Research

Evaluation potentiality of *Rhizophora mucronata* plantation for pollutants remediation on the Red Sea Coast, Egypt

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Abstract

The planted *Rhizophora mucronata* was evaluated in two plant ages (one year and eight years) as a biological tool for reducing the mobility of heavy metals in sediments in Safaga and Hamata, Red Sea Coast, Egypt. It is an important region for tourism and nature reserves; however, this area suffers from various anthropogenic contaminants. The ability of mangrove plantations to reduce sediment contamination through bioaccumulation, phytostabilization, or phytoextraction must be clarified through the investigation of metal behavior in mangrove plants and sediments. All of the studied heavy metals had significantly higher concentrations in the Safaga site's sediments. Elder plants had much lower levels of heavy metals in their sediments than younger plants, also rhizosphere samples were less contaminated than non-rhizosphere ones. The order of remediation efficiency was Mo > Ni > Mn ≥ Co > Al > Cu > Zn ≥ Cr > Fe > V, where the highest % was 99.25, 58.97, 42.64, 42.48, 41.91, 39.47, 37.93, 37.01, 36.89, and 29.44, respectively. *R. mucronata* parts were more significantly contaminated with Co, Cr, Cu, Mo and Zn in Safaga site, while at the Hamata site, they were more significantly contaminated with Al, Fe, Mn, Ni, and V. The elder plants accumulated higher concentrations than younger ones and the contents of heavy metals in plant samples followed the order of root > aerial roots > shoot. Bioconcentration factor (BCF) values representing the accumulation efficiency of *R. mucronata* were Ni > Mo > Zn > Cu > Cr > Co > Mn ≥ Al > V > Fe, where their highest values were 17.74, 7.89, 3.95, 3.84, 2.66, 1.91, 1.67, 1.66, 1.6, 1.18, respectively. BCF values exceeded one for all metals and values of translocation factor (TF) were less than unity in all cases, thus *Rhizophora mucronata* can be considered as a good phytostabilizer of ten studied heavy metals able to reduce their mobility through accumulation by roots, thereby reducing off-site contamination.

Article highlights

- *Rhizophora mucronata* was planted on Red Sea Coast, Egypt in an attempt to reduce pollution of sediments with ten studied heavy metals.
- Elder plants (eight years old) accumulated higher heavy metals contents than younger ones (one year old).
- The remediation % averaged between 99.25 to 29.44% with superior efficiency of roots more than other plant parts.

Keywords *Rhizophora mucronata* · Mangroves · Heavy metals · Phytostabilization · Ecological restoration · Plantation

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1 Introduction

Egypt, a developing nation, faces a serious dilemma due to pollution. In 2018, Egypt was ranked 66 out of 180 countries on the Environmental Performance Index (EPI), while heavy metals pollution was ranked 171 [1]. The majority of Egypt's coastal areas are distinguished by a unique diversity of environmental ecosystems and natural habitats, with the Red Sea Coast featuring coral reefs, mangrove trees, and other natural features, and the Mediterranean coast featuring wetlands, marshes, and sand dunes, among other natural features [2].

Mangroves are a group of trees that can grow under conditions of flooding with brackish water in tidal zones of tropical and subtropical regions [3]. Around 60% to 75% of the world's tropical coastlines are covered by mangroves, which are highly productive ecosystems. Mangrove habitats are characterized by high biodiversity, including crustaceans (82 species), insects (40 species), algae (36 species), echinoderms (17 species) and fish (22 species) with economic importance, mangrove trees are considered a habitat for providing protection and food for small fish [1]. In Egypt, two species of mangrove trees are grown naturally along the habitat of the Red Sea Coast, these are *Avicennia marina* and *Rhizophora mucronata*. Hurghada, on the Red Sea Coast, is home to the northernmost distribution of mangroves, which is primarily made up of *Avicennia marina*. However, from Mersa El-Madfa (Lat. 23°N) to Mersa Halaib, on the Sudano-Egyptian border, *Rhizophora mucronata* predominates or dominates with *Avicennia marina* [4]. The evergreen *Rhizophora mucronata* is a small to medium-sized tree that can reach a height of 10 or 15 m along the coast. The tree's trunk is supported by numerous aerial stilt roots [5]. *Rhizophora mucronata* is a desirable species for silvicultural practices and planting programs due to its notable characteristics, such as viviparous seeds that are simple to plant and a rapid growth rate [6]. Ecological restoration and plantation of mangroves are part of Egypt's plan to improve environmental conditions and biodiversity preservation on the Red Sea Coast. The inventory studies along the Red Sea Coast found that many sites have deteriorated as a result of establishments of the tourist resorts, and pollution by the waste and oil ships.

Desert Research Center of Egypt planted many hundreds of seedlings of *A. marina* and *R. mucronata* about ten years ago (2009–2010) in the polluted sites along the Red Sea Coast. Recently (2017–2018), Desert Research Center of Egypt conducted a project aiming at *A. marina* and *R. mucronata* plantation, especially in the localities of Safaga and Hamata polluted sites adjacent to the elder plantation. This study concerns with *R. mucronata* only, meanwhile, another study about *A. marina* was published [7].

The aim of this work is the plantation of *R. mucronata* and the evaluation of its potentiality as a phytoremediator on the Red Sea Coast through a comparison of heavy metals contents in recent *R. mucronata* plantation sites with the elder ones. Previous measurements (carried out in the study area before the new generation plantation by the authors in 2017 concerning *A. marina*) were used for comparison as initial concentrations for the recent plantation sites [7].

In the next section, methods are shown, afterward Sect. (3) exposed the results, and then in Sect. (4), the discussion is evinced, followed by Sect. (5) where the conclusions were summarized.

2 Methods

2.1 Study area

Two polluted localities were chosen for the study, the first locality was 17 km south of Safaga and the second one was at Hamata (Map 1).

2.2 *Rhizophora mucronata* plantation:

Rhizophora mucronata seedlings were planted in the polluted sites in both Safaga and Hamata sites in (2010) and (2018) (Fig. 1). In each locality, the seedlings of *Rhizophora mucronata* (12 months of age) are planted in a plantation area (2 × 2 m).

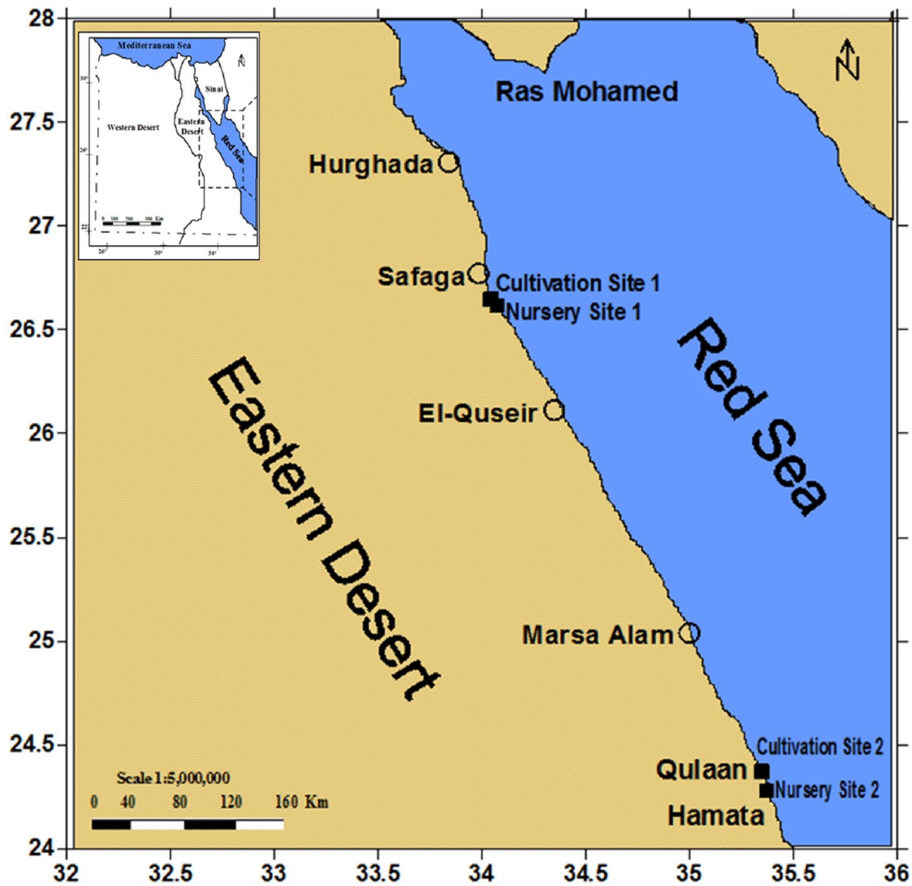
2.3 Sampling and analyses

In both Safaga and Hamata sites, samples of water, sediments (rhizosphere and non-rhizosphere) and plant parts (shoots, roots and aerial roots) were collected from recently planted *R. mucronata* (one-year-old) as well as elder ones (eight years old).

Water samples were collected from the vicinity of collected plants. Light-proof plastic containers were prewashed with distilled water and used to preserve the samples. In the field, a part of the water sample was preserved using a few drops of H_2SO_4 for COD analysis, another part was preserved using a few drops of HNO_3 for heavy metals analysis and a third part was kept as it is for salinity and pH measurements. Water samples were filtered before analysis. Chemical Oxygen Demand (COD) and Biochemical Oxygen Demand (BOD) were analyzed according to [8].

Sediments were collected from the rhizosphere and non-rhizosphere regions at depth (0–30 cm). They were

Map 1 Location map of the study area and samples showing nursery and cultivation sites



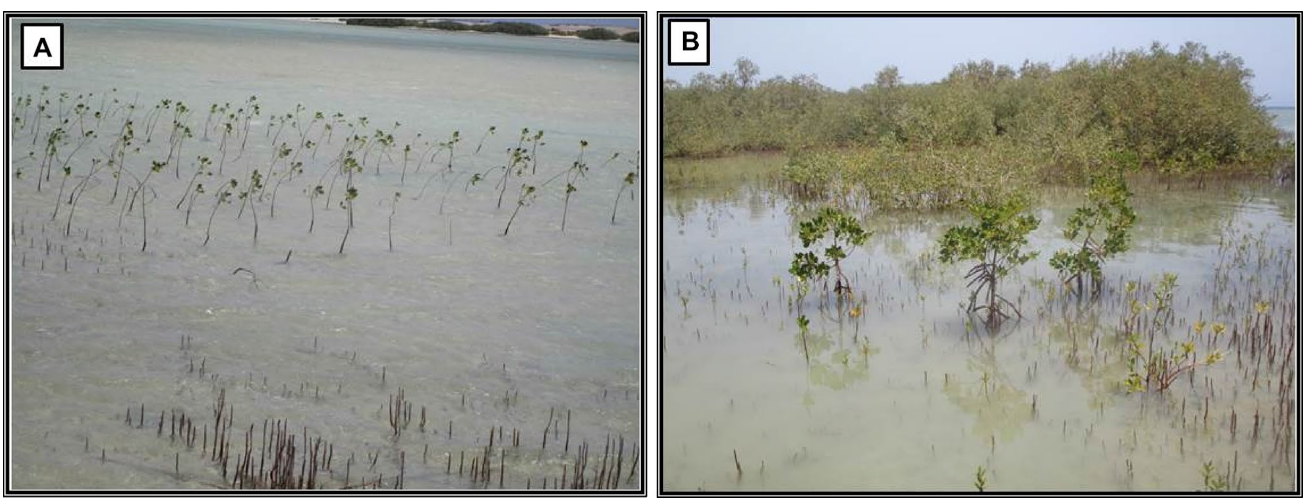


Fig. 1 Plantation of *Rhizophora mucronata* on the Red Sea Coast: **A** one-year-old, **B** 8 years old

air-dried, crushed gently and passed through a 2 mm sieve to eliminate gravel and debris. Water extracts of sediment (1: 2.5 ratio) were prepared according to the methods described by [9, 10] and used to determine pH and EC. Another part of the sample was digested as outlined by [11] using HNO_3 and H_2O_2 mixture before the analysis of total heavy metals contents.

Plant samples were washed thoroughly with distilled water, air dried at 60ºC and ground to fine particles before digestion according to [11].

2.4 Heavy metals analysis

Ten heavy metals, Al, Co, Cr, Cu, Fe, Mn, Mo, Ni,V and Zn, were analyzed in water and extracts of both plant and sediment samples using Inductively Coupled Argon Plasma, iCAP 6500 Duo, Thermo Scientific, England. Multi-element certified standard solution, Merck, Germany was used as a stock solution for instrument standardization.

2.5 Statistical analysis

MSTAT-C was used for the analysis of triplicate results using a randomized complete block design (RCBD) [12]. Mean values were compared using Duncan's new multiple tests according to [13], means having the same alphabetical letter in the same column are not significant at a significance probability value (P) = 0.05 level.

2.6 Calculations

Data were calculated and tabulated in accordance with [6, 14–16].

$$P\% = \frac{C_i - C_f}{C_i} \times 100$$

where (P%) is the parameter change percentage, (C_i) is the initial parameter concentration, (C_f) is the final parameter concentration.

$$R\% = \frac{C_n - C_r}{C_n} \times 100$$

where (R%) is the remediation % of heavy metal in sediments, (C_n) is the metal concentration in non-rhizosphere, (C_r) is the metal concentration in rhizosphere.

$$BCF = \frac{C_p}{C_s}$$

where; (BCF) is the bioconcentration factor, (C_p) is the metal concentration in plant part, (C_s) is the metal concentration in sediments.

$$TF = \frac{C_p}{C_r}$$

where; (TF) is the translocation factor, (C_p) is the metal concentration in plant part, (C_r) is the metal concentration in the root.

3 Results

3.1 Water analyses

Significantly higher concentrations of parameters were distributed among both sites (Table 1). There was no significant difference in pH between both sites; meanwhile salinity level (i.e. electrical conductance and total dissolved solids) was significantly higher in Safaga site. Hamata site recorded the higher significant BOD and COD values that were 46.49 and 5.2 mg/l against 23.24 and 3.5 mg/l in Safaga site, respectively. Also, Mn and Zn higher significant values were recorded in Hamata site, meanwhile, Safaga site showed significantly higher values of Al and Fe. Concentrations of recorded heavy metals followed the descending order of Al (0.101–1.438 mg/l) > Fe (0.068–0.318 mg/l) > Mn (0.029–0.051 mg/l) > Zn (0.026–0.035 mg/l).

In comparison with the initial measurements before the plantation of the new generation in a previous study performed by the authors [7], some changes were observed except for pH values (Table 2). In Safaga site, water salinity (TDS), BOD, COD, Mn and Zn concentrations were elevated by 0.65, 364.8, 34,900, 38.76 and 266.2%, respectively, while concentrations of Al and Fe were eliminated by 25.86 and 37.43%, respectively. In Hamata site, BOD and Zn concentrations were elevated by 93.71 and 35.14%, respectively, while concentrations of water salinity, COD, Al, Fe and Mn were eliminated by 4.09, 98.18, 97.35, 95.28 and 64.14%, respectively.

3.2 Sediment analyses

pH was significantly higher in Safaga site, where it ranged from 7.9 to 8.2 in Safaga site and from 7.8 to 8.1 in Hamata

Table 1 Physicochemical parameters and heavy metals contents of Red Sea surface coastal water samples in *Rhizophora mucronata* plantation sites

Site	pH	EC, µS/cm	TDS, mg/l	BOD, mg/l	COD, mg/l	Al, mg/l	Fe, mg/l	Mn, mg/l	Zn, mg/l
Safaga	7.9^a	60600^a	42271^a	23.24^b	3.5^b	1.438^a	0.318^a	0.029^b	0.026^b
Hamata	8.0^a	59700^b	42201^b	46.49^a	5.2^a	0.101^b	0.068^b	0.051^a	0.035^a

Remarks: concentrations of Co, Cr, Cu, V, Mo, Ni were not detected in both samples

Superscript letters are statistical letters indicating the significance of values

Table 2 Initial measurements and change % of physicochemical parameters and heavy metals contents of Red Sea surface coastal water samples in *Rhizophora mucronata* plantation sites

	Site	pH	EC, µS/cm	TDS, mg/l	BOD, mg/l	COD, mg/l	Al, mg/l	Fe, mg/l	Mn, mg/l	Zn, mg/l
Initial measurement	Safaga	7.95	57,200	42,000	5	0.01	1.9395	0.5082	0.0209	0.0071
	Hamata	8	58,200	44,000	24	285.7	3.812	1.442	0.1422	0.0259
Change (%)	Safaga	0.63	−5.94	−0.65	−364.80	−34,900	25.86	37.43	−38.76	−266.20
	Hamata	0.00	−2.58	4.09	−93.71	98.18	97.35	95.28	64.14	−35.14

Remarks: negative values mean that concentration increased after plantation

Table 3 pH and salinity of sediment samples in *Rhizophora mucronata* plantation sites (water extract 1:2.5)

Site	Plant	Localization	pH	EC	TDS
				µS/cm	mg/l
Safaga	Younger	Rhizosphere	8.1^{b}	10330^{c}	5957^{c}
		Non-rhizosphere	8.2^{a}	9720^{d}	5890^{d}
	Elder	Rhizosphere	7.9^{c}	11170^{a}	6662^{a}
		Non-rhizosphere	8.1^{b}	10870^{b}	6369^{b}
Hamata	Younger	Rhizosphere	7.8^{d}	7190^{g}	4336^{g}
		Non-rhizosphere	8.1^{b}	6340^{h}	3695^{h}
	Elder	Rhizosphere	7.8^{d}	7980^{e}	5081^{e}
		Non-rhizosphere	7.9^{c}	7440^{f}	4578^{f}

Superscript letters are statistical letters indicating the significance of values

site (Table 3). pH was significantly higher in younger plants than elder ones and also in non-rhizosphere sediments than rhizosphere ones. On the same approach as water samples, EC and TDS were significantly higher in Safaga site than in Hamata. EC ranged from 9720–11,170 µS/cm and from 6340–7980 µS/cm in Safaga and Hamata sites, respectively. TDS values ranged from 5890–6662 mg/l and from 3695–5081 mg/l in Safaga and Hamata sites, respectively. In general, rhizosphere samples were significantly more saline than non-rhizosphere ones. Also, the sediments of elder plants were significantly more saline than younger plants'.

Regarding the initial measurements before the plantation of the new generation in a previous study performed by the authors [7], both pH and salinity were changed by decreasing and increasing respectively (Table 4). pH was obviously lower in the rhizosphere sediments than non-rhizosphere ones in both sites, also pH decreased in sediments of elder plants than in sediments of younger plants. The decrease ranged between 10.99 to 15.05%. The salinity of six of eight sediment samples was increased after plantation, where the increase in sediments of elder plants was higher than younger plants; moreover, the increase in salinity of samples from the rhizosphere was higher than the non-rhizosphere ones. The increase ranged between 1.62 to 116.51%.

On the same approach as salinity, Safaga site showed higher significant concentrations of all studied heavy metals (Table 5). In Safaga site, ranges of heavy metals concentrations were 2777.5–4873.0 mg/kg (Al), 2.03–3.365 mg/kg (Co), 11.655–19.725 mg/kg (Cr), 1.995–4.75 mg/kg (Cu), 2997.8–4375.3 mg/kg (Fe), 70.85–93.65 mg/kg (Mn), 1.01–1.89 mg/kg (Mo), 2.31–4.23 mg/kg (Ni), 22.06–25.15 mg/kg (V) and 4.10–9.86 mg/kg (Zn). Meanwhile, in Hamata site, the

Table 4 Initial measurements and change % of pH and salinity of sediment samples in *Rhizophora mucronata* plantation sites (water extract 1:2.5)

	Site	Localization	pH	EC	TDS
				µS/cm	mg/l
Initial measurement	Safaga	Non-rhizosphere	9.3	5020	3077
	Hamata	Non-rhizosphere	9.1	7730	4505
Change %	Safaga Younger plant	Rhizosphere	12.90	−105.78	−93.60
		Non-rhizosphere	11.83	−93.63	−91.42
	Safaga Elder plant	Rhizosphere	15.05	−122.51	−116.51
		Non-rhizosphere	12.90	−116.53	−106.99
	Hamata Younger plant	Rhizosphere	14.29	6.99	3.75
		Non-rhizosphere	10.99	17.98	17.98
	Hamata Elder plant	Rhizosphere	14.29	−3.23	−12.79
		Non-rhizosphere	13.19	3.75	−1.62

Remarks: negative values mean that concentration increased after plantation

Table 5 Total contents of heavy metals in sediment samples in *Rhizophora mucronata* plantation sites (mg/kg)

Site	Plant	Localization	Al	Co	Cr	Cu	Fe	Mn	Mo	Ni	V	Zn
Safaga	Younger	Rhizosphere	4817.5^{b}	3.095^{b}	17.42^{b}	2.875^{b}	4285.8^{b}	80.60^{b}	1.695^{b}	3.08^{b}	24.27^{b}	6.18^{b}
		Non-rhizosphere	4873.0^{a}	3.365^{a}	19.725^{a}	4.75^{a}	4375.3^{a}	93.65^{a}	1.89^{a}	4.23^{a}	25.15^{a}	9.86^{a}
	Elder	Rhizosphere	2777.5^{e}	2.03^{e}	11.655^{d}	1.995^{d}	2997.8^{e}	70.85^{d}	1.01^{d}	2.31^{d}	22.06^{d}	4.10^{d}
		Non-rhizosphere	3756.5^{d}	2.61^{c}	12.895^{c}	2.445^{c}	3946.3^{c}	77.70^{c}	1.33^{c}	2.51^{c}	22.17^{c}	5.95^{c}
Hamata	Younger	Rhizosphere	2491.5^{f}	1.450^{f}	5.24^{f}	1.135^{f}	2469.8^{f}	44.57^{e}	N.D	1.2^{f}	10.01^{f}	0.90^{f}
		Non-rhizosphere	4289.09^{c}	2.425^{d}	7.03^{e}	1.17^{e}	3375.3^{d}	77.70^{c}	N.D	1.69^{e}	13.21^{e}	1.45^{e}
	Elder	Rhizosphere	841.09^{h}	0.440^{h}	2.425^{h}	0.83^{h}	1131.8^{g}	15.37^{g}	N.D	0.48^{g}	5.32^{h}	0.72^{h}
		Non-rhizosphere	1313.5^{g}	0.765^{g}	3.85^{g}	0.905^{g}	1793.3^{g}	25.15^{f}	N.D	1.17^{f}	7.54^{g}	0.85^{g}

Superscript letters are statistical letters indicating the significance of values

ranges were 841.09–4289.09 mg/kg (Al), 0.44–2.425 mg/kg (Co), 2.425–7.03 mg/kg (Cr), 0.83–1.17 mg/kg (Cu), 1131.8–3375.3 mg/kg (Fe), 15.37–77.70 mg/kg (Mn), 0.48–1.69 mg/kg (Ni), 5.32–13.21 mg/kg (V) and 0.72–1.45 mg/kg (Zn). It was clear that total heavy metal contents in the elder plants' sediments were significantly lower than in younger ones. Also, total heavy metal contents in rhizosphere samples were significantly lower than in non-rhizosphere ones.

Regarding the initial measurements before the plantation of the new generation in a previous study performed by the authors [7], heavy metals content was lower after plantation in all samples except one (Table 6). The decrease was observed in the sediments of elder plants more than younger ones, moreover, it was more evident in rhizosphere samples than in non-rhizosphere ones. The decrease ranged between 8.75 to 100%. The highest decrease was achieved descendingly as follows 100, 97.10, 97.02, 95.18, 93.89, 91.51, 90.08, 89.78, 86.07, 83.73% for Mo > Zn > V > Cu > Ni > Co > Cr > Mn > Al > Fe.

In another way of calculation, based on metals concentrations in the rhizosphere relative to non-rhizosphere sediments, Safaga site showed the highest significant remediation efficiency of two metals under study, where the efficiency reached 39.47% (Cu) and 99.25% (Mo) (Table 7). Meanwhile, Hamata site showed the highest significant remediation efficiency of eight metals under study, where the efficiency reached 41.91% (Al), 42.48% (Co), 37.01% (Cr), 36.89% (Fe), 42.64% (Mn), 58.97% (Ni), 29.44% (V) and 37.93% (Zn). Thus, the order of remediation efficiency as % was Mo > Ni > Mn ≥ Co > Al > Cu > Zn ≥ Cr > Fe > V. This order of remediation didn't coincide with the aforementioned order calculated according to the initial measurements. Concerning plant age, the younger plants achieved the highest significant remediation efficiency of Al, Cu, Mn and Zn that reached 41.91, 39.47, 42.64 and 37.93%, respectively. While the elder plants achieved the highest significant remediation efficiency of Co, Cr, Fe, Mo, Ni, V that reached 42.48, 37.01, 36.89, 99.25, 58.97 and 29.44%, respectively.

3.3 Plant analyses

As shown in Table 8, the highest significant concentrations of Co, Cr, Cu, Mo and Zn were found in Safaga site, meanwhile, the highest significant concentrations of Al, Fe, Mn, Ni and V were found in Hamata site. It was an important finding that the elder plants accumulated higher concentrations than younger ones. Moreover, the contents of heavy metals in plant samples followed the order of root > aerial roots > shoot.

Values of bioconcentration factor (BCF) also revealed that heavy metals' contents in plant samples followed the order of root > aerial roots > shoot (Table 9). In general, BCF values ranged from zero to 17.74. The highest significant values were recorded in the case of roots of the elder plants in Hamata. BCF values exceeded one mostly in the case of elder plants than in younger ones and in the case of Hamata site than Safaga ones. On the whole, *R. mucronata* has been able to accumulate all metals under study. The order of accumulation according to BCF values was Ni > Mo > Zn > Cu > Cr > Co > Mn ≥ Al > V > Fe.

On the other hand, values of translocation factor (TF) were less than one in all cases, and ranged from zero to 0.99 (Table 10). The highest significant TF values of Co, Mn, Mo, Ni and Zn were in Safaga site, meanwhile, the highest significant TF values of Al, Cr, Cu, Fe and V were in Hamata site. Quantitative translocation of heavy metals was noticed in younger plants than elder ones, as the highest significant TF values of seven metals (Al, Co, Cr, Fe, Mo, V and Zn) out of ten were recorded in younger plants in both sites. TF values were significantly higher in aerial roots than shoot in all cases. There were different

Table 6 Initial measurements and change % of heavy metals total contents in sediment samples in *Rhizophora mucronata* plantation sites (mg/kg)

	Site	Localization	Al	Co	Cr	Cu	Fe	Mn	Mo	Ni	V	Zn
Initial measurement	Safaga	Non-rhizosphere	5369	4.915	19.09	20.42	6035	163.05	4.132	8.135	64.07	32.81
	Hamata	Non-rhizosphere	6040	5.185	24.45	17.23	6955	150.35	32.45	7.86	178.25	24.81
Change %	Safaga Younger plant	Rhizosphere	10.27	37.03	8.75	85.92	28.98	50.57	58.98	62.14	62.12	81.16
		Non-rhizosphere	9.24	31.54	−3.33	76.74	27.50	42.56	54.26	48.00	60.75	69.95
	Safaga Elder plant	Rhizosphere	48.27	58.70	38.95	90.23	50.33	56.55	75.56	71.60	65.57	87.50
		Non-rhizosphere	30.03	46.90	32.45	88.03	34.61	52.35	67.81	69.15	65.40	81.87
	Hamata Younger plant	Rhizosphere	58.75	72.03	78.57	93.41	64.49	70.36	100.00	84.73	94.38	96.37
		Non-rhizosphere	28.99	53.23	71.25	93.21	51.47	48.32	100.00	78.50	92.59	94.16
	Hamata Elder plant	Rhizosphere	86.07	91.51	90.08	95.18	83.73	89.78	100.00	93.89	97.02	97.10
		Non-rhizosphere	78.25	85.25	84.25	94.75	74.22	83.27	100.00	85.11	95.77	96.57

translocation rates for each metal from root to shoot and to aerial roots. The order of metals translocation from root to aerial roots was Co > Al > Cr > V > Fe > Cu > Mn > Ni > Zn > Mo. The order of metals translocation from root to shoot was Cr > Ni > Al > Zn > Cu > Mo > Co ≥ Mn ≥ V > Fe.

4 Discussion

As a part of environmental restoration and management, mangrove communities may provide effective traps to immobilize water and soil-borne metals. Physical properties of soil and water may affect the phytoremediation process, as salinity and pH may represent a sort of stress on mangrove plants. In the present study, salinity and pH results of water samples as well as previous initial concentrations, were in agreement with a report has been made along the Red Sea Coast by the Ministry of State for Environmental Affairs [2], where minor changes were recorded in the salinity, ranged between (39,400–43,700 mg/l) and pH values ranged between (8.1 and 8.2). This finding clarifies that physical measurements were at their normal levels and the impact of pollutants discharging or human activities in the Red Sea is still limited.

The noticed relatively high BOD and COD concentrations in Hamata site may be attributed to the widespread tourist activity and its impact on the water bodies, where Wadi El-Gemal and Hamata Mountain Reserve is a major attractions for tourism. BOD and COD results were extremely higher than those reported by [17] in their study on Safaga surface coastal water, where BOD and COD values ranged from 1.43 to 1.23 mg/l and 7.54 to 8.32 mg/l, respectively. On the other hand, an obvious increase in BOD in both sites and COD in Safaga site occurred in comparison with the previous initial concentrations, while a great decrease in COD value was noticed in Hamata site. Safaga site is very near Safaga harbor (about 15 km), where oil and other contaminants were frequently released in small amounts, which led to marine pollution. Additionally, garbage and animal carcasses tossed overboard by ferries and ships pollute the waters [18].

The recorded concentrations of Fe, Mn and Zn were slightly higher than those reported by [17] which were 0.0361, 0.0019 and 0.0129 mg/l, respectively. Meanwhile, the non-detected concentrations of Cu, Ni and Cr in the current study were less than those that were 0.0037, 0.0013 and 0.0010 mg/l, respectively. With regard to the initial measurements before plantation, Mn and Zn concentrations were elevated while concentrations of Al and Fe were eliminated in Safaga site. In the other site, Hamata, Zn concentration was elevated

Table 7 Heavy metals remediation efficiency of *Rhizophora mucronata* in Safaga and Hamata sediments

Site	Plant	Remediation (%)									
		Al	Co	Cr	Cu	Fe	Mn	Mo	Ni	V	Zn
Safaga	Younger	1.140^{d}	8.020^{d}	11.69^{c}	39.47^{a}	2.05^{d}	13.93^{c}	10.32^{b}	27.19^{b}	3.48^{c}	37.32^{b}
	Elder	26.06^{c}	22.22^{c}	9.62^{d}	18.40^{b}	24.04^{c}	8.82^{d}	99.25^{a}	7.97^{c}	0.50^{d}	31.09^{c}
Hamata	Younger	41.91^{a}	40.21^{b}	25.46^{b}	2.99^{d}	26.83^{b}	42.64^{a}	0.00	28.99^{b}	24.22^{b}	37.93^{a}
	Elder	35.97^{b}	42.48^{a}	37.01^{a}	8.29^{c}	36.89^{a}	38.89^{b}	0.00	58.97^{a}	29.44^{a}	15.29^{d}

Superscript letters are statistical letters indicating the significance of values

Table 8 Contents of heavy metals in *Rhizophora mucronata* samples (mg/kg dry weight)

Site	Plant	Plant part	Al	Co	Cr	Cu	Fe	Mn	Mo	Ni	V	Zn
Safaga	Younger	Shoot	126.04^{k}	0.06^{j}	1.655^{i}	0.575^{k}	140.75^{j}	2.62^{k}	0.89^{f}	1.28^{k}	0.485^{i}	1.715^{f}
		Root	270.24^{g}	0.135^{g}	4.12^{e}	1.01^{h}	364.95^{f}	8.815^{g}	1.85^{e}	1.74^{h}	1.205^{f}	2.560^{d}
		Aerial roots	188.44^{h}	0.135^{g}	2.68^{h}	0.595^{j}	280.55^{g}	5.24^{i}	1.375^{d}	1.325^{j}	0.785^{g}	2.045^{e}
	Elder	Shoot	307.59^{f}	0.165^{f}	6.40^{c}	1.74^{e}	422.3^{e}	10.64^{e}	2.085^{c}	2.745^{f}	1.305^{e}	3.935^{c}
		Root	1197.09^{b}	0.865^{a}	8.455^{a}	4.765^{a}	1151.3^{b}	24.425^{b}	7.97^{a}	3.925^{c}	7.225^{b}	16.175^{a}
		Aerial roots	712.59^{c}	0.325^{c}	7.685^{b}	2.545^{d}	625.3^{c}	21.405^{c}	2.19^{b}	3.405^{d}	2.605^{c}	8.645^{b}
Hamata	Younger	Shoot	108.14^{l}	0.035^{k}	1.365^{j}	0.395^{l}	85.35^{k}	1.595^{l}	N.D	1.085^{k}	0.175^{l}	N.D
		Root	149.04^{i}	0.11^{h}	3.195^{f}	1.245^{g}	240.4^{i}	5.755^{h}	N.D	2.005^{g}	0.395^{j}	N.D
		Aerial roots	143.69^{j}	0.08^{i}	2.94^{g}	0.785^{i}	216.8^{h}	4.535^{j}	N.D	1.620^{i}	0.36^{k}	N.D
	Elder	Shoot	327.99^{e}	0.19^{e}	5.135^{d}	1.445^{f}	421.6^{e}	9.705^{f}	0.075^{i}	3.125^{e}	0.66^{h}	N.D
		Root	1392.59^{a}	0.84^{b}	6.445^{c}	3.185^{b}	1336.8^{a}	25.69^{a}	0.445^{g}	8.515^{a}	8.535^{a}	1.70^{f}
		Aerial roots	441.14^{d}	0.25^{d}	5.185^{d}	2.845^{c}	446.8^{d}	13.37^{d}	0.135^{h}	6.895^{b}	2.54^{d}	N.D

Superscript letters are statistical letters indicating the significance of values

Table 9 Bioconcentration factor (BCF) values of heavy metals in *Rhizophora mucronata* parts

Site	Plant	Plant part	Al	Co	Cr	Cu	Fe	Mn	Mo	Ni	V	Zn
Safaga	Younger	Shoot	0.03^{i}	0.02^{h}	0.10^{k}	0.20^{j}	0.03^{i}	0.03^{k}	0.53^{f}	0.42^{l}	0.02^{j}	0.28^{g}
		Root	0.06^{g}	0.04^{g}	0.24^{i}	0.35^{i}	0.09^{g}	0.11^{h}	**1.09^{d}**	0.56^{j}	0.05^{g}	0.41^{e}
		Aerial roots	0.04^{h}	0.04^{g}	0.15^{j}	0.21^{j}	0.07^{h}	0.07^{i}	0.81^{e}	0.43^{k}	0.03^{i}	0.33^{f}
	Elder	Shoot	0.11^{f}	0.08^{e}	0.55^{g}	0.87^{g}	0.14^{e}	0.15^{f}	**2.06^{c}**	**1.19^{h}**	0.06^{f}	0.96^{d}
		Root	0.43^{c}	0.43^{c}	0.73^{d}	**2.39^{c}**	0.38^{c}	0.34^{d}	**7.89^{a}**	**1.70^{d}**	0.33^{d}	**3.95^{a}**
		Aerial roots	0.26^{e}	0.16^{d}	0.66^{e}	**1.28^{e}**	0.21^{d}	0.30^{e}	**2.17^{b}**	**1.47^{f}**	0.12^{e}	**2.11^{c}**
Hamata	Younger	Shoot	0.04^{h}	0.02^{h}	0.26^{h}	0.35^{i}	0.03^{i}	0.04^{j}	0.00	0.90^{i}	0.02^{j}	0.00
		Root	0.06^{g}	0.08^{e}	0.61^{f}	**1.10^{f}**	0.10^{f}	0.13^{g}	0.00	**1.67^{e}**	0.04^{h}	0.00
		Aerial roots	0.06^{g}	0.06^{f}	0.56^{g}	0.69^{h}	0.09^{g}	0.10^{h}	0.00	**1.35^{g}**	0.04^{h}	0.00
	Elder	Shoot	0.39^{d}	0.43^{c}	**2.12^{c}**	**1.74^{d}**	0.37^{c}	0.63^{c}	0.00	**6.51^{c}**	0.12^{c}	0.00
		Root	**1.66^{a}**	**1.91^{a}**	**2.66^{a}**	**3.84^{a}**	**1.18^{a}**	**1.67^{a}**	0.00	**17.74^{a}**	**1.60^{a}**	**2.36^{b}**
		Aerial roots	0.52^{b}	0.57^{b}	**2.14^{b}**	**3.43^{b}**	0.39^{b}	0.87^{b}	0.00	**14.36^{b}**	0.48^{b}	0.00

Bold values exceed 1, it has a significant meaning in detecting the mechanism of metal removal by plant

Superscript letters are statistical letters indicating the significance of values

while concentrations of Al, Fe and Mn were eliminated. Seawater is dynamic and in continuous flow. Its movement is influenced by its physical characteristics, such as temperature, salinity, and density, as well as external forces like the sun, moon, and winds. The horizontal and vertical motions that occur in water bodies cause water to advance from one location to another. That is why it is predictable to observe numerous changes in its contents and pollutants from time to another.

Table 10 Translocation factor (TF) values of heavy metals in *Rhizophora mucronata* from root to plant parts

Site	Plant	Plant part	Al	Co	Cr	Cu	Fe	Mn	Mo	Ni	V	Zn
Safaga	Younger	Shoot	0.47^{e}	0.44^{c}	0.40^{g}	0.57^{d}	0.39^{c}	0.30^{g}	0.48^{b}	0.74^{d}	0.40^{d}	0.67^{b}
		Aerial roots	0.70^{c}	0.99^{a}	0.65^{e}	0.59^{c}	0.77^{b}	0.59^{c}	0.74^{a}	0.76^{c}	0.65^{b}	0.80^{a}
	Elder	Shoot	0.26^{g}	0.19^{h}	0.76^{d}	0.37^{g}	0.37^{d}	0.44^{e}	0.26^{d}	0.70^{e}	0.18^{g}	0.24^{d}
		Aerial roots	0.60^{d}	0.38^{d}	0.91^{b}	0.53^{e}	0.54^{c}	0.88^{a}	0.27^{c}	0.87^{a}	0.36^{e}	0.53^{c}
Hamata	Younger	Shoot	0.73^{b}	0.32^{e}	0.43^{f}	0.32^{h}	0.36^{d}	0.28^{h}	0.00	0.54^{f}	0.44^{c}	0.00
		Aerial roots	0.96^{a}	0.77^{b}	0.92^{a}	0.63^{b}	0.90^{a}	0.79^{b}	0.00	0.81^{b}	0.91^{a}	0.00
	Elder	Shoot	0.24^{h}	0.23^{g}	0.80^{c}	0.45^{f}	0.32^{f}	0.38f	0.00	0.37^{g}	0.08^{h}	0.00
		Aerial roots	0.32^{f}	0.30^{f}	0.80^{c}	0.89^{a}	0.33^{e}	0.52^{d}	0.00	0.81^{b}	0.30^{f}	0.00

Superscript letters are statistical letters indicating the significance of values

In sediments, pH was significantly higher in younger plants than elder ones and also in non-rhizosphere sediment than rhizosphere. This may be attributed to the extensively fibrous root system which forms thick peat-like mud and subsequently lowers the pH after decomposition [4]. Mangrove plants possess a variety of adaptations to high salt concentrations as extreme environmental stresses. One of them is salt exclusion by root ultra-filtration driven by the pulling force generated by transpiration. In particular, *Rhizophora* sp. lacks salt glands like some other mangroves, but has a more strict salt exclusion mechanism at the root level, avoiding salt entering the sap of the tree [19]. This explains why sediments of elder plants were more saline than those of younger plants and why samples from the rhizosphere were more saline than those from the non-rhizosphere.

Higher significant concentrations of all studied heavy metals in Safaga sediments can be attributed to the industrial and economic activities in Safaga, as it is not only a tourist city but also a seaport that represents a gateway for Duba sea port to travelers or some pilgrims to Saudi Arabia by ferries, meanwhile Hamata is considered as a tourist area in the first place. The site may affect heavy metals' concentrations in sediments as a result of their significant positive correlation with sediment particle size and organic carbon content [20, 21].

The significantly lower heavy metal contents in the elder plants' sediments than younger ones and the significantly lower contents in rhizosphere samples than non-rhizosphere ones reflect the high efficiency of *Rhizophora mucronata* to remediate heavy metals from the contaminated sediments, especially in the long run.

Based on the calculated remediation % of sediments, elder plants achieved the highest significant sediments remediation efficiency of six metals (five in Hamata and one in Safaga) against four metals in younger plants (three in Hamata and one in Safaga). This is because of the lower concentrations in Hamata than Safaga, which makes the calculated percentage of removal higher by a smaller taken amount.

The calculated remediation % (based on the concentration of elements in the rhizosphere versus the non-rhizosphere sediment) is more realistic than the calculated change % (based on the initial measurements of the sediment against after plantation state), because the state of the sediment is in persistent change as a result of many factors, including the continuous deposition of new pollutants, movement of sediments due to continuous horizontal and vertical motions of water and the presence of the mangrove plant in its natural habitat next to the plantation area that decreases the sediments content of heavy metals. All of these reasons make the other values only estimated ones that reflect the change in heavy metals state in plantation area but can't be taken as accurate evaluation values of *R. mucronata* accumulation efficiency.

Numerous factors influence the heavy metals' discharge, accumulation and distribution in sediments, such as the texture, total organic matter amount, chloride, sulphate, bicarbonate, mineralogical composition, salinity, physical transport, and depositional environment of the area [22–25]. Mangrove sediments, as illustrated by [26], can effectively immobilize waste water-borne heavy metals and phosphorus, despite their inability to retain nitrogen, this may be due to the great inclination of organic matter for such pollutants thereby act to accumulate them [27–29].

In solidarity with the results of sediments analyses, plant parts analyses revealed that the elder plants accumulated higher concentrations than younger ones [30] suggested that plant age and biomass production affect the ability of mangroves to accumulate heavy metals. Also, [31] demonstrated that the amount of metal in young leaves is lower than in older leaves, where younger leaves were more difficult to accumulate heavy metals than older leaves. As well as, [32] illustrated that the plantation period increase of *Rhizophora apiculata* from 5 to 20 days was found to increase Zn removal efficiency from wastewater. Mangroves can survive under pollution conditions; by storing a lot of water to dilute the concentrations of heavy metals in their tissues, mangrove plants can reduce the toxicity of those metals and help prevent the spread of other toxic substances by weakening their toxic effects [33].

According to [34], accumulator plants are those that can take in and store pollutants in the body, while plants that can take up to 100 mg/l are referred to as hyperaccumulator plants. The calculated value of the bioconcentration factor indicates the ability of plants to remove metal compounds from the soil/substrate. Meanwhile, the value of the translocation factor indicates the ability of the compound to be transferred from plant roots to other organs [35, 36]. Bioaccumulator plants should have bioconcentration and translocation factors > 1. Plants that have bioconcentration factor values > 2 are considered to be hyperaccumulators. Plants can be used as phytoextractors if they have bioconcentration factors < 1 and translocation factors > 1 and as phytostabilizers if they have bioconcentration factors > 1 and translocation factors < 1 [37].

Phytostabilization involves the establishment of a plant cover on the contaminated sites' surfaces aiming to reduce the mobility of contaminants through accumulation by roots, thereby reducing off-site contamination [38]. Regarding the calculated BCF values, *R. mucronata* has been able to accumulate all metals under study following the order of root > aerial roots > shoot. The same finding were obtained by [39] where metal concentrations decreased from the root region to the stem and leaves of *Rhizophora apiculata* seedlings and also coincide with [40] and [41] where roots of mangroves plants were found to have the higher metal concentrations than aerial parts. The majority of the heavy metals are held in place by the mangrove roots through bounding with the cell wall material or other macromolecules, thus roots act as a barrier and reduce their transfer to other sensitive plant parts [42]. Whereas, the roots of *Rhizophora* can absorb concentrated amounts of heavy metals from the surrounding soil and water, mangrove plants possess detoxification mechanisms in an effort to prevent metal toxicity against cells and tissues by trapping metals in the roots [43, 44]. It was thought that heavy metals accumulation by roots is inversely proportional to sediment particle size [45, 46]. As well as, the root system and surface area have an impact on the root's capacity to absorb heavy metals [47]. As mangrove plants' aerial roots spread oxygen into the substrate, oxidation happens in the rhizosphere, causing metal accumulation in fine roots, which is why aerial roots came in second place to roots [15].

Hereby values of BCF and TF values, *R. mucronata* can be considered a good phytostabilizer of heavy metals under study. The wide range of BCF values in the current study that ranged from zero to 17.74 revealed the variation of the phytostabilization capacity of *R. mucronata* in the mangrove ecosystem from one metal to another. It was illustrated that the translocation rates of each metal from root to shoot varied significantly, where Cu, Mn and Fe showed restricted mobility, while Cd, Ni, Cr, Zn and Pb had greater mobility [6]. This conclusion concurred with findings in the current study, where the translocation factor from root to shoot followed the order of Cr > Ni > Al > Zn > Cu > Mo > Co ≥ Mn ≥ V > Fe. These outcomes probably are in association with the different solubility and availability of each metal ion, as well as the unique ability of *R. mucronata* as mangrove species to store non-essential metals in the tree's aerial parts, where these metals were accumulated in the leaves before falling off and being eliminated. Similar findings on the transfer of metals in *Rhizophora stylosa* were also reported by [48].

5 Conclusions

Rhizophora mucronata plantation on the Red Sea Coast sea, Egypt is an efficient long-run way to reduce contamination of sediment by heavy metals through the phytostabilization mechanism. The accumulation capacity of planted *R. mucronata* varies from metal to metal that Ni > Mo > Zn > Cu > Cr > Co > Mn ≥ Al > V > Fe. Rhizosphere sediments contained less significant heavy metals concentrations than non-rhizosphere ones in both one-year and eight years old plants. Elder plants attained less heavy metals content in their sediment than younger plants, which coincides with their concentrations in plant tissues, where the elder plants accumulated higher concentrations than younger ones. Roots were able to accumulate more heavy metals contents than aerial roots and shoot comes in third place. Widening of ecological restoration and plantation of mangroves along the Red Sea Coast is recommended to eliminate the pollution of heavy metals in such important tourist areas.

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Declarations

Competing interests The authors declare no competing interests.

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