. Solid and liquid pollutants present in mangrove habitats can cause mortality by adversely affecting the respiratory and osmoregulatory functions of plants, as well as impacting the aquatic organisms residing in these ecosystems **(Elnaggar *et al.*, 2022; Elkady & Younis, 2023)**. It is worth noting that the persistent, toxic, and widespread occurrence of heavy metals in the environment primarily contributes to their detrimental impact on mangrove swamps, as emphasized by **Cosma *et al.* (1979)**.

The analysis of Fig. (2) reveals distinct patterns in the concentrations of heavy metals across the investigated region. Position 15, corresponding to sector 6 of the mangrove patch, exhibited the highest concentration of Cu (1.029µg/ L), indicating a localized accumulation of this metal. Similarly, site 15 demonstrated the highest concentration of Mn (1.146µg/ L), suggesting a potential association between the mangrove ecosystem and elevated Mn levels.

Furthermore, within sector 4 of the mangrove patch, the area denoted as 9 displayed notable concentrations of Fe (38.63µg/ L) and Pb (3.318µg/ L), indicating a localized hotspot for these elements. The vulnerability of this sector to intensive human activities and sewage contamination likely contributes to the observed elevated levels of Fe and Pb.

Location 4, corresponding to sector 2 of the salt marsh water, stood out with the highest recorded amount of Cd (0.339µg/ L). This finding highlights a specific site within the investigated region that is particularly impacted by Cd contamination.

In terms of Zn concentrations, location 14 in sector 5 of the intertidal area water exhibited the greatest concentration (10.33µg/ L). This suggests a potential association between Zn accumulation and the specific characteristics of this location.

The findings regarding Cd and Pb indicate moderately elevated levels of these metals in the investigated region. Additionally, these concentrations can be primarily attributed to significant anthropogenic actions, such as shipyard operations, marine activities, petrochemical waste discharge, and oil spill incidents involving boats.

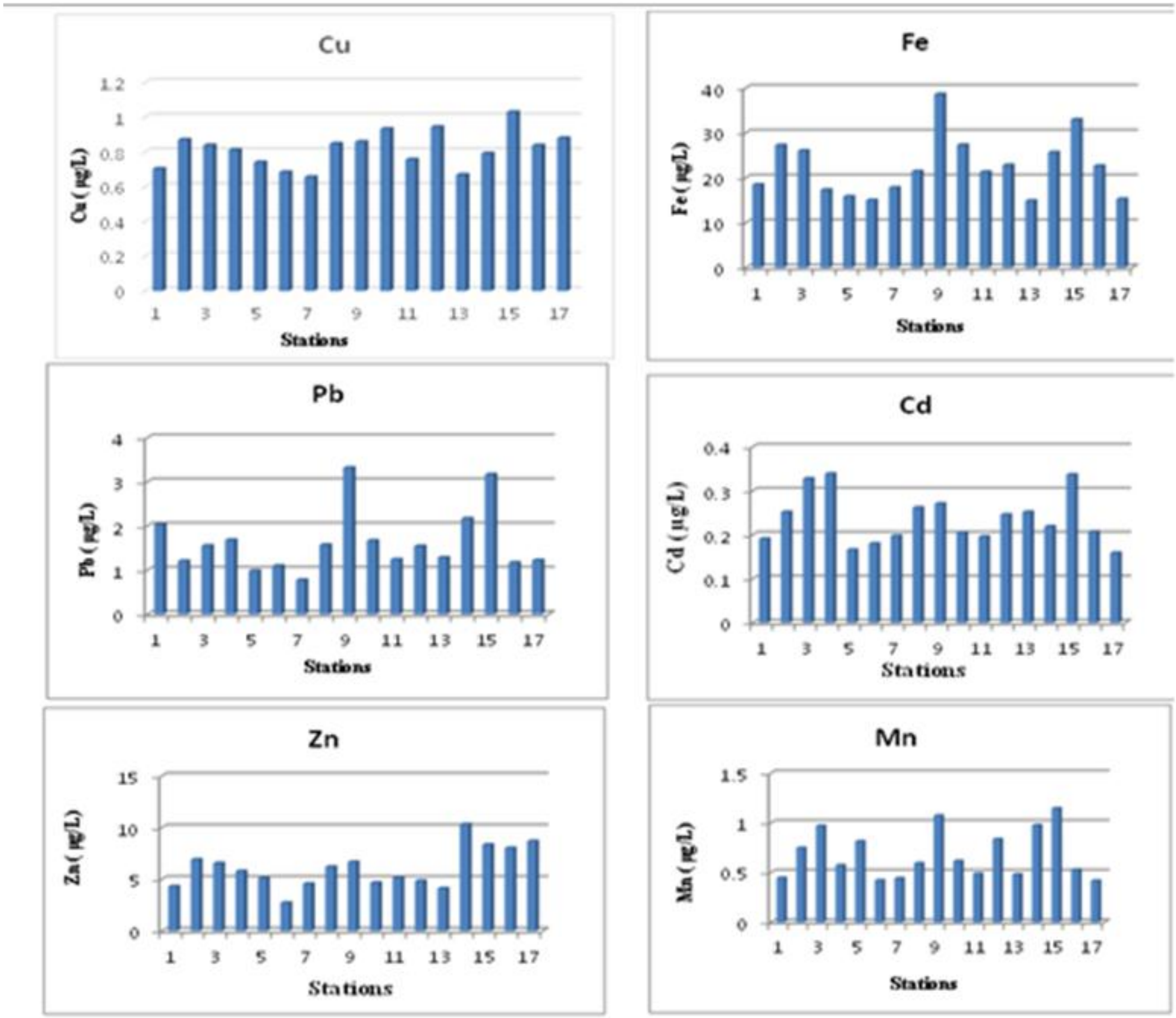

Fig. 2. Metal concentrations (µg/ L) in water samples collected from Nabq protectorate

Additionally, the enrichment factor (EF) values observed across various sites provide insights into the contamination levels. Notably, all sampled locations within the investigated region displayed EF values below 1 for Fe, Cd, Cu, Zn, Mn, and Pb, suggesting minimal contamination by these metals.

Fig. (3) provides insights into the Metal Pollution Index (MPI) of water in the Nabq area. The analysis reveals that the examined sites within the Nabq protectorate experienced a minor degree of metal pollution, as evidenced by their classification in class III. This classification is based on the MPI values falling within the range of 1- 2 levels for all sites within the protectorate.

Table 1. Enrichment factor (EF) of investigated heavy metals in water samples collected from the Nabq protectorate

Location	Cu	Fe	Pb	Cd	Zn	Mn
1	0.0703	0.3698	0.2039	0.0191	0.21565	0.0223
2	0.087	0.5452	0.1207	0.0252	0.34575	0.03735
3	0.0838	0.521	0.1552	0.0328	0.32805	0.0485
4	0.0811	0.3468	0.1684	0.0339	0.28955	0.0485
5	0.074	0.317	0.0987	0.0166	0.2562	0.0407
6	0.0683	0.3006	0.1096	0.018	0.1363	0.02105
7	0.0655	0.3562	0.0776	0.0198	0.2286	0.02205
8	0.0847	0.429	0.1572	0.0262	0.3106	0.02965
9	0.0858	0.7726	0.3318	0.0271	0.33385	0.05365
10	0.0932	0.5466	0.1667	0.0205	0.2333	0.0308
11	0.0756	0.4264	0.1241	0.0196	0.25845	0.02445
12	0.0943	0.4568	0.1542	0.0246	0.24315	0.04175
13	0.0668	0.2982	0.1283	0.0252	0.20565	0.02405
14	0.0791	0.5138	0.2169	0.0219	0.5165	0.04885
15	0.1029	0.6598	0.3168	0.0337	0.41765	0.0573
16	0.0837	0.4534	0.1171	0.0207	0.4013	0.0264
17	0.0879	0.3058	0.1223	0.0159	0.4347	0.02085

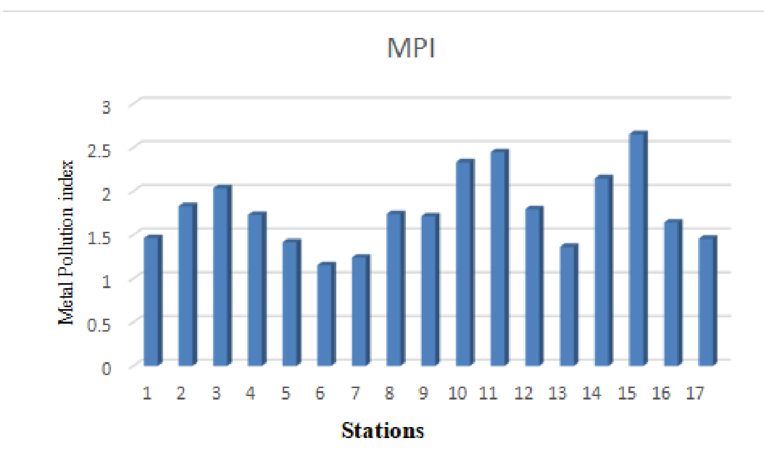

Fig. 3. Metal Pollution Index (MPI) in water samples collected from the Nabq protectorate

Assessment of heavy metal concentrations in mangrove tree

Mangrove ecosystems possess a remarkable capacity to capture suspended solids, which may contain trace metals originating from diverse sources, such as upstream soils, rocks, and human activities **(Elnaggar *et al.*, 2022)**. Recognized as effective natural barriers, mangroves serve as repositories for trace metals, playing a vital role in safeguarding coastal waterways against pollution. However, the effectiveness of this function relies on specific soil attributes and hydrological conditions **(Kaly *et al.*, 1997)**. The dynamics of trace metals within mangroves exhibit complexity due to the occurrence of diverse biogeochemical processes throughout the intertidal zone **(Noël *et al.*, 2015)**.

The issue of heavy metal cycling in mangrove habitats raises significant concerns due to its detrimental effects on these ecosystems. The toxic nature of heavy metals and their tendency to accumulate within the mangrove environment have been extensively documented through numerous research studies **(Shriadah, 1999)**.

Based on the data presented in Tables (2, 3, 4), it was observed that the mangrove patch located in sector seven exhibited the highest concentration of iron (Fe) in its leaves, measuring at 170.2µg/ g. This particular sector demonstrated the most significant accumulations of elements in foliage, with the following order of concentrations from highest to lowest: Fe, Mn, Zn, Pb, Cu, Cd, with respective concentrations of 170.2, 33.13, 14.15, 4.889, 2.52, and 0.708µg/ g. The presence of elevated copper (Cu) concentrations in the mangrove leaves suggests the existence of localized sources of metal pollution. Despite the exceeding amounts of Mn, Fe, and Zn beyond their reported values, the mangrove displayed no observable signs of toxicity. These findings provide further evidence in line with existing scholarly research that *A. marina* possesses a remarkable capacity for the bioaccumulation of heavy metals. Previous studies, including those by **Usman *et al.* (2013)** and **Alongi *et al.* (2003)**, have also reported elevated levels of copper (Cu). Discrepancies between our study and previous ones may be attributed to the specific characteristics of the study sites and the nature of anthropogenic influences. Earlier research has documented high metal accumulation in the tissues of various mangrove species without apparent negative effects on plant health **(Gleason *et al.*, 1979; Clough *et al.*, 1983; MacFarlane & Burchett, 2000, 2001; MacFarlane *et al.*, 2007; Elnaggar *et al.*, 2022)**.

Table 2. Heavy metal content (μg/ g) in mangrove roots in Nabq protectorate area

Location	Sample no.	Cu	Fe	Pb	Cd	Zn	Mn
		μg/ g					
NA1	1	1.159	28.05	2.494	0.384	3.785	5.428
	2	0.955	8.391	1.752	0.373	3.613	3.653
	3	1.128	32.91	3.454	0.852	6.186	4.008
	4	1.001	68.13	3.603	0.738	6.764	6.255
	5	2.171	104.1	7.302	1.297	11.1	15.8
	6	0.993	11.89	1.944	0.489	3.376	3.083
NA2	7	1.613	20.09	7.581	1.433	10.56	4.34
	8	1.074	25.36	3.486	0.737	7.394	4.609
	9	0.999	36.7	2.901	0.756	6.127	4.443
NA3	10	0.759	9.048	1.947	0.434	5.924	2.599
	11	0.717	9.165	3.043	0.642	7.818	2.07
	12	0.498	13.11	2.088	0.617	4.877	2.123
NB1	13	0.259	3.998	0.568	0.272	3.94	0.928
	14	1.315	4.781	0.776	0.362	2.244	1.285
	15	1.219	29.48	2.765	0.622	5.462	5.837
	16	1.6	13.36	2.2	0.551	3.895	2.707
NB2	17	1.16	14.75	3.445	1.107	4.116	3.043
	18	1.113	13.71	2.868	0.856	4.462	2.257
	19	0.87	15.66	2.724	0.609	3.908	2.292
NC1	20	2.12	30.12	2.414	0.67	5.875	8.289
	21	1.916	76.9	2.651	0.55	5.711	13.53
NC2	22	0.803	42.81	4.018	0.656	5.835	6.71
	23	0.808	50.06	3.168	0.556	3.949	6.058
	24	0.743	36.97	3.4	0.414	4.372	6.727
ND1	25	2.204	30.27	2.875	0.397	4.419	7.279
	26	1.225	26.34	2.633	0.327	4.842	7.934
	27	0.646	10.24	2.976	0.447	4.404	10.45
NE1	28	0.707	19.59	4.973	0.561	6.752	3.3
	29	0.62		3.151			
	30	0.481	40.04	4.108	0.454	7.686	5.169
	31	0.685	15.96	2.629	0.417	3.849	2.82
	32	1.118	23.7	3.63	0.539	6.907	3.605
NE2	33	1.166	37.03	5.722	0.886	7.6	5.471
NF1	37	1.368	56.23	5.336	0.771	6.057	6.175
NG1	38	-	-	3.158	-	-	-
	39	0.746	9.244	2.079	0.274	4.933	1.476

Table 3. Heavy metal content (µg/ g) in mangrove leaves in Nabq protectorate area

Location	Sample no.	Cu	Fe	Pb	Cd	Zn	Mn
		µg/ g					
NA1	40	1.545	30.14	2.748	0.554	6.744	16.51
NA2	41	0.92	42.83	1.973	0.564	5.398	7.887
	42	1.631	29.95	2.983	0.458	8.006	11.38
	43	0.959	27.98	2.514	0.513	5.13	8.082
NA3	44	0.743	35.83	2.804	0.703	4.844	8.421
	45	1.018	28.28	2.378	0.454	6.582	8.703
	46	1.134	26.71	3.851	0.639	7.413	13.7
NB1	47	2.762	33.71	3.015	0.421	7.927	11.9
	48	2.867	22.21	2.76	0.509	7.558	8.817
	49	1.442	22.39	5.26	0.622	8.666	29.53
NB2	50	0.716	11.21	2.912	0.636	4.765	10.34
	51	1.676	7.009	1.306	0.45	3.078	2.859
	52	0.393	4.349	1.19	0.231	3.628	1.39
NC1	53	1.315	40.02	4.255	1.084	8.432	103.1
	54	0.699	19.99	2.614	0.685	5.061	43.5441
	55	2.853	41.72	4.676	1.258	11.48	52.96
NC2	56	0.861	43.5	5.633	1.01	8.708	11.04
	57	0.06	2.661	0.324	0.066	0.523	0.634
	58	1.809	119.6	6.522	0.806	10.53	30.17
ND1	59	1.741	12.06	2.879	0.362	7.003	27.02
	60	2.224	16.16	2.995	0.472	6.253	23.55
	61	2.877	18.43	3.177	0.474	7.3	25.85
NE1	62	1.123	32.34	3.758	0.4	8.585	13.24
	63	0.99	29.22	4.781	0.604	12.1	13.69
	64	1.045	29.92	4.059	0.457	12.49	10.97
NF1	65	1.775	35.48	3.607	0.497	9.238	37.02
	66	1.144	18.08	4.725	0.846	6.255	3.372
	67	1.397	31.56	2.956	0.626	7.164	29.11
NG1	68	2.521	170.2	4.889	0.708	14.15	33.13

Table 4. Heavy metal content (μg/ g) in mangrove stem in Nabq protectorate area

Location	Sample no.	Cu	Fe	Pb	Cd	Zn	Mn
		μg/ g					
NA1	69	0.946	16.04	2.525	0.536	3.524	3.348
	70	0.901	13.72	2.639	0.5	3.541	3.761
	71	0.885	36.09	2.719	0.708	6.725	15.5
NA2	72	1.262	23.21	2.582	0.651	5.084	3.938
	73	1.434	17.38	2.233	0.564	5.707	3.558
	80	1.914	18.47	1.96	0.494	5.539	4.105
NA3	81	1.384	17.53	3.092	0.862	7.467	4.266
	82	1.09	16.16	1.498	0.764	4.579	2.749
	92	1.021	16.3	2.072	0.698	4.522	3.226
NB1	93	0.818	9.864	2.544	0.486	5.272	1.684
	94	1.561	7.525	1.647	0.468	5.133	1.724
	102	1.004	9.781	1.923	0.603	5.364	1.802
NB2	103	0.882	11.85	1.562	0.472	4.126	1.776
	104	0.774	8.438	2.793	0.851	5.008	1.791
	108	0.908	10.36	2.808	0.826	5.718	1.842
NC1	109	1.074	20.52	4.193	0.762	5.219	4.735
	110	1.139	23.26	5.062	0.973	10.13	6.277
	121	0.817	12.8	2.957	0.527	4.619	4.999
NC2	122	0.3	6.21	2.345	0.507	3.149	0.773
	123	0.122	4.341	0.438	0.071	0.473	0.659
	128	1.026	49.74	3.251	0.428	5.765	7.654
ND1	129	1.364	65.84	6.204	0.939	12.96	7.396
	130	9.826	23.01	5.565	0.59	10.34	18.55
	140	1.538	29.5	5.937	0.698	15.97	11.11
NE1	141	0.661	15.56	4.141	0.58	4.792	6.766
	142	1.687	26.16	4.618	0.678	16.56	28.55
	155	1.871	32.94	6.163	1.059	15.3	30.6
NE2	158	1.348	22.32	3.779	0.633	14.46	27.48
	159	-	-	0.255	-	-	-
	160	1.163	17.83	4.41	0.775	8.632	4.496

NF1	161	2.38	25.95	5.923	0.767	8.609	10.85
	162	1.894	31.59	3.636	0.583	10.66	19.27
NG1	174	0.676	11.6	2.66	0.37	5.68	2.093
	175	0.786	8.654	2.208	0.279	2.15	1.682
	183	0.813	7.724	2.576	0.378	3.375	1.69

Where, a= Salt marsh; b= Mangrove patch, and c= Intertidal area.

Similar observations were made in sector 7 of the Nabq protectorate, where the vegetation exhibited robust growth unaffected by contamination. Abundant seedlings were detected within the study area, showing signs of thriving. The success of *A. marina* can be attributed to its active avoidance mechanism, which enables it to prevent the uptake of metals, even under conditions of elevated sediment concentrations. Plant resistance to heavy metals is believed to involve mechanisms, such as cell wall immobilization, sequestering, root epidermis barriers, ion exclusion **(Baker & Walker, 1990)**, and peroxidase activation **(Dietz *et al.*, 1999)**. **Wong *et al.* (1988)** observed that the absorption and accumulation of heavy metals by plants resulted in vessel constriction and the formation of unidentified deposits, obstructing the vascular system and impeding water transfer. The ability of mangroves to accumulate pollutants depends on the nature of the pollutants, the plant species involved, and the prevailing environmental conditions.

Bioconcentration factor of heavy metals

In the current study, relative measures of metal uptake were utilized to differentiate the intake of individual heavy metals. The biological concentration factor (BCF) was estimated for roots, stems, and leaves to assess the susceptibility of different tissue types to various environmental stressors. Mangroves play a crucial role in reducing contaminant concentrations, particularly heavy metals, within the surrounding ecosystem. Through their intricate root network, mangrove vegetation has the ability to uptake heavy metals and sequester them in their tissues. Roots, stems, and leaves often contain substantial amounts of heavy metals. The binding of heavy metals in plants is facilitated by mechanisms of metal accumulation and tolerance. Consequently, the presence of mangrove roots can effectively mitigate the accumulation of heavy metals in the surrounding ecosystem. The tissues and leaves of trees possess the potential to store and remove significant quantities of heavy metal pollutants present in sediments.

The current investigation involved determining the bioconcentration factor by dividing the concentration of the test substance in specific tissues (expressed as mg/ kg) by the concentration of the chemical substance in the surrounding medium (expressed as mg/ L or mg/ kg).

The bioconcentration factor (BCF), also known as metal phytoextraction efficiency, represents a plant's ability to absorb metals from the soil through the process of bioaccumulation **(Zhang *et al.*, 2002; Almahasheer, 2019)**.

The concentrations of six metals in mangrove trees situated in salt marshes (group a), mangrove patches (group b), and intertidal areas (group c) were determined based on the data presented in Table (5).

A significant accumulation of manganese was observed in the primary root systems of seven distinct mangrove locations, particularly in location 4 of subgroup a, with a concentration of 43.8636. This research analyzed several heavy metals, including iron, copper, and manganese. These metals occur naturally and play a vital role in the physiological growth of plants as long as their concentrations remain below a threshold at which they become toxic. Our observations indicate that location 4 exhibited the highest density of mangrove trees and covered the largest vegetation area.

To determine the greatest bioconcentration factor (BCF) within the mangrove trees of the Nabq protectorate, it is necessary to examine the relative concentrations of leaves, roots, and stems.

Based on the data presented in Table (6), a significant accumulation of manganese (Mn) was observed in mangrove leaves at site 3, with a value of 233.787 (BCF). These calculations demonstrate a notable capacity to mitigate the elevated bioavailability of manganese (Mn) in mangrove silt compared to other metallic elements. **Abou Seedo *et al.* (2017)** conducted a study examining metal concentrations in mangrove tree leaves in Bahrain and investigated regional variations in leaf content. The authors reported the following order of concentration for mangrove leaves in the region: Fe> Mn> Ni> Cr> Zn> Cu. Furthermore, they found elevated levels of iron in mangrove leaves throughout the region, indicating the presence of site-specific sources of heavy metal (HM) contamination.

Table 5. The bio-concentration factor of heavy metals in the Nabq protectate area's *Avicennia marina* roots

Location	Sample no.	Cu	Fe	Pb	Cd	Zn	Mn
		BCF					
NA1	1	1.33218	1.02898	2.06628	1.52381	0.54736	7.2664
	2	1.0977	0.30781	1.45153	1.48016	0.52249	4.89023
	3	1.29655	1.20726	2.86164	3.38095	0.89458	5.36546
	4	2.4954	3.81878	6.04971	5.14683	1.60521	21.1513
	5	1.14138	0.43617	1.6106	1.94048	0.48821	4.12718
	6	1.33218	1.02898	2.06628	1.52381	0.54736	7.2664
NA2	7	1.85402	0.73698	6.28086	5.68651	1.52711	5.80991
	8	1.14828	1.34629	2.40348	3.00000	0.88604	5.94779
NA3	9	0.87241	0.33191	1.61309	1.72222	0.85669	3.47925
	10	0.82414	0.33621	2.52113	2.54762	1.13059	2.77108
	11	0.57241	0.48092	1.72991	2.44841	0.70528	2.84203
NB1	12	0.35	0.25224	0.57548	1.63855	0.76893	1.14005
	13	1.77703	0.30164	0.78622	2.18072	0.43794	1.57862
	14	1.6473	1.85994	2.80142	3.74699	1.06596	7.17076
	15	2.16216	0.8429	2.22898	3.31928	0.76015	3.32555
NB2	16	1.56757	0.9306	3.49037	6.66867	0.80328	3.73833
	17	1.50405	0.86498	2.90578	5.15663	0.8708	2.77273
	18	1.17568	0.98801	2.75988	3.66867	0.76269	2.81572
NC1	19	3.23664	1.69118	3.11082	3.38384	1.285	18.7959
	20	2.92519	4.3178	3.41624	2.77778	1.24913	30.6803
NC2	21	1.22595	2.40371	5.17784	3.31313	1.27625	15.2154
	22	1.23359	2.81078	4.08247	2.80808	0.86374	13.737
	23	1.13435	2.0758	4.38144	2.09091	0.95626	15.254
ND1	24	1.31438	0.96378	1.57948	1.59512	1.03772	12.8799
	25	0.69313	0.37468	1.78524	2.18049	0.94385	16.9643
	26	1.86803	0.44127	1.72705	1.76585	1.50086	43.8636
NE1	27	0.74973	0.85771	3.22503	2.28049	1.38844	3.9521
	28	0.65748	-	2.04345	-	-	-
	29	0.51007	1.75306	2.66407	1.84553	1.58051	6.19042
	30	0.72641	0.69877	1.70493	1.69512	0.79149	3.37725

NE2	31	1.23648	1.62128	3.71077	3.60163	1.56282	6.5521
NF1	32	1.32945	1.70446	1.68434	2.28783	0.72513	5.38831
NG1	33	-	-	2.69684	-	-	-
	37	0.89128	0.40776	1.77541	1.32367	0.61463	2.79545

Table 6. Bio-concentration factor of heavy metals in *Avicennia marina* leaves of Nabq protectorate area

Location	Sample no.	Cu	Fe	Pb	Cd	Zn	Mn
		BCF					
NA1	40	1.7759	1.1057	2.2767	2.1984	0.9753	22.102
NA2	41	1.0575	1.5712	1.6346	2.2381	0.7806	10.558
	42	1.8747	1.0987	2.4714	1.8175	1.1578	15.234
	43	1.1023	1.0264	2.0829	2.0357	0.7419	10.819
NA3	44	0.854	1.3144	2.3231	2.7897	0.7005	11.273
	45	1.1701	1.0374	1.9702	1.8016	0.9518	11.651
	46	1.3035	0.9798	3.1906	2.5357	1.072	18.34
NB1	47	3.7324	2.1268	3.0547	2.5361	1.547	14.619
	48	3.8743	1.4013	2.7964	3.0663	1.475	10.832
	49	1.9487	1.4126	5.3293	3.747	1.6913	36.278
NB2	50	0.9676	0.7073	2.9504	3.8313	0.9299	12.703
	51	2.2649	0.4422	1.3232	2.7108	0.6007	3.5123
	52	0.5311	0.2744	1.2057	1.3916	0.708	1.7076
NC1	53	2.0076	2.2471	5.4833	5.4748	1.8443	233.79
	54	1.0672	1.1224	3.3686	3.4596	1.107	98.73
	55	4.3557	2.3425	6.0258	6.3535	2.5109	120.09
NC2	56	1.3145	2.4425	7.259	5.101	1.9046	25.034
	57	0.0916	0.1494	0.4175	0.3333	0.1144	1.4376
	58	2.7618	6.7153	8.4046	4.0707	2.3032	68.413
ND1	59	2.3863	0.5913	1.7966	2.3024	1.3401	38.231
	60	3.0869	0.6744	1.9058	2.3122	1.5645	41.964
	61	1.4635	2.4091	3.7217	4.5805	2.7775	12.007
NE1	62	1.1909	1.4159	2.4371	1.626	1.7654	15.856
	63	1.0498	1.2793	3.1005	2.4553	2.4882	16.395

	64	1.1082	1.31	2.6323	1.8577	2.5684	13.138
NF1	65	1.725	1.0755	1.1386	1.4748	1.106	32.304
	66	1.1118	0.548	1.4915	2.5104	0.7488	2.9424
	67	1.3576	0.9567	0.9331	1.8576	0.8577	25.401
NG1	68	3.012	7.5077	4.1751	3.4203	1.763	62.746

Despite exceeding the established thresholds for chromium, copper, and nickel, no observable signs of toxicity were detected in the mangrove. These findings further support existing scholarly research indicating that *A. marina* has a significant ability to bioaccumulate heavy metals. Discrepancies between our study and previous ones can be attributed primarily to the unique characteristics of each study location and the distinct anthropogenic stressors present.

Table 7. Bio-concentration factor of heavy metals in *Avicennia marina* stem of Nabq protectorate area

Location	**Sample no.**	**Cu**	**Fe**	**Pb**	**Cd**	**Zn**	**Mn**
		BCF					
NA1	69	1.08736	0.58841	2.09196	2.12698	0.50962	4.48193
	70	1.03563	0.5033	2.18641	1.98413	0.51208	5.03481
	71	1.01724	1.32392	2.25269	2.80952	0.97252	20.7497
NA2	72	1.45057	0.85143	2.13919	2.58333	0.73521	5.27175
	73	1.64828	0.63756	1.85004	2.2381	0.82531	4.76305
	80	2.2	0.67755	1.62386	1.96032	0.80101	5.49531
NA3	81	1.5908	0.64307	2.56172	3.42063	1.07983	5.71084
	82	1.25287	0.59281	1.24109	3.03175	0.66218	3.68005
	92	1.17356	0.59795	1.71665	2.76984	0.65394	4.31861
NB1	93	1.10541	0.62233	2.57751	2.92771	1.02888	2.0688
	94	2.10946	0.47476	1.66869	2.81928	1.00176	2.11794
	102	1.35676	0.6171	1.94833	3.63253	1.04684	2.21376
NB2	103	1.19189	0.74763	1.58257	2.84337	0.80523	2.18182
	104	1.04595	0.53237	2.82979	5.12651	0.97736	2.20025
	108	1.22703	0.65363	2.84498	4.9759	1.11593	2.2629
NC1	109	1.63969	1.15216	5.40335	3.84848	1.14151	10.737
	110	1.73893	1.30601	6.5232	4.91414	2.21566	14.2336

	121	1.24733	0.7187	3.81057	2.66162	1.01028	11.3356
NC2	122	0.45802	0.34868	3.02191	2.56061	0.68876	1.75283
	123	0.18626	0.24374	0.56443	0.35859	0.10346	1.49433
	128	1.56641	2.79281	4.18943	2.16162	1.26094	17.356
ND1	129	10.5429	0.84193	3.33833	2.87805	2.21603	30.1136
	130	1.65021	1.0794	3.56149	3.40488	3.42263	18.0357
	140	1.31438	0.96378	1.57948	1.59512	1.03772	12.8799
NE1	141	0.70095	0.68126	2.68547	2.35772	0.9854	8.10299
	142	1.78897	1.14536	2.99481	2.7561	3.40531	34.1916
	155	1.98409	1.44221	3.99676	4.30488	3.14621	36.6467
NE2	158	1.42948	0.97723	2.45071	2.57317	2.97347	32.9102
	159	-	-	0.16537	-	-	-
	160	1.2333	0.78065	2.85992	3.15041	1.77504	5.38443
NF1	161	2.31293	0.7866	1.86963	2.27596	1.03065	9.46771
	162	1.84062	0.95756	1.14773	1.72997	1.27619	16.815
NG1	174	0.80765	0.51169	2.27156	1.78744	0.7077	3.96402
	175	0.93907	0.38174	1.88557	1.34783	0.26788	3.18561
	183	0.97133	0.34071	2.19983	1.82609	0.42051	3.20076

According to the findings presented in Table (7), the highest bioconcentration factor (BCF) for the element manganese was observed at site 5 on the stem of mangrove trees in association with the salt marsh. The recorded BCF value at this position was 36.6467.

Over the past few decades, the coastal region of the Red Sea in Saudi Arabia has witnessed increased anthropogenic activities, particularly industrialization, leading to the introduction of pollutants including heavy metals into the area. This phenomenon has been documented in the study of **Badr *et al.* (2009)**, which highlights the significant concentrations of metals that accumulate in mangrove sediments and subsequently transfer to the leaves.

In a study conducted by **Khan *et al.* (2020)**, it was demonstrated that the accumulation of manganese (Mn) was more pronounced in the leaves of 80-year-old trees compared to the levels observed in the roots and sediments. Similar findings were documented by **Kaewtubtim *et al.* (2016)**, showing that the accumulation of Mn in plant tissues was notably higher than that of other metals. **Greger (2004)** suggests that the limited uptake of heavy metals in plants can be attributed to elevated soil salinity levels, which result in the formation of metal-chloride complexes. These complexes lead to reduced bioavailability and accumulation of heavy metals (HMs) in plants.

Translocation factor (TF) of heavy metal

The efficacy of the translocation factor (TF) in facilitating the movement of heavy metals (HMs) from belowground structures to aboveground organs in plants was demonstrated in a study conducted by **Usman *et al.* (2012)**. Furthermore, the translocation factor (TF) was determined by dividing the amounts of heavy metals in the leaves by the concentrations found in the aerial roots. This metric signifies the capacity to facilitate the translocation of heavy metals from the root system to the aerial parts of the plant.

Table 8. Translocation factors of heavy metals in mangrove trees of Nabq protectorate area

Location	Cu	Fe	Pb	Cd	Zn	Mn
	TF					
NA1	1.05324	0.696	0.955	1.109	1.014	0.806
NA2	0.413	1.825	1.447	1.58	1.491	1.916
NA3	0.406	1.624	1.727	1.55	0.964	0.122
NB1	0.933	0.984	0.713	0.65	0.67	0.608
NB2	1.266	2.51	0.999	1.097	0.631	0.269
NC1	0.804	0.634	0.683	1.654	0.956	6.027
NC2	1.16	1.277	1.179	1.157	1.396	2.146
ND1	1.679	0.879	1.067	1.117	1.504	2.978
NE1	1.45758	1.22846	1.13551	0.98833	1.75571	2.54093
NE2	1.07676	0.54213	0.4919	0.79458	1.51921	2.92232
NF1	1.05166	0.50459	0.70515	0.85128	1.24688	3.7518
NG1	3.37936	18.4119	1.8671	2.58394	2.86844	22.4458

The aforementioned calculations were previously conducted within our research area, as indicated in Table (8).

According to the data presented in Table (8), the location identified as N7b within the mangrove patch exhibited the highest translocation factor (TF) for the element manganese (Mn), with an approximate value of 22.4458. Following Mn, the elements Fe, Cu, Zn, Cd, and Pb displayed TF values of 18.41194, 3.379357, 2.868437, 2.583942, and 1.867099, respectively. Key metals, such as magnesium, iron, manganese, zinc, and copper, play crucial roles in various physiological processes within chloroplasts, including protein synthesis, enzyme activity, growth hormone regulation, and glucose metabolism. The presence of elevated concentrations of these metals in mangrove leaves suggests that they serve as micronutrients and essential elements for the growth and metabolic processes of mangrove vegetation, being absorbed and utilized by the plants.

The current study revealed that the concentrations of heavy metals in mangrove leaves ranged from non-polluted levels to slightly exceeding the limits permitted by the World Health Organization (WHO). Copper, lead, and cadmium concentrations were slightly above the WHO's permissible levels, while zinc, manganese, and iron concentrations were within the established limits. The relatively low translocation factors observed for key metals in mangroves suggest their utilization for metabolic processes and plant development. However, there is a notable disparity in the translocation of non-essential metals from the roots to the leaves.

CONCLUSION

In conclusion, the investigation of heavy metal concentrations in the tissue of *Avicennia marina* collected from the Nabq protectorate area contributes to our understanding of the extent of metal pollution in this ecologically important region. The enrichment factor (EF) values of seawater reveal that the contamination levels of the sampled locations within the investigated region are minimal, with all EF values below 1. This indicates a relatively low level of metal contamination by the examined metals. Furthermore, the analysis of the Metal Pollution Index (MPI) of water in the Nabq area provides insights into the overall degree of metal pollution in the examined sites within the Nabq protectorate. The classification of these sites in class III, with MPI values falling within the range of 1- 2 levels, indicates a minor degree of metal pollution. This classification underscores the importance of continued monitoring and effective management strategies to preserve the coastal ecosystem and estuary in the Nabq area. The findings of this study shed light on the concentrations of heavy metals in mangrove leaves and their potential implications for environmental and human health. The results indicate that the levels of heavy metals in the examined mangrove leaves ranged from non-polluted to slightly exceeding the limits set by the World Health Organization (WHO). Specifically, copper, lead, and cadmium concentrations were found to be slightly above the permissible levels established by the WHO. This suggests the presence of localized pollution sources or anthropogenic activities in the surrounding areas that contribute to the elevated levels of these metals. On the other hand, the concentrations of zinc, manganese, and iron in the mangrove leaves were within the acceptable limits.

Overall, these findings highlight the importance of addressing heavy metal contamination and implementing measures to mitigate its impact on mangrove ecosystems. Preserving the health and integrity of these ecosystems is crucial for the sustainable management of coastal regions and the protection of marine biodiversity.

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